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Bushfires and their implications for management of future water supplies in the Australian Capital Territory.

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Abstract Periodic, often ENSO-related widespread droughts in eastern Australia frequently generate severe bush fires. These can devastate water supply catchments and have serious impacts on the quality and quantity of domestic water supplies. The implications for water supplies sourced from native forests and their management are profound. The Cotter River Catchment in the Australian Capital Territory (ACT), eastern Australia has been a major source of water for the national capital, Canberra, since 1918. Previous work following the 1939 bushfires in alpine ash (*Eucalyptus Regnans*) catchments in the southern Australia state of Victoria found large decreases in yields (of the order of 30%) for up to 50 years following the fires as forests regrew. It is shown here that the response of catchments with mixed native forests to fires differs from the alpine ash forests in Victoria. Slight increases in yield appear apparent initially over the first 30 months because of the decreases in evapotranspiration. It is thought that as epicormic regeneration of eucalypts continues small decreases in yield of less than 10% could occur for some years but the similar results occur after severe droughts without bushfires. Dramatic increases in turbidity, iron, manganese, organic carbon, phosphorous and nitrogen in the reservoirs resulted from the 2003 fires and these persisted for over 12 months. This made water unfit for reticulation as the water needed treatment and forced water restrictions on the ACT for the first time since 1968. The fires revealed problems in the monitoring of catchment water resources and in the management of water resources in the ACT. From our analysis of the aftermath of the fires we suggest changes to the management of water resources in the ACT to improve planning for and response to bush fires and their consequences for domestic water supplies.

Keywords Drought; bushfires; catchment yield, water quality; water resource management.

INTRODUCTION

Bushfire effects on the catchments of rivers that are used for town water supplies are of great concern. The primary effects are the elimination of the vegetation and the generation of watershed pollution from ash and burnt litter. The secondary effects resulting from the fire are hard to predict and vary from catchment to catchment but can include short-term increase/decrease in runoff and baseflow, and an increase in sediment and ion concentrations in runoff. During the process of recovery this reduction in runoff from the catchment and increase in suspended and dissolved loads are of major concern for the reliability of supply to the city depending on the water. The relationship between the occurrence and effects of major bush fires with climate and hydrological variables is investigated in this paper.

The Cotter River catchment in the Australian Capital Territory (ACT), eastern Australia has been a major source of water for the national capital, Canberra, since 1918. The Cotter catchment is located along the western edge of the ACT as shown in Fig 1. Three dams: Corin, Bendora and Cotter (from upper to lower catchments) have been built on the Cotter River and their capacities and relative contributing catchment areas shown in Table 1. The other major water source for Canberra is the Googong dam located on the Queanbeyan River (Fig 1).

Table 1. Summary of dams in the Cotter catchment

DAM	Catchment Area (km^2)	Capacity (GL)	Mean runoff (GL/yr)
Corin	197	76	76
Bendora	91	11	34
Cotter	193	4.7	36

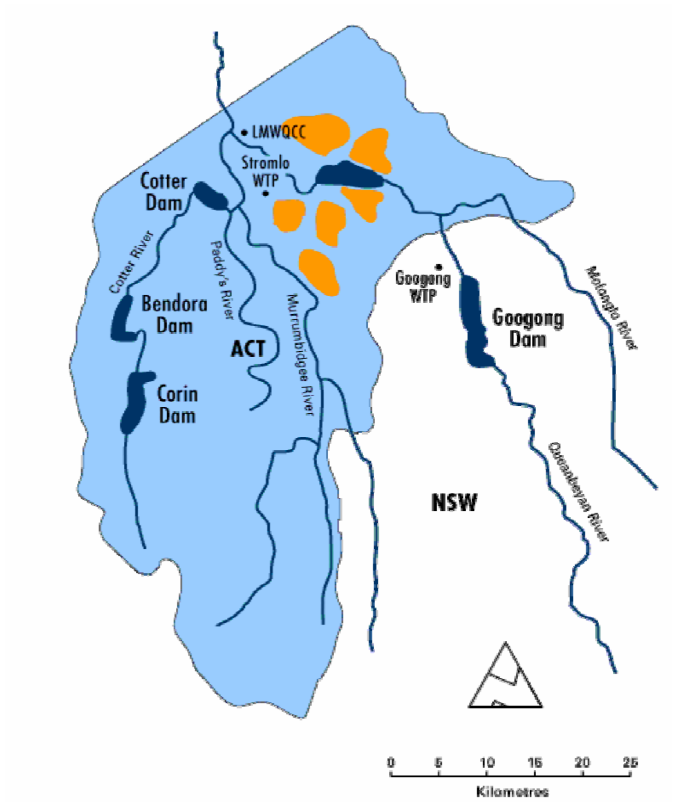


Figure 1 The location of the main dams of the ACT and their relevant catchments.

Following construction of the Cotter Dam, cleared grazing land in the lower Cotter catchment was quickly replaced with Pinus Radiata to improve the quality of water in the Cotter Reservoir but the commercial forestry practices compromised water quality in the lower catchment. Dams in the upper Cotter, completed in 1968, were fed from a near pristine, mixed native forested catchment. Water quality was so good from this source that flocculation and filtration facilities were not installed and water only required chlorination, minor pH adjustment and fluoridation.

Previous work following the 1939 bushfires in alpine ash (*Eucalyptus Regnans*) catchments in the southern Australia state of Victoria found large decreases in yields for up to 50 years following the fires as forests regrew (Langford, 1976; Kuczera, 1985).
There were known to be fires in the ACT in 1920, 1926 and 1939. The 1939 fire was exacerbated by weather with strong winds, which resulted in spot-fires up to twenty-four kms ahead of the fire-front (Carey et al, 2003).

In January 1983, following a prolonged drought approximately 30% of the upper Cotter catchment was burnt in a bushfire. This was the last major fire in the ACT prior to the fires of December 2001 where 20 000 ha of grasslands and 145 ha of pine plantations were burnt. At the end of the 2002-3 drought, major bushfires swept through the Australian Capital Territory (ACT). These January 2003 fires devastated the national capital, Canberra, and burnt out 165 000 hectares of landscape, caused major loss of private housing, infrastructure including water supply treatment plants, softwood plantation, and publicly owned facilities. Approximately 70% of the ACT, including 90% of Namadgi National Park and, five of the nine ACT river catchments were burnt to varying intensities—all or almost all of the Cotter, Gudgenby–Naas and Paddys River catchments, and parts of the Molonglo and Murrumbidgee River catchments.
(http: //www.environmentcommissioner.act.gov.au /text/fire03.html)

In this paper we review the impact of those fires on both the quality and quantity of water from the Cotter catchment and examine the implications for the management of catchments and water resources in the ACT.

CLIMATE ISSUES

Droughts are one of the main driving mechanisms for bushfires in that soil moisture levels are lowered significantly due to low rainfall and the forests become stressed. There is evidence of a strong relationship between El Niño Southern Oscillation (ENSO) and The Interdecadal Pacific Oscillation (IPO) severe droughts and subsequent bushfires.

El Niño Southern Oscillation (ENSO) Effect

ENSO is a natural fluctuation of the tropical Pacific atmosphere and ocean. ENSO variability is defined in terms of the Southern Oscillation Index (SOI) which is the Tahiti minus Darwin mean sea-level pressure difference, normalized with a base period of 1933–1992 (Troup, 1965; Folland et al, 2002). Sea temperatures, winds, and rainfall patterns in the Pacific show a distinct difference between the El Niño and La Niña phases. In the El Niño phase, when the SOI is strongly negative, the key feature is that tropical sea surface temperatures in the central and eastern near-equatorial Pacific can become several degrees warmer than normal. The resulting climate on the East coast of Australia is one of drought. Major bushfires and drought are linked as the natural forested catchments dry and become more prone to bushfires, both natural and human generated.

The Interdecadal Pacific Oscillation (IPO)

The Interdecadal Pacific Oscillation (IPO) is a natural fluctuation of sea surface temperatures and winds in the Pacific. The IPO has been shown to modulate interannual ENSO-related climate variability over Australia (Power *et al.*, 1999). The key difference is that IPO operates over decades, whereas ENSO operates over 2 to 7 year cycles, and the IPO involves higher latitudes (particularly the North Pacific) as well as the tropics and New Zealand (Salinger *et al.*, 1995). The IPO is characterized using the time series of an Empirical Orthogonal Function of 13 year low pass filtered global Sea Surface Temperatures as shown in Fig 2 (Folland et al., 1999; Power et al., 1999). Three main phases of the IPO have been identified during the 20th century: a positive phase (1922 –

1944), a negative phase (1946 – 1977) and another positive phase (1978 – 2000). The positive phases of the IPO correspond to generally drier periods in eastern Australia.

There is a strong link between the occurrence of ENSO events and positive IPO events as shown in Fig 2. During positive IPO periods, there are frequent or more intense El Niño events which are highly correlated with drought and risk of fire in the Eastern regions of Australia. (Verdon et al, 2004). Bushfires that have occurred in the Canberra region are marked on Fig 2. The combined effect of natural and human caused severe fires in the Alps in the fire seasons of 1851/52, 1902/03, 1938/1939 and 2002/2003. In the case of most of these wildfires, much of the Cotter catchment was burnt out. These all correspond with positive IPO.

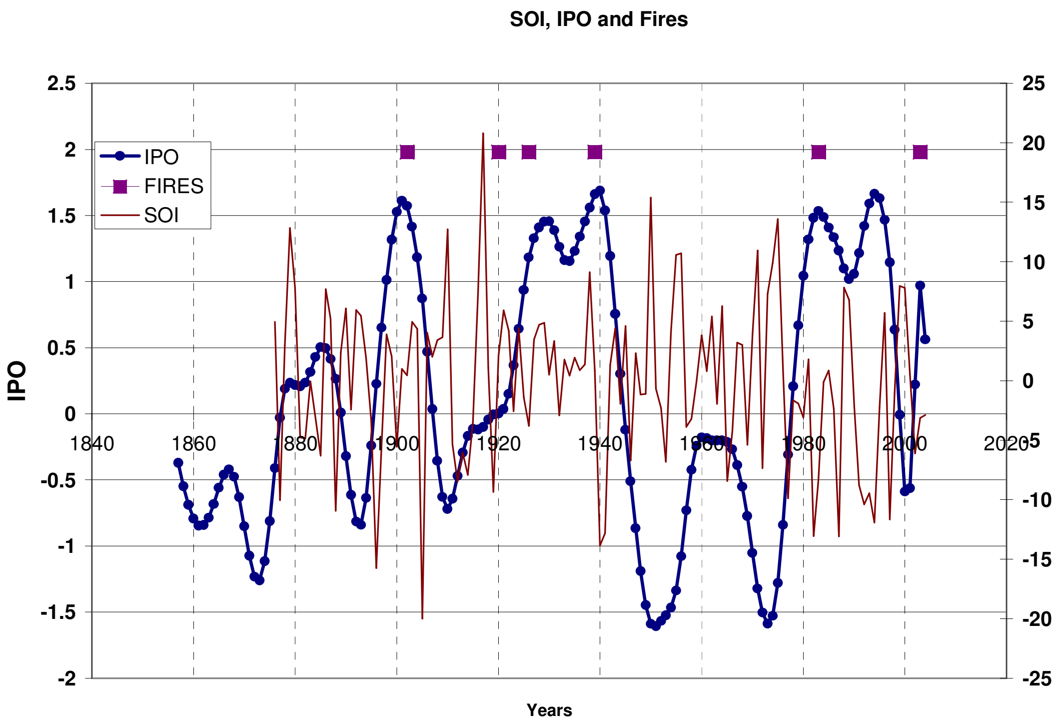


Figure 2 SOI, Interdecadal Pacific Oscillation (IPO) and Cotter Bushfire Occurrence

In drought conditions the availability of dry fuel is a major factor in fire spread which is highly likely in the summer January –early February period. Nevertheless, it is possible to estimate the probability that rainfall and temperature over Australia will be above or below the median for up to a season ahead, using relationships such as IPO and the Southern Oscillation Index (SOI). ENSO has the greatest impact on the Australian region, but it needs to be borne in mind that linear correlation coefficients of SOI with regional rainfall are at most in the range 0.6 to 0.7 (Verdon et al, 2004) and many regions are lower than this, Even where the relationship is strongest less than 50% of the variation in rainfall is predictable from this source. ENSO relationships have a strong influence on the seasonal climate of certain parts of Australia, but there are other ocean/atmosphere systems that impact, including the Madden-Julian Oscillation (MJO) in the tropics, described in http://envam1.env.uea.ac.uk/~e058/mjo.html and Indian Ocean sea surface temperatures (Drosdowsky and Chambers, 2001).

SEVERITY OF FIRES

Most of the Cotter catchment was severely burnt in the 2003 fire. The classes of fire intensity classes in eucalypt forests (Cheney, 1981) are shown in Table 1 which includes a column (AMOG and EcoGIS, 2005) that relates fire intensities and flame heights to severity effects in eucalypt forests.

Table 1. Range of Fire Intensities and Flame Heights (Cheney, 1981)

Class	Fire intensity (kw/m)	Max. flame height (m)	Remarks	Severity Effects in Eucalypt Forest
Low	**< 500**	**1.5**	Upper limit recommended for fuel-reduction burning.	Partial removal of litter and ground cover layer. Scorch or partial removal of low shrub canopy
Moderate	**501-3000**	**6**	Scorch of complete Crown in most forests.	More complete removal of litter layer. Low and medium shrub layer canopy consumed. Partial canopy scorch, depending on tree height.
High	**3000-7000**	**15**	Crown fires in low forest types - spotting > 2 km.	Litter layer removed down to mineral soil. 100% canopy scorch of tree layer.
Very High	**7000-70000**	**> 15.0**	Crown fire in most forest types - fire storm condition at upper intensities.	Litter and top of soil layer completely burnt. All vegetation layers completely removed.

The 1983 fire was assumed to be an infrequent mixed severity fire, which equated to High /Very High in Table 2. This fire produced soil erosion in both topsoil and sub-soil, mainly from granite derived soils, principally yellow podzolics. The 2003 fire varied in intensity but large areas, particularly steeper eastern slopes had Very High fire intensities. Organic and sediment production in the years following the 1983 fire was about half that of the 2003 fire.

ISSUES FOR CATCHMENT AND WATER SUPPLY MANAGERS

Following a bushfire in the Cotter Water Supply catchment, a number of impacts affect the operation of Canberra's water supply system. Pristine streamflows from the forested catchment become polluted with the residues of the fire and soils are prone to erosion as there is no vegetative cover. There has been a great deal of conjecture on the changes in yield of streamflow that come from the burnt catchment. The vegetative of the catchment is altered dramatically as is the dynamics of the soil water. Forecasting of fires and the resultant effects both in water runoff and water quality is important to managers of the Canberra water resources for the town supply.

Runoff Quantity

There were a number of reports and papers written on the Jan 1983 fire (Kulik and Daniell, 1986; Daniell and Kulik, 1988; Kuczera, 1998) and following the Feb 2003 fire (Carey et al, 2003; White et al., 2005). Bushfires usually occur during drought conditions when the vegetation dries out. This creates difficulty in establishing whether any trends in water yield are due to the fire event or due to the drought. The 1983 fire event also corresponded to the most severe short term drought on record further complicating the problem. If the duration of the drought is considered then the present drought from 2000-2005 is the most severe on record in terms of 24 month rainfall totals, while the 1983 drought is the most severe in terms of 12 month rainfalls.

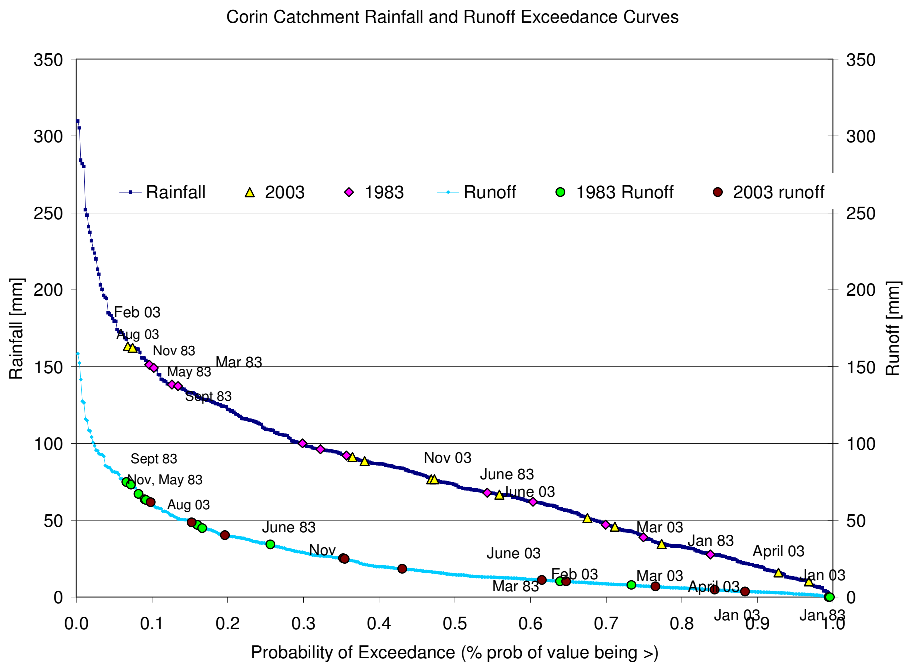


Figure 3 Corin Catchment Rainfall and Runoff Exceedance Values

A simple method used to find whether there was any definitive relationship before or after a bushfire is to use a flow duration curve mapped against an equivalent monthly rainfall exceedance curve as shown in Fig 3. March 1983 and February 2003 were high rainfall events with low runoff events but this was mainly due to recovery from the drought. Generally after the bush fire, initial moisture levels had recovered an equivalent exceedance runoff corresponded to an equivalent rainfall probability. Note that there were some months immediately after the fire where their exceedances for both rainfall and runoff corresponded very closely as well as some months where they were higher for rainfall and/or for runoff.

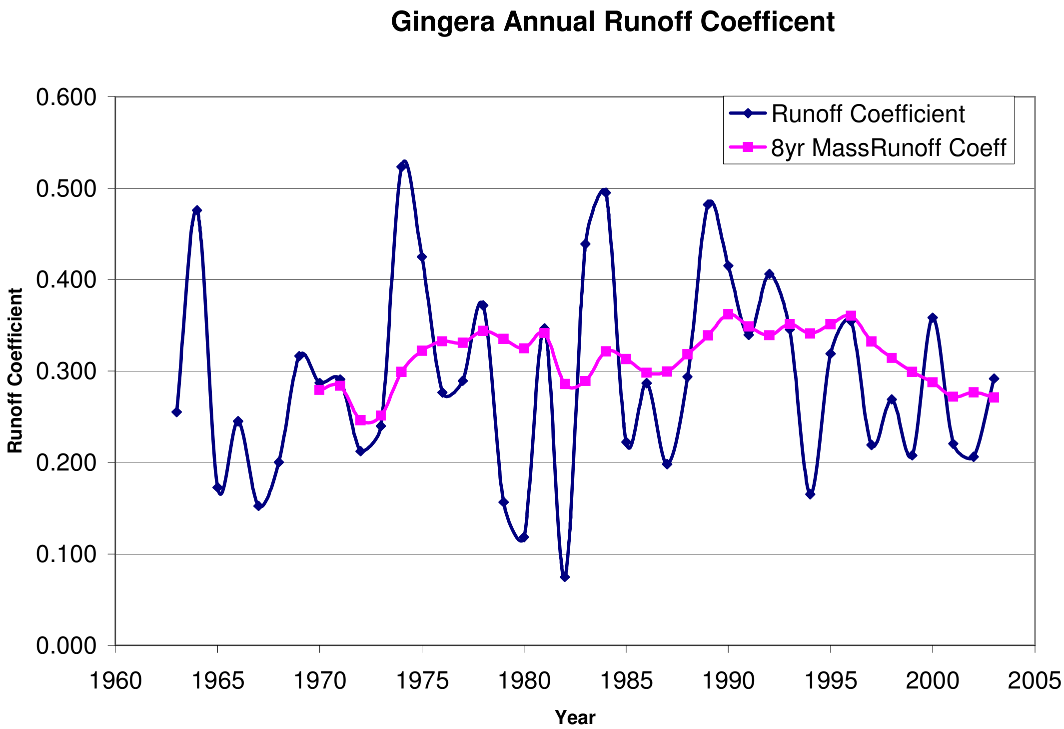


Figure 4 Plot of Monthly Runoff Coefficient for Gingera Station in Corin Catchment

Fig 4 shows the monthly runoff coefficient for the catchment for the 40 years of record for Gingera gauging station upstream of Corin Reservoir. The monthly average runoff coefficient over the period of record is 0.24 i.e. 24%. However if calculated as an average annual runoff coefficient it is 0.292 and if calculated as total runoff coefficient over the period of record (1963 to 2003) it is 0.309 i.e. 30.9%. When comparing different periods of time pre- and post-bushfire we shall use the total runoff coefficient. There is no appreciable change from the 20 years prior to the 1983 fire which has a runoff average of 29.5% and an average rainfall of 967.8 mm. The 20 years following the fire has a runoff average of 32.3% with an average rainfall of 997.5 mm. Examination of Fig 4 suggests that the annual dry periods were not as low post-bushfire as those pre-bushfire. Very low runoff averages occurred in 1968, 1980 and 1982. There is no statistical evidence that the runoff has changed following the bushfire although both the standard deviation of rainfall has dropped from 283 to 183mm and that of runoff has dropped from 181mm to 140mm. Visually in Figure 5 there is a perceptible increase in runoff following the fire.

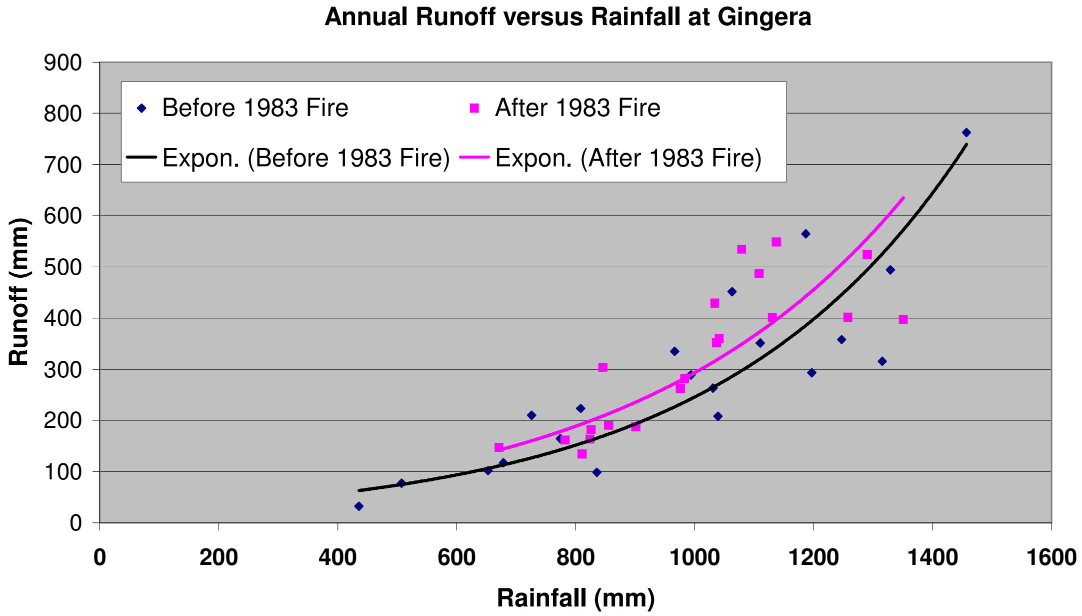


Figure 5 Curves of rainfall and runoff pre 1983 and post 1983 bushfire.

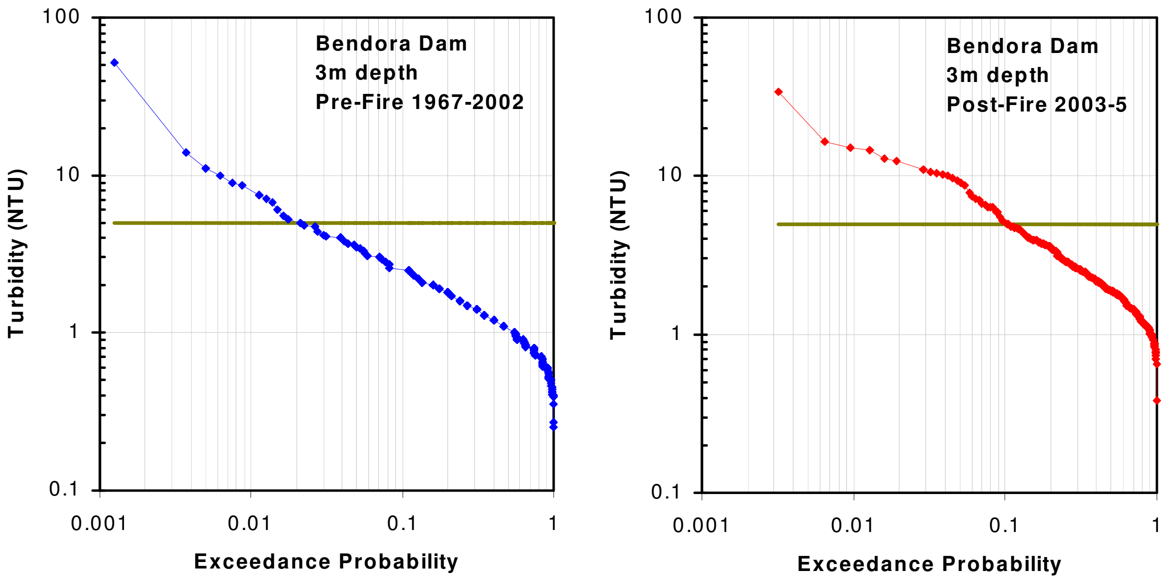
In order to assess whether there have been significant yield trends following fire, it is necessary to use an approach that is capable of filtering out climate variations. Kuczera (1998) used a daily lumped catchment model to analyse temporal trends in monthly residual catchment yields for the Licking Hole catchment following the 1983 fire. He found that there was an increase in yield which was discernible up to about 36 months after the fire. After that there was no long-term change in catchment yield. This increase in yield was attributed to reductions in interception and evapotranspiration due to vegetation loss. More mature trees largely survived the fire and regenerated by epicormic growth so resulting in no long-term yield reduction.

Runoff Quality

There have been a number of reports on water quality following the bushfires for both the 1983 and the 2003 events. Water quality data in Bendora dam for the period 1968 to 2003 shows that despite the near pristine conditions of the pre-fire catchment, a build-up in turbidity, and in Fe and Mn occurred annually in the dam in the past. This is due to the release of Mn and Fe from bottom sediments into the increasingly anoxic waters. This mechanism is consistent with the pH and EC profiles in the reservoir. The turbidity in the water is strongly correlated to the iron concentrations. In the pre-fire period, only two major turbid inflows occurred. The first in April 1983 was due to intense rainfall following the 1982-3 drought and the January 1983 bushfire in the upper third of the catchment above Corin Dam. In this event the turbid plume flowed along the bottom of Bendora reservoir. The second was due to intense rains in January 1995 following the 1994 dry period when the turbid plume was injected above the hypolimnion. In March 2003, following the bushfires, the peak turbidity was thirty times that of the 1983 peak. Large quantities of sediment were deposited into the dams from the denuded catchments. After the 2003 fires, the turbid plume flowed along the bottom of the reservoir. (White et al, 2005). In addition after the 2003 fires, Mn, Fe, P and N concentrations were up to one order of magnitude higher than previous peaks. Further sediment flows have led to the construction of a $40 million WTP.

One of the key questions facing water resource managers in Canberra is the long term implication for water quality. Fig. 6 compares the pre- and post- 2003 fire turbidity exceedance values for the 3 m level in Bendora Dam, close to the off-take level. Taking the guideline level of problem turbidity as 5 NTU, Fig. 6 shows that the pre-fire exceedance value of this limit was 2% compared to a post-fire exceedance of 10%.

Figure 6. Pre- and post-fire exceedance probabilities in Bendora Dam at 3 m depth for the 2003 bushfire.



Sediment movement and Water quality runoff

Immediate post fire measurements for both the 1983 and 2003 events of dissolved nutrients, dissolved organic carbon, turbidity, sediment, and dissolved oxygen (Daniell and Kulik, 1988; Wasson et al 2003) showed a shift from pre-fire conditions towards less favourable aquatic living conditions for either aquatic vertebrates, such as fish, or invertebrates. The sediments contain much higher concentrations of particulate matter, lower oxygen levels, and higher concentrations of Manganese and Iron. The first flush appeared to contain higher levels of nutrients, because of the initial higher delivery of organic sediment into streams. A month later similar measurements showed much lower concentrations of organic carbon, sediment, and Manganese and Iron.

The anoxic conditions in reservoirs, caused by increased organic sediments and lower dissolved oxygen, create reducing conditions which led to further release of Manganese and Iron in the storages. Concentrations of Manganese in soil in the upper Cotter catchment is between 0.01 and 0.03 mg per litre (Talsma 1983), and appears to be two to three times higher in granite derived soils compared with that found in soils derived from Ordovician sediments. Post-fire concentrations of dissolved Manganese immediately after storms in 2003 were about two orders of magnitude higher than that found in the soil, which might suggest concentrations of Manganese increased because of the organic-rich sediment reaching streams. Smaller fires which burn less of a catchment than the 1983 and 2003 fires and are of low-to moderate intensity are unlikely to produce similar increases in organic carbon, sediment, and nutrients that were seen with fires of high to severe intensity across most of the catchment.

Effects on Water Storages

It is estimated that 19300 tonnes of inorganic sediment and 1900 tonnes of organic matter were deposited in Bendora Dam (White et al, 2005) in the aftermath of the 2003 fires. The sources of the sediment pre and post fire were found to be mainly from topsoil and these are shown in Table 2 (Roach, 2004).

Table 2: Estimates of sediment and organic matter washed into Corin reservoir for before and after bushfire (Roach, 2004)

Year	Inorganic sediment (t/yr)	Particulate organic carbon (t/yr)	Sediment yield ($t/km^2/yr$)
Annual-from 1968	316	23	2.3
2003	1663	137	9.2

The sediment and organic matter yield were shown to markedly increase within a few weeks after the runoff events and then drop back to pre-fire levels within 2 years post-fire. Examples of event runoff and suspended sediment are shown in Figure 7 for the 1983 fire indicating that the process of transport of material within an event is not simple and depends on the deposition and availability across the catchment.

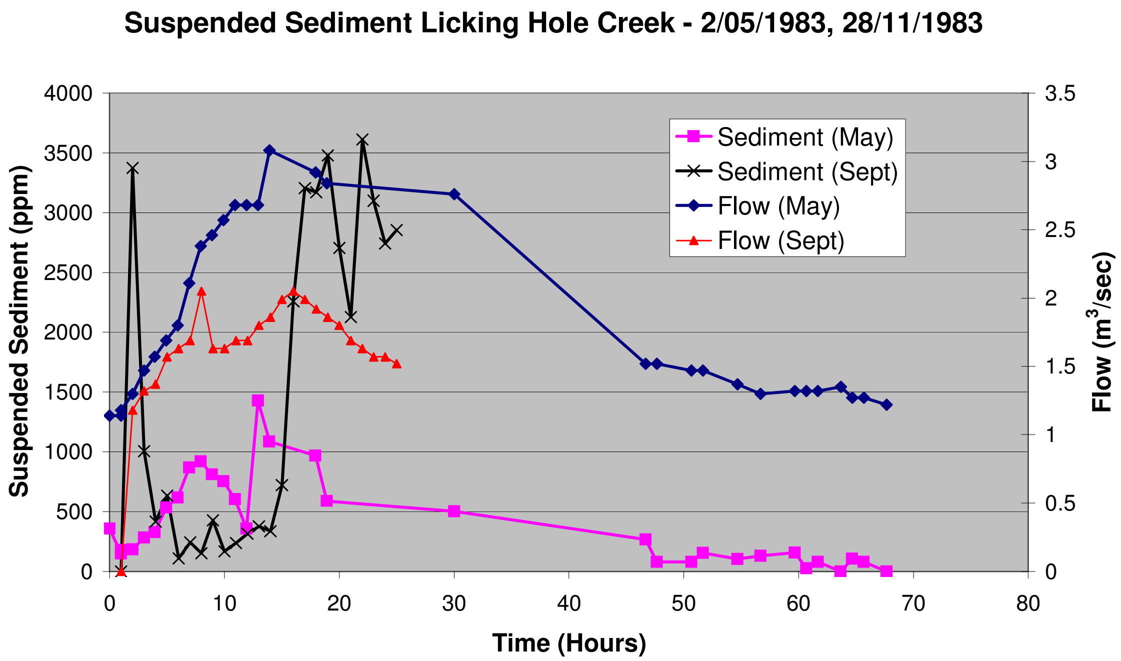


Figure 7 Suspended Sediment and Flow following 1983 bushfire in Corin Catchment

The two peaks of suspended sediment on the rising limb of a hydrograph show the erosive mechanism operating. Many different forms of hysteresis loops for water quality and sediment transport were observed. Overall sediment inflows into the reservoirs in the immediate post-fire period led to a drastic decrease in water quality making the water unfit for reticulation for extended periods.

STUDIES UNDERTAKEN

To compare the fire affected period of runoff with non-fire affected period is difficult as only two significant fires have occurred within the Corin catchment during the time that data has been available. The analyses are compounded by the fact that the fires in 1983 and 2003 burnt different proportions of the catchment. The 1983 fire is estimated to have burnt nearly 29% of the Corin catchment (Worthy and Wasson, 2004) with one catchment the Licking Hole Creek Catchment being monitored following the fire (Daniell and Kulik, 1988). The 2003 bushfires damaged almost all the Cotter catchment with 42% of the forest canopy destroyed in the Corin sub-catchment (ACTEW, 2004a). However, these estimates are only approximate.

Bushfires usually occur during drought conditions when the vegetation dries out. This creates difficulty in establishing whether any trends in water yield are due to the fire event or due to the drought. The 1983 fire event also corresponds to the most severe 12 month drought on record further complicating the problem.

Catchments can take years to recover fully from fire events. ACTEW (2004b) suggested that reduced flows could be expected for more than 50 years following a fire event. This was based on experience following the 1939 bushfires in alpine ash (*Eucalyptus Regnans*) catchments in the southern Australia state of Victoria. There is however no scientific evidence to support this assertion for the mixed eucalyptus forests of the Cotter catchment. There is also no evidence to suggest that the Corin catchment had fully recovered from the 1983 Licking Hole Creek fire before the advent of 2003 fire, although Kuczera's (1998) analysis suggests that their was no long-term trend in catchment yield for the period 1986-1998. It is difficult to ascertain the state of growth the whole catchment before the 1983 fire and what factors cause the variability of streamflow in the catchment (NCDC, 1986). As these factors cannot be established it is difficult to determine whether the effects of the two fire events are overlapping. For example, changes in vegetation structure resulting from the 1983 fire could still have been occurring at the onset of the 2003 fire. Some of the factors and discussion are included in Kulik and Daniell (1986) where the water quality effects from both surface flow and groundwater flow are presented for the 1983 fire.

CATCHMENT MANAGEMENT

A whole-of-government, Cotter Catchment Management Committee used to oversee management of the Cotter water supply catchment but this was abandoned in the 1980s. Management is now embedded in ACT Urban Services, a federation of customer-focussed businesses. Environment ACT is one of those businesses and ACT Parks and Conservation, within Environment ACT, manages the Namadgi National Park, containing the Cotter Catchment, for a broad range of interests, but concentrating on the preservation of biodiversity.

The ACT's *Water Resources Act 1998* appointed ACT Environment as one of the regulators for water in the ACT (the others are the ACT Prices Commissioner and ACT Public Health). ACT Forests manages the Lower Cotter Plantations and monitors water quality throughout its plantations and reports results to the Environment Protection Authority. Water in dams and pipes in the Cotter is overseen by the multi-utility, ACTEW Corporation, a government-owned holding company with interests in providing water and wastewater services (as well as natural gas, telecommunications and energy) to Canberra and surrounds. The ACT Government through ACTEW Corporation owns the existing water and wastewater network, catchment and treatment infrastructure and associated strategic water and wastewater assets.

ACTEW Corporation formed a joint venture with the private company AGL in 2000. The public-private joint venture company *ActewAGL* is an ACT-based electricity, natural gas, water and sewerage services utility that contracts its services to ACTEW Corporation for a fixed fee. ACTEW Corporation buys bulk water from the ACT Government, and contracts *ActewAGL* to treat water and on-sell it on behalf of ACTEW to communities and industry in the ACT who also pay to have sewerage and wastewater removed and treated by *ActewAGL. ActewAGL* returns almost half of the water abstracted from catchments to the Murrumbidgee River as high-quality treated water, part of the environmental flow obligations negotiated by Environment ACT. Because of the fixed fee contract, the major incentive for *ActewAGL*, which has the major concentration of water supply and treatment expertise in the ACT, is for cost minimisation. Monitoring of rainfall, quantity and quality of water in the water supply dams and catchments is contracted to ECOWISE Environmental, a subsidiary of *ActewAGL.*

The ACT Prices Commissioner has ruled that ACTEW should pay the ACT Government a water abstraction fee to cover the environmental costs of for water abstracted from catchments. This abstraction fee is not hypothecated, that is the environmental levee is not exclusively devoted to catchment management and improvements to aquatic environments.

Sydney had a major water crisis in 1998 when *Cryptosporidium* and *Giardia* were detected in Sydney's water supply. Peter McClellan, QC, in a subsequent detailed inquiry, examined the events leading to this water crisis. He found that there was no single authority ultimately responsible for the health of Sydney's water supply catchments and storage reservoirs. The Sydney Catchment Authority was established in 1999 following Mr McClellan's recommendations. The Authority's tasks are to protect catchments, improve water quality, protect and manage Sydney's 21 dams and to educate and involve communities in protecting its catchments.

It is salutary to compare the mission statements of the ACT's water organisations with that of the Sydney Catchment Authority, "*healthy catchments, quality water-always.*" ACT Environment's vision, *environment and heritage -secure, shared sustainable*, reflects its broad responsibilities. ACTEW Corporation's vision is *to be the benchmark multi-utility operating in the private-public partnership model* while the vision of *ActewAGL*, *to connect with customers*, clearly reflects its responsibility to its shareholders. These ACT water organisation vision statements strongly suggest that water is but one of many responsibilities.

Following the 1983 bushfire, a report was submitted to the then ACTEW Board, pointing out the vulnerability of ACT catchments and water supplies and the need for a full water supply treatment plant. The report was not acted on until after the 2003 fire. The immense value of a well-managed catchment as the primary water quality barrier is widely recognised. The formation of an ACT Catchment Authority, dedicated to the protection, wise use, management and planning of the ACT's bulk water supply sources could help avoid future water crises in the ACT.

CONCLUSIONS

The runoff immediately following the 1983 bushfire in the Corin Catchment seems to increase but then settles down within about 36 months to runoff no different than prior to a bushfire. The small period of record following the 2003 fire seems to follow the same trend. The natural variability in the catchments of streamflow makes it difficult to discern any trend as recoveries from drought tend to influence the runoff achieved as does the persistence of the effect of one wet year to the next.

It is clear that the 2003 fires were a unique event for the Upper Cotter catchment water reservoirs. The fire and subsequent rainfall appear to be a one in 400 year event. Because of the quality of water when large quantities of sediment were deposited into the reservoirs from the denuded catchments the construction of a $40M treatment plant was required. Some of the questions on frequency of severe events and the consequences of such events have attempted to be answered by this paper. There will need to be changes in dam operation and catchment management to better respond and enable the systems to be more resilient to such events.

The biggest concern of bushfires is the immediate effects on the water storages and the vulnerability of the catchment to large storms that can severely erode the catchment and create sediment and turbidity problems in downstream storages.
It is imperative that the response of water supply reservoir systems to extreme events is studied. These studies can help identify the frequency of occurrence and recovery times of reservoirs and their catchments, and assist in long term risk evaluation and management strategies for water supply managers. Agencies dedicated to the task of managing water supply catchments for good quality water appear to be desirable.

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