Fire reduces water harvest from Melbourne's water supply catchments.

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In an international survey of 94 forest catchment studies, Bosch and Hewlett (1982) concluded that disturbance to reduce forest canopy cover resulted in increased streamflow, an expected outcome explained by diminished transpiration due to lost leaf area. The only exception to this general finding was the counter-intuitive Australian observation for reduced streamflow in the Maroondah catchments following the 'Black Friday" bushfires (Jan 13 1939).

John Langford, a research hydrologist with MMBW (Melbourne and Metropolitan Board of Works responsible for Melbourne's water supply) published statistical proof in 1976 that reduced streamflow had been persistent since 1939 in the set of Maroondah experimental catchments (east of Melbourne near Healesville). In this paper, there was an important qualification that the level of catchment streamflow reduction was in direct proportion to the amount of mountain ash regrowth (*Eucalyptus regnans*) in the catchment and inversely proportional to the area under the mixed set of four eucalypt species that coexist in this mountain ash ecosystem; as catchment average annual rainfall increases above 1200 mm so the proportion of mountain ash increases.

Explaining this counter-intuitive response to forest defoliation has been the topic of ongoing research to elucidate ecosystem function in determining the balance of water allocation between forest regrowth and streamflow in this rainfall regime, generally above 1500mm annual rainfall. It needs to be noted that the Langford conclusion was unsurprising among the local forest hydrology fraternity since 1949 and curiosity to account for this anomaly has sponsored the ongoing research.

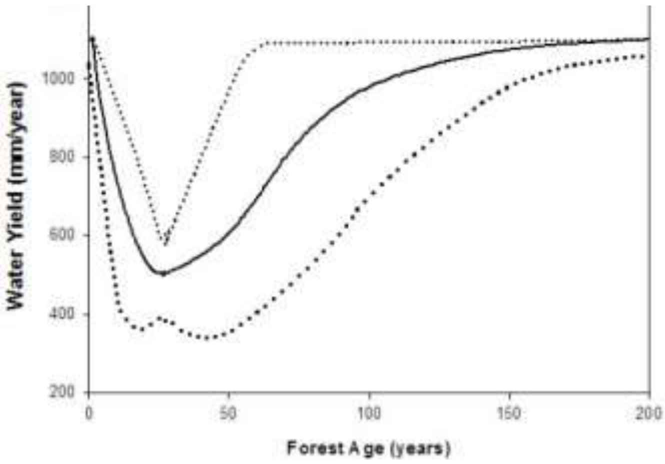

Fig 1: Showing annual water yield from mountain ash catchments (—) as a function of age under fixed annual rainfall of 1600mm with 95% confidence limits shown as dotted lines.

George Kuczera (1987), a MMBW colleague, published a time series of streamflow to indicate reduction since 1939 in the Maroondah region for catchments of even age mountain ash. This series is then taken to indicate the effect of forest age, with peak depression of streamflow in 1966 (27 years after fire as shown in Fig 1) after which there is an asymptotic progression towards pre-1939 levels with restoration in the streamflow regime suggested for 2090. This time series implies a succession in forest function of the fire sensitive ash ecosystem with maximum resource use rate at 27 years post fire devastation after which progression towards maturity is marked by declining rates of water consumption.

In parallel with these studies in stochastic hydrology, Peter Attiwill (Attiwill, 1994) and David Connor (Connor et al., 1977) directed University study in ecophysiology to understand dynamics of control of resource use (water and carbon dioxide), thereby affording an account of the physical factors implicated in the age effects on water use by ash forest. The CRC on Catchment Hydrology entered in the 80's to become an integrating force in developing the scientific understanding of this unique response to fire as long term depression of streamflow (Rob Vertessey et al., 1998).

Research outcomes of studies into the unexpected response as streamflow reduction are summarised:

- Soil structure of the krasnozem soils at Maroondah remains stable under intense heat of > 300°C but emerges with greater permeability. Infiltration capacity is preserved even in the absence of forest vegetation to ensure that the mode of outflow generation comprised essentially of subsurface flow remains unperturbed between the forest and burnt states (Fred Craig, PhD thesis, Forestry School, Melbourne University).
- Langford's association of streamflow depression with ash regrowth implies that mode of regeneration confers distinctive patterns of water use. In the case of the fire sensitive ash species, regrowth occurs only from the seedling stage to use water at rates enhanced relative to pre-1939 mature forest and also enhanced relative to the corresponding regrowth stages of the mixed set of coexisting eucalypts whose regrowth is characteristically through canopy sprouting and lignotubers.

- The Kuczera time series has been derived from streamflow data, subject to scaling adjustments for the proportion of ash regrowth within the catchment and also for variability in annual rainfall. This statistically contrived sequence in representing age effects on ash forest implies that the dynamic control of water use by the forest vegetation undergoes a shift in character from parsimony to profligacy before reverting back to parsimony. However, before pursuing analysis to elucidate factors implicated in the ageing process, checks for physical relevance of the statistically derived series need to be applied. Ceiling water use of 1100 mm/year can be justified for a 25 year old stand of mountain ash having full canopy cover, using Met Bureau information at Ferny Creek. Radiation data at this site provide an estimate of the upper limit of evapotranspiration as 780 mm/year – evapotranspiration represents the cumulative total of soil water extraction for that fraction of the year when the canopy is non-wetted. An interception loss component of 320 mm/year (wetted condition of the canopy) is added to evapotranspiration for an annual water use of 1100mm – Mike Feller (1981) suggests that interception loss from eucalypt forests can be 20% of annual rainfall of 1600mm. The parsimonious state, being the pre-1939 mature forest with partial canopy cover, has an implied annual water use of 600mm. Our independent determination invokes an evapotranspiration component as half the ceiling rate (390mm) for mature forest plus interception loss component as 240 mm – rated as 15% of annual rainfall due to lesser upper canopy cover. With confirmed values for the extremes of water use between 600 and 1100 mm/year, we can proceed with analysis to account for water relations of ash regrowth across three distinct stages of ecological succession.
- The early phase of declining streamflow over 27 years has been characterised with an average annual growth rate as 15 tonne/ha/year standing dry matter that is expressed as an annual height increment at pole stage of 1.25 m/year (Attiwill 1979; Langford & O'Shaughnessy, 1977). Solar radiation annual input of 4500 MJ/m^2 is required along with a transpiration soil water uptake of 600mm/year to support growth rate of the ash forest over the initial phase of establishment of ~25 years.

Plate 1: *Juvenile plantations of E. regnans ranging in planting date and height but maintaining high foliar densitv.*

Plate 2: *40 year old even aged stand of mountain ash*

- Interrogation of meteorological data in the region, suggests that these growth rates are consistent with energy and water requirements to achieve observed growth rate. What is intriguing is a near doubling in annual water use over 27 years when growth rate appears to be steady after an initial establishment phase of 3years.Tree height increase for a canopy height of 35-40m at 27years is an obvious factor to explore in attempting an explanation for an additional 500mm in annual water use; conceptually, canopy height elevation by 40m can treble aerodynamic roughness for a 25% increase in potential transpiration, equivalent to an additional 150mm combined with a pronounced increase in interception loss from 50 to 320 mm/year. This attribution for the role of canopy height to increase annual water use by 420mm over 27 years essentially explains the observed near doubling in the initial phase of forest recovery with vigorous growth.
- The second phase at about 25 years involves reversal of the streamflow response for progressive increase in the annual rate of discharge. This phase following maximum streamflow reduction would appear to result from declining water use brought about by stand thinning and reduced canopy cover without change to foliage properties, termed stomatal control; stomatal response is the determinant of rates of gaseous exchange of both water vapour and carbon dioxide per unit of sunlit leaf area (Attiwill, 1979; Connor et al., 1977). Reduced transpiration rate due to lesser canopy appears to be the cause of the turnaround in streamflow response in this phase of forest thinning.
- The third phase starting at 50 years (1989) is characterized by a slowed progression towards that streamflow discharge from the

mature forest pre-1939. An inverse exponential pattern of transpiration reduction can be traced to a progressive control of transpiration flow in the vascular pathway along the trunk between root and canopy (Dunn and Connor 1993; CRC, Vertessey et al.,1998). The expression of progressive restriction to transpiration flow is through canopy stomatal response which exhibits non-linear control such that halving conductance only results in a 15% reduction in transpiration rate.

These research findings afford a mechanistic understanding of streamflow dynamics from ash forest that has been subject to severe wildfire. The vigorous growth that ensued in the 25 years following "Black Friday" was expressed as a rate of increase in forest height of 1-1.5 m/year during this period. This height progression was deemed to be a significant factor contributing to a doubling of that water use by the mature forest pre-1939. This level of increase in water use explains a near halving in streamflow in that 27 years of re-establishment of mountain ash forest post 1939.

The extent of this response across Australian forest catchments is being debated in the context of optimum catchment management for fire control as it relates to water harvest. One view holds that all eucalypt forested catchments will decline in streamflow after wildfire. This overlooks the caveat introduced by Langford that streamflow reduction after fire is a response exclusive to ash forest. Furthermore, John Brown reported in 1972 that wildfire during 1965 at Yarrangobilly in the Snowy Mountains with catchment vegetation dominant in the set of mixed eucalypt species resulted in an expected response of increased streamflow that persisted for 5years before a return to the normal regime.

The Langford/Kuczera focus has been on ash forest catchments dominant in fire sensitive *E.regnans* but recently, ash catchments with fire sensitive *E.delegatensis* as the dominant species, have been qualitatively similar in streamflow reduction response to wildfire, this time in January 2003 (renowned for its impact in Canberra). ANU researchers (Matt Brookhouse *et al.*, 2013) offer statistical evidence that the Maroondah experience of unexpected response as streamflow reduction can be repeated in those high altitude, high rainfall regions of the upper Murray and Upper Murrumbidgee basins that support ash forest.

These catchments dominant in ash forest rate highly in terms of water harvest to become important contributors to river flow in the Murray Darling Basin. Where wildfire is sufficiently intense to cause death of forest ash, a modified streamflow regime will ensue for many decades to reduce water harvest from the upper reaches of river basins in Victoria, NSW and Tasmania. An offsetting effect of short term bursts of increased streamflow can occur from burnt areas under the mixed set of eucalypt species that possess a fire recovery strategy of re-sprouting from canopy and lignotubers. These forest stands typically occupy lower terrain of lesser precipitation for moderate water harvest. We deduce that fire control is critical for our upper basin reaches to maintain high water yield for water supply from the major dam networks.

A policy of complete reservation for Melbourne's water supply catchments has been longstanding with origins in the 1880's as a precaution against typhoid. The policy has been reinforced through the understanding that mature forests have evolved for minimal rates of water use to enhance streamflow discharge. Every precaution is practised against fire intervention that has the effect of ecological rejuvenation with a jeopardized water harvest.

This policy of reservation also runs the risk of increased wildfire frequency through the build-up of forest litter as fuel for conflagration. Control burning, designed to lessen fuel loads on the forest floor and affording protection to the canopy, has been canvassed extensively as a protective measure against devastating wildfire, most notably as a major recommendation by the Royal Commission on the 2009 Victorian bushfires. This option has not been entertained by Melbourne Water (successor to MMBW) for catchment management, apparently on the basis that any fire will compromise water harvest. Interrogation of streamflow response to the 2009 fires (Black Saturday, February 7, 2009) in the catchment network for Melbourne's water supply may well be instructive on the effect of "cool" burns in ash forest. There are indications are that this devastating fire, with 177 lost lives, had moderate impact on the ash forest canopy in the Maroondah/O'Shannessy catchments as part of the network servicing Melbourne 's water supply.

Melbourne draws its water supply from a network of ten storages having a combined capacity of ~ 1.8 million Ml. Since 1984 when the Thompson dam was completed, storage capacity has been attained or approached in four of the intervening years in the 1990's after which the level dwindled to minimum of 16% capacity in 2007. This level of depletion has prompted a controversial programme to augment supply through water imports involving a pipe line from the Goulburn River and a desalination plant on the Bass Coast near Wonthaggi. Concern over climate-change in causing increased drought frequency has been a background consideration to undertake debatable diversions of water resources for Melbourne's benefit. Climate-change also carries the potential threat of increased fire frequency with prospects of a compromised Melbourne water supply with impaired quality and quantity.

Melbourne's water supply is poised on a double edged sword of climate change. Water harvest as a proportion of rainfall decreases with the reduction in average annual rainfall, anticipated due to the impact of climate-change. A potential role of increased fire frequency is regular reversal of ecological succession for a climate-change impact to compound reductions in water harvest. The legacy of "Black Friday" has been an alert that ecological succession has profound impacts on the water balance for long term impairment to Melbourne's water supply. The legacy of "Black Saturday" may well be to offer solutions to this impairment by offering an insight into the nature of perturbation to the streamflow regime in the wake of ash forest fire that resembles a control burn. A possible outcome of an analysis that demonstrates tempered streamflow response is to endorse control burning as a mitigating agent against climate-change reductions to Melbourne's water supply.

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