TECHNICAL NOTE 2007/11

Department of Water, Land and Biodiversity Conservation

THE IMPACT OF PLANTATION FORESTRY ON RUNOFF IN THE MOUNT LOFTY RANGES, CASE STUDY: BURNT OUT CREEK

A J Greenwood and D J Cresswell

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Knowledge and Information Division

25 Grenfell Street, Adelaide

GPO Box 2834, Adelaide SA 5001

Telephone	National	(08) 8463 6946
	International	+61 8 8463 6946
Fax	National	(08) 8463 6999
	International	+61 8 8463 6999
Website	www.dwlbc.sa.gov.au	

Government of South Australia
Department of Water, Land and Biodiversity Conservation

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EXECUTIVE SUMMARY

The impacts of forestry on water availability are receiving increasing attention in national and state water resources management initiatives. They have been studied by a range of Australian and international researchers, employing a range of methods to quantify them. Recent assessments completed by DWLBC have relied on measured data collected at its Burnt Out Creek gauging station in the Onkaparinga River catchment, in the western Mount Lofty Ranges.

This Technical Note presents the Burnt Out Creek data and provides a rigorous justification of its applicability and appropriateness for use in water resources management and policy development. The data can be used to construct empirical relationships between forestry induced runoff reductions and annual rainfall, which are considered more robust than theoretical approaches endorsed by leading Australian research organisations for estimating the impact of forestry on runoff. Of primary concern here is its application in South Australia, however the findings are probably relevant to all areas with mean annual rainfall less than 1,000 mm.

The long-term reduction in annual runoff due to *Pinus radiata* forestry was found to be approximately 85% of pre-forest runoff. The magnitude of the reduction is consistent with proportional estimates made in Australian and international studies, but may be conservative since a remnant stand of pine forest remained through the period of the assessment. Stated reductions are therefore not relative to cleared pasture, but to a mixed-vegetation catchment with 33% forest, arguably more typical of many catchments across the Mount Lofty Ranges and Kangaroo Island.

Maximum impacts were detected after five years of forest regrowth, earlier than in most published literature, probably arising from the coincidence of a period of severe drought depleting soil and shallow, perched water resources and the plantation forest reaching a stage of development when its water use could be expected to increase significantly.

A number of policy implications of these findings are discussed. When used in conjunction with the South Australian 25% use limit guideline, the amount of forestry should be limited to around 30% of any catchment to ensure sustainable water resources management. The application of the 25% rule in this manner provides a convenient way by which volumetric water use can be translated into areal extent of forestry and vice-versa. It is expected that these findings will prove a useful starting point in meeting objectives of sustainable resource management articulated in State and Regional NRM plans and the implementation of the National Water Initiative.

INTRODUCTION

Burnt Out Creek comprises a pair of ephemeral streams that empty into Mount Bold Reservoir on the Onkaparinga River in the western Mount Lofty Ranges, south east of Adelaide, South Australia (Figures 1 and 2). The catchment area totals 60 ha. Landuse has been and remains, exclusively plantation forestry (*Pinus radiata*). There are no farm dams or other water resources development within the catchment.

Its lack of competing water resources development and complete dedication to plantation forestry places Burnt Out Creek as one of the few places in Australia where the impact of plantation forestry on runoff can be readily assessed. Data collected to date provide valuable knowledge and information regarding the impacts of plantation forestry on runoff in the Mount Lofty Ranges, with potential application in the Fleurieu Peninsula, Kangaroo Island and areas of south-eastern Australia with comparable rainfall.

Runoff from Burnt Out Creek decreased markedly five years after two-thirds of the catchment was harvested and replanted. This technical note illustrates the character of the decline, quantifies its magnitude using simple analytical modelling and discusses the findings of the analysis in the context of climatic variability, the state of knowledge in published literature and their implications for water resources management and Departmental policy development.

SITE HISTORY

The largest reservoir in South Australia, the construction of Mount Bold Reservoir on the Onkaparinga River System began in 1932 and continued until 1938. In 1962 the level of the dam was raised by 6.4 metres to increase the storage capacity of the reservoir by 17,000 megalitres to its current capacity of 46,180 megalitres (ML) (SA Water 2007).

In early 1977 a bushfire destroyed a small part of the plantation forest established around Mount Bold Reservoir. The impact was limited to a pair of unnamed gullies on the dam’s southern slopes to become known later as Burnt Out Creek.

In March of that year the site was selected by the Engineering and Water Supply Department to establish a water quality monitoring project to collect information on nutrient loads flowing into the reservoir following clearing of the burned trees. The information was also to be used in assessing the change in streamflow and water quality due to forest regrowth following replanting (GSA 2007a).

Burned pines were cleared in February and March 1977 (Plates 1 and 2, Appendix D). Around 20 ha of pines or 33% of the catchment was left as uncleared pine forest (Figure 2). By late November 1978, the cleared sections of the catchment were completely replanted with *P. radiata* (McGuire *pers comm*).

Construction of a hydrometric weir commenced in late July 1977 and was completed in December (Plates 3 and 4, Appendix D). Data collection commenced on 12 January 1978 following instrument installation. In 1988 the site was closed as water quality monitoring had ceased and the objectives of the station appeared to have been satisfactorily met (GSA 2007a). In 2001 DWLBC (then the Department for Water Resources, DWR) re-opened the site to further its understanding of the impact of plantation forestry on water resources.

In February 2007 the area was burned again and will be subject to another rotation. At the time of writing it was not clear how much of the catchment would be cleared.

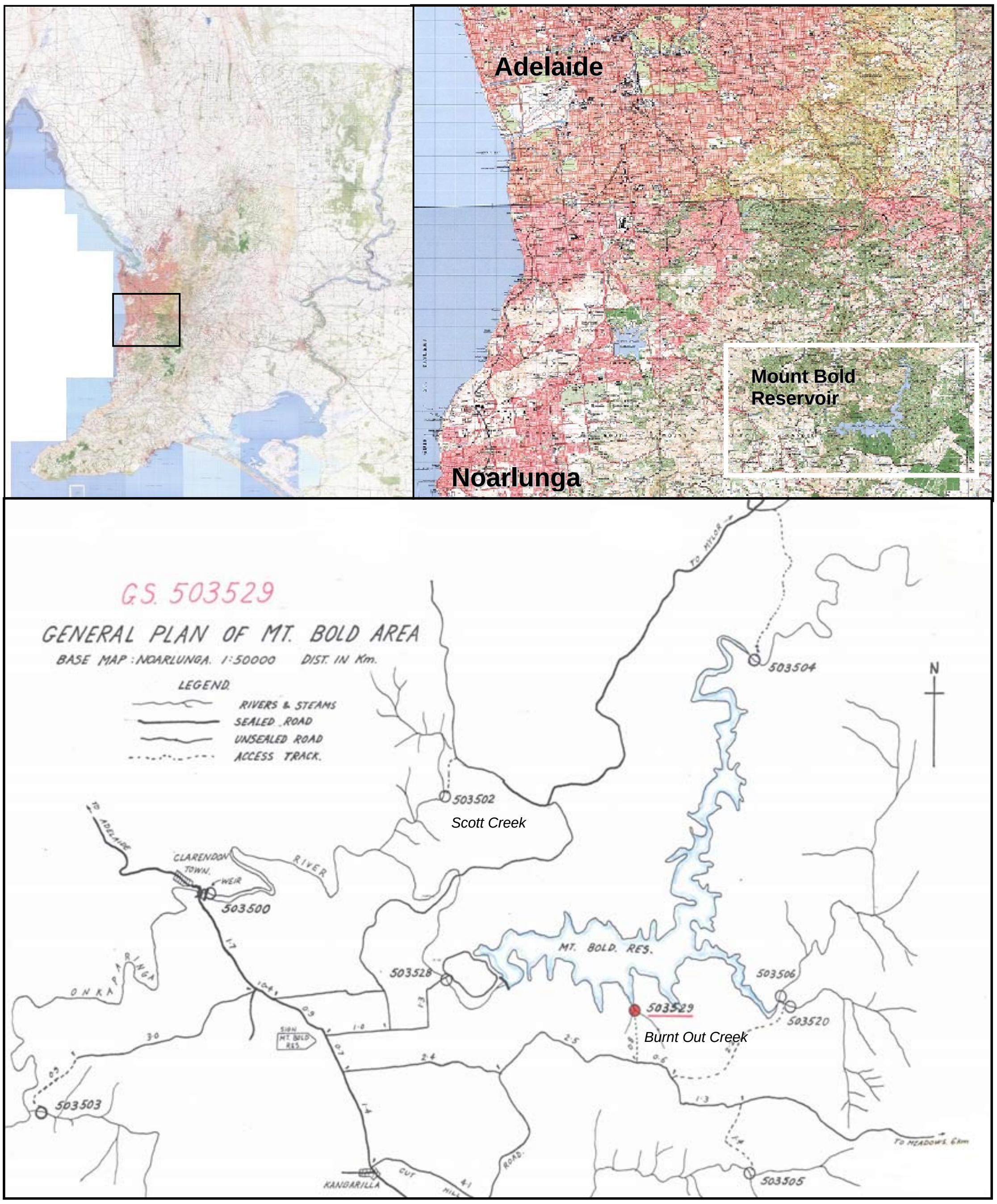


Figure 1. Location of Burnt Out Creek gauging station (503529) and environs, including Scott Creek (503502) and other Mount Lofty Ranges gauging stations.

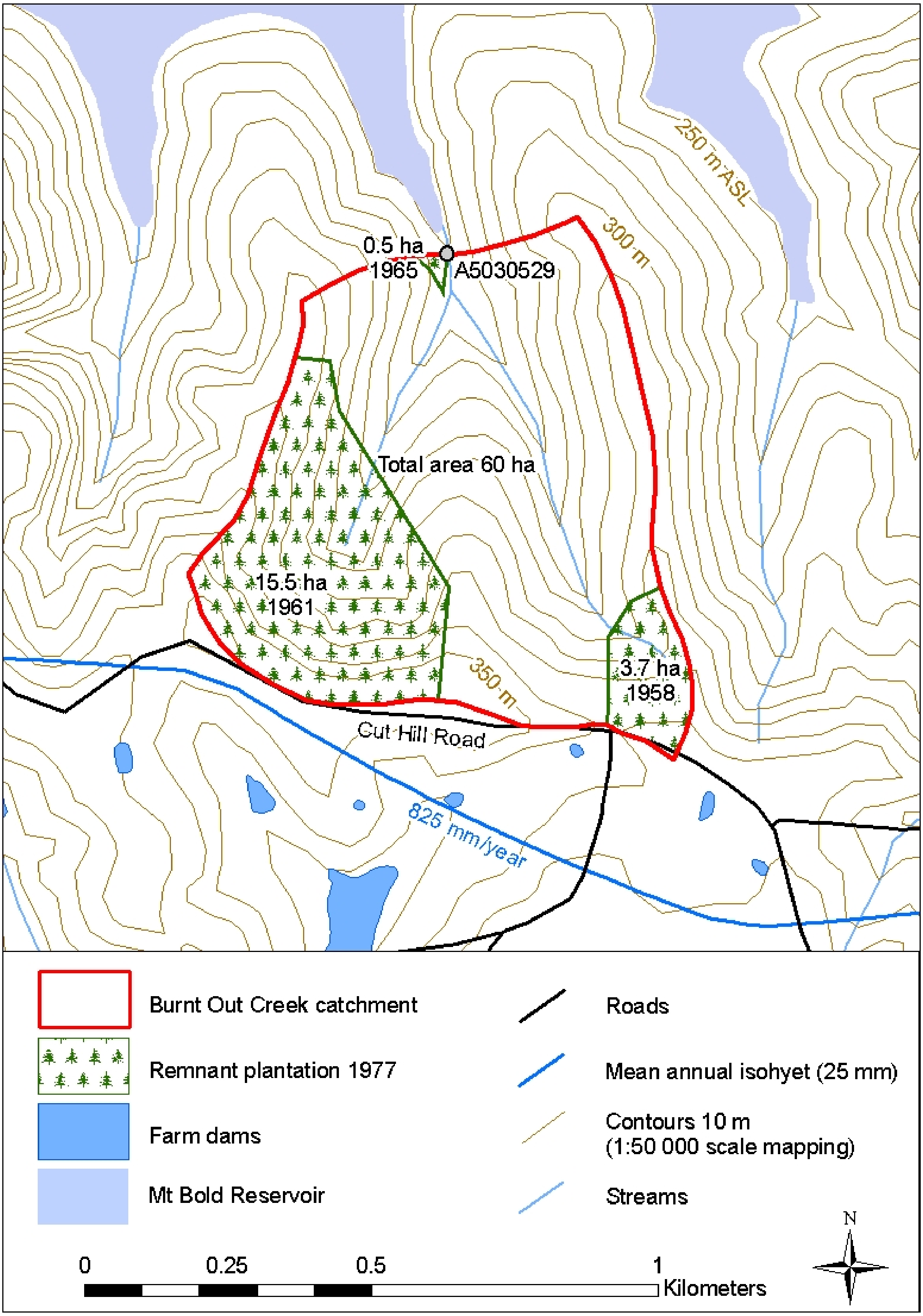


Figure 2. Burnt Out Creek, showing areas of remaining forest and cleared area replanted in 1978. Unpublished forest area mapping provided by ForestrySA (McGuire *pers comm*.)

DATA

Daily rainfall data has been collected by the Bureau of Meteorology (BOM) at Mount Bold Reservoir station 023734 since 1938. Long term mean annual rainfall was 770 mm/year (1939 to 2006). The average rainfall for the two periods of complete Burnt Out Creek streamflow record (1978 to 1986 and 2002 to 2005) was 812 mm/year (Appendix A).

Continuous streamflow measurements have been collected by the Government of South Australia since 1978 with a break in operation from 1988 to 2001. The hydrometric weir is a relatively large v-profile structure, 1.8 m tall by 4.5 m wide with a 59.5° control designed for the accurate measurement of low flows (see Plates 4 to 8 in Appendix D). Comments recorded by hydrographic staff indicate that the design is prone to debris fouling the control, suggesting that very low flows should be used with caution (Appendix B).

The small catchment area and very quick streamflow response have proved challenging to the direct measurement of streamflow, particularly in the absence of a dedicated gauging site. However gaugings taken volumetrically or completed under conditions of steady stage closely agree with the theoretical stage-discharge relationship. The established stage-discharge rating was reviewed for this work by station operator Water Data Services Pty Ltd, who derived a revised rating in close accord with the original established in 1978 (GSA 2007a).

In general the data can be considered high quality. During the 16 years of operation just over 99% of the record was coded as reliable and less than 1% was missing or of poor quality (Appendix B). Annual data used in this assessment is shown in Figure 3 below.

Only years with complete runoff data were used in this assessment since the time required to model and infill missing data was not available. Nonetheless as much runoff data was included as possible given the constraints. Despite missing data from the first 12 days of January, the year 1978 was also included since the daily rainfall record at Mount Bold showed that rainfall totalled a meagre 1 mm for the period, unlikely to have generated any runoff. Other years with data gaps had appreciable rainfall and runoff generation could not be simply discounted: 1987 = 44 days missing and 126 mm rainfall; 1988 = 45 days missing and 82 mm rainfall; 2001 = 138 days missing and 207 mm rainfall. Final years used in the analysis were 1978 to 1986 and 2002 to 2006 (Appendix B).

ANALYSIS

The analysis comprised two parts:

1. The first established that a significant change in runoff occurred in Burnt Out Creek, when it occurred and how it took effect.

2. The second quantified the magnitude of the change using rainfall-runoff curves constructed before and after the period of change which enabled the magnitude of the change to be assessed under wet and dry conditions.

BURNT OUT CREEK RUNOFF REDUCTION

Annual runoff data from Burnt Out Creek were firstly compared with that from another site in the area with stable land-use, as a control for climatic variability. These data and cumulative double-mass analysis were then used to identify when the change in runoff occurred. The significance of the change was then assessed using standard statistical tests.

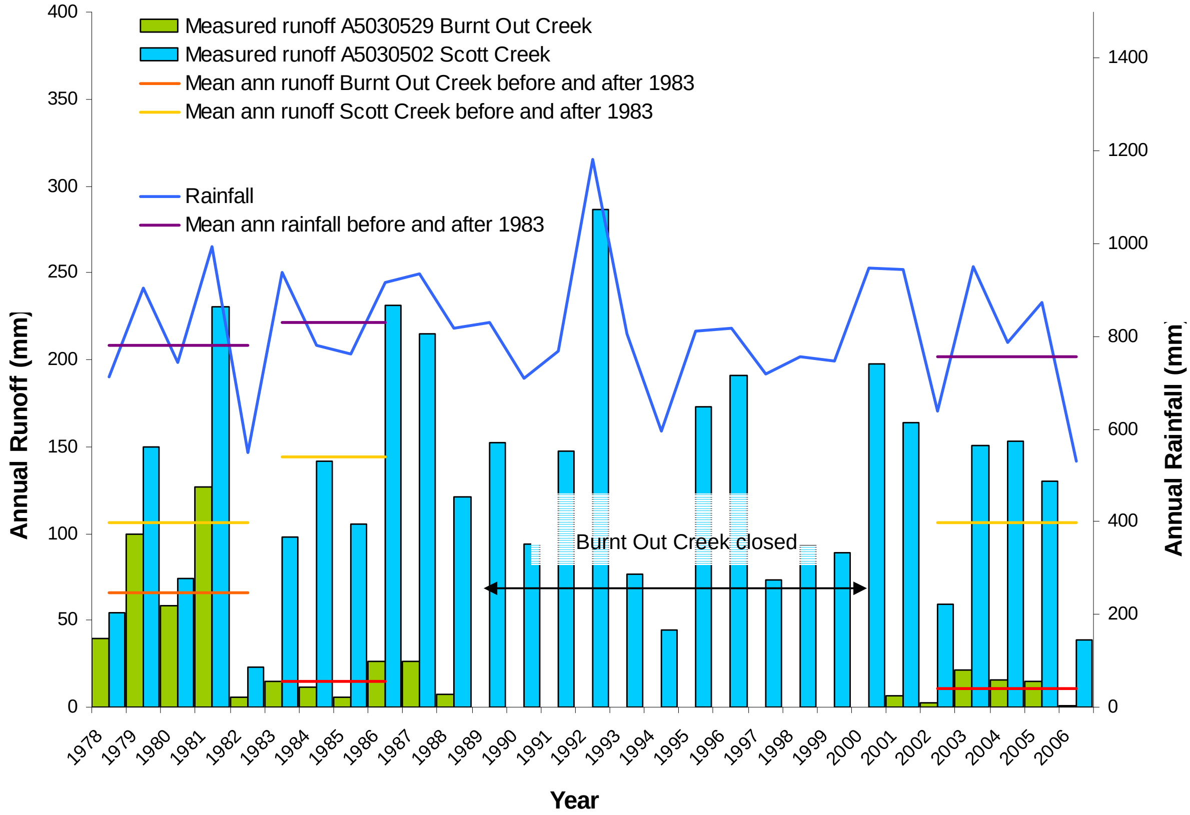


Figure 3. **Burnt Out Creek and Scott Creek measured annual runoff and annual rainfall at Montt Bold.**

Annual runoff data from Burnt Out Creek (complete years only) were plotted with that of nearby gauging station Scott Creek (A5030502, catchment area 26.6 sqkm, see Figure 1 for location), and annual rainfall at Mount Bold in Figure 3 for comparison. Scott Creek gauging station was selected as it was considered particularly suitable for use as a control for climate and land-use variability. Located only 4 km to the north (Figure 1) and having a similar elevation (Appendix B), Scott Creek is climatically similar to Burnt Out Creek. It has mixed land-use, typical of the region, relatively light farm dam development (Teoh 2003) and has not been subject to any significant expansion in forestry or clearing. Scott Creek is also unique among active hydrometric stations in the Mount Lofty Ranges as having no missing data in the last 30 years.

Up until 1983 Burnt Out Creek runoff displayed similar inter-annual variability to Scott Creek. However following the drought year of 1982, Burnt Out Creek runoff remained anomalously low compared to runoff from catchments with stable land-use in the area and remained so until the station was closed in 1988. On its reopening in 2001, Burnt Out Creek runoff remained low.

The timing of the change can be seen in Figure 4, which shows cumulative Burnt Out Creek and nearby Scott Creek runoff data between 1978 and 1986. Runoff decreased significantly in both Scott and Burnt Out Creek during the drought of 1982, more of which will be discussed later. In 1983 the drought broke and Scott Creek runoff recovered, however Burnt Out Creek runoff remained low and seems to have remained close to these levels ever since.

Table 1. Mean annual runoff in Burnt Out Creek compared to Scott Creek

Period	Mean Annual Rainfall (mm/year)	Burnt Out Creek Mean Annual Runoff (mm/year)	Scott Creek Mean Annual Runoff (mm/year)
1978 to 1981 (pre 1982 drought)	839	81.1	127
1978 to 1982	781	66.1	106
1983 to 1986	850	14.6	144
1983 to 2005* (pre 2006 drought)	828	13.9	139
1983 to **2006***	815	12.8	134
2002 to 2005	812	13.5	123
2002 to **2006**	456	10.9	106

* Excludes 14 year gap when station closed

Data summarising the average differences in runoff from Burnt Out Creek before and after 1983 are shown in Table 1. Runoff reduced from an average of 66 mm/year to 15 mm/year (-77%), despite an increase in mean annual rainfall from 780 to 850 mm/year (+9%) for the same period. At the same time data from Scott Creek showed an increase in runoff from 106 to 144 mm/year (+36%), in accord with the observed increase in average rainfall.

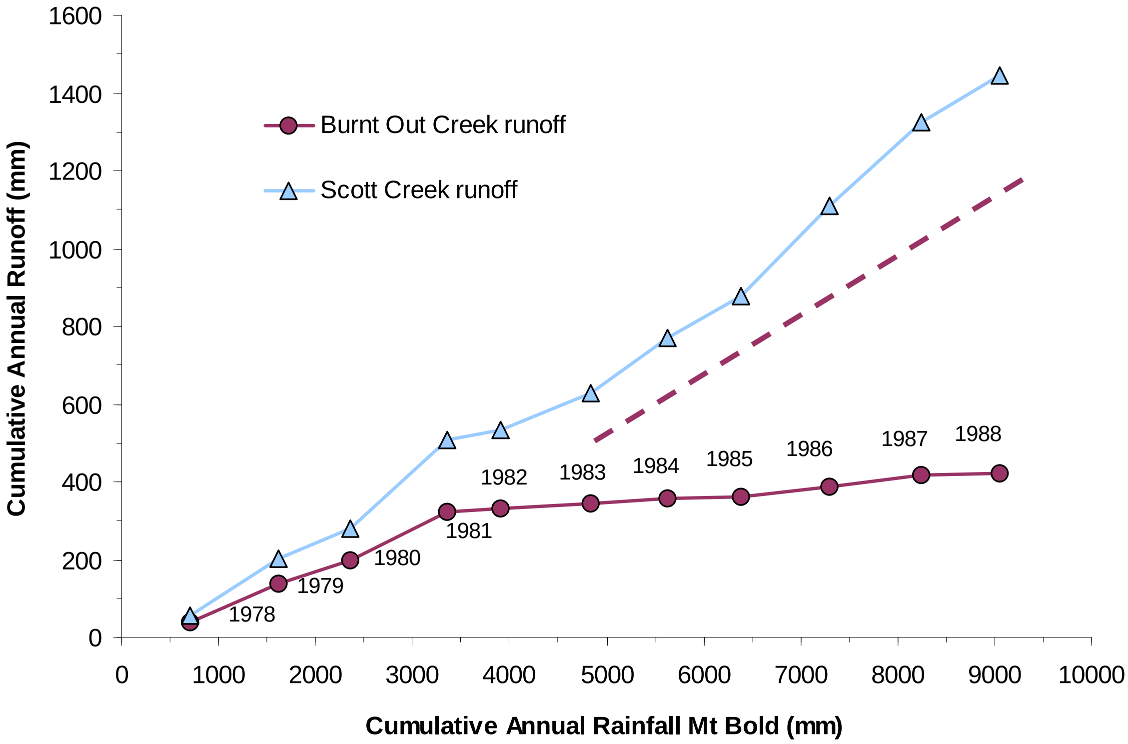
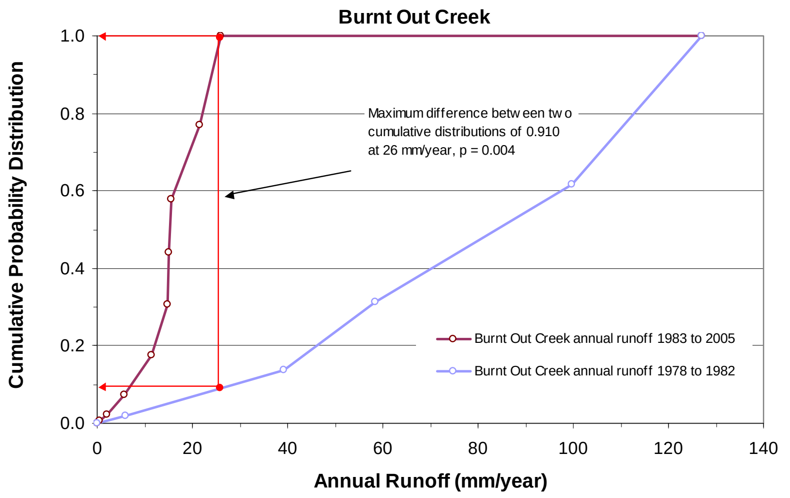


Figure 4. Cumulative double mass plot of Scott Creek and Burnt Out Creek annual runoff. The expected trend in cumulative Burnt Out Creek runoff without forest regrowth is indicated by the dashed line. 1982 drought is evident in flattened section in both data sets. 1987 and 1988 data shown, but include 45 and 138 days missing data with 82 and 207 mm of rainfall respectively.

Table 2. Significance of change in average runoff in Burnt Out Creek and Scott Creek.

Statistic	Burnt Out Creek runoff		Scott Creek runoff	
	1978-1982	1983-1987 2002-2006	1978-1982	1983-1987 2002-2006
N	5	9	5	9
Mean (mm)	66	13	106	123
Variance (mm)	2302	73	6975	3242
F - test				
DOF	4	8	4	8
F	37.9		2.15	
p (two tailed)	**0.0001**		**0.33**	
t - test				
t (different variances)	2.41		-0.40	
DOF	4.1		6.1	
p (two tailed)	**0.07**		**0.70**	



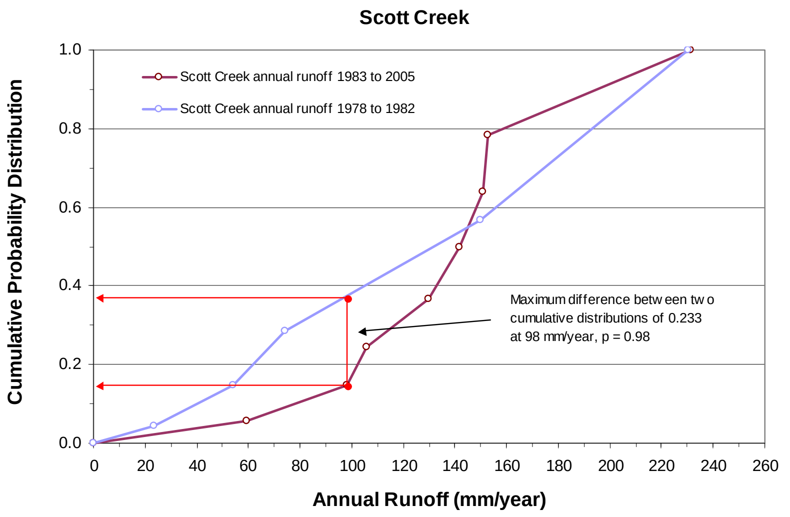


Figure 5. Kolmogorov-Smirnov distributions for Burnt Out Creek and Scott Creek.

The significance of the change in average Burnt Out Creek runoff was firstly assessed using a Student t test. A highly significant difference was detected in the variances of the pre- and post-regrowth runoff data using an F-test. The differing variances lead to the use of the Student t for different variances as described in Press *et al* (1992). Results are summarised in Table 2.

Scott Creek data were analysed in the same way and over the same period for comparison. The Student t test showed that the chance of the difference in average Burnt Out Creek runoff before and after 1983 being due to chance alone was 7% ($p = 0.07$), or that there was a 93% chance that the data sets were different. No significant change in average Scott Creek runoff was detected over the same period ($p = 0.70$).

The limited size of the runoff data sample called for a more robust estimation of difference between the pre- and post-regrowth data sets. The non-parametric Kolmogorov-Smirnov (K-S) test for difference between distributions was also completed on both Burnt Out Creek and Scott Creek runoff data. The K-S test was considered particularly attractive in that it is not based on raw data, is insensitive to outliers and the calculated significance is considered accurate for very small sample populations (Press *et al* 1992). Results are shown in Figure 5, which indicated that the chance of the pre- and post-regrowth runoff belonging to the same data set was less than 0.5% ($p = 0.003$), while the Scott Creek data showed no significant change over the same period.

QUANTIFYING RUNOFF REDUCTION

The change in runoff due to forest regrowth was quantified by fitting annual Burnt Out Creek runoff data with rainfall-runoff curves for both the 1978 to 1982 pre-regrowth period and 1983 and after regrowth period. The validity of the approach was then explored by comparing the difference between the modelled pre-forest data and observed data with findings from published literature, including international studies. The difference between the pre- and post-regrowth rainfall-runoff curves was then calculated for a sequence of annual rainfall to provide an empirical basis for estimating runoff reductions due to afforestation.

Rainfall-Runoff Curves

Pre- and post-1983 Burnt Out Creek runoff data were fitted with Tanh rainfall-runoff curves after Grayson *et al* (1996) (Figure 6, below). Initial and continual loss parameters were fitted to the data using MS Excel® Solver to optimise the similarity between cumulative modelled and observed data distributions using the Kolmogorov-Smirnov statistic. This procedure is discussed in detail in Appendix C. The final parameters were 250 and 880 mm for the pre-regrowth period and 400 and 1465 mm for the post-regrowth period.

Observed data were then subtracted from modelled Tanh pre-regrowth data to gain an impression of the timing and magnitude of the runoff change. Results are shown in Figure 7. Up to 1982 inclusive, Burnt Out Creek measured runoff varied around modelled pre-forested runoff by an average of 5%. In 1983 runoff suddenly reduced by 87%. Runoff reductions have ranged between 73 and 93% in the ensuing years when data were collected. The apparent outlier in 1980 only appears conspicuous because of the relative tightness of other data. In that year the Tanh modelled pre-forest runoff estimate was 46 mm while the observed runoff was 59 mm (difference -27%), still relatively robust given the range of variability seen in measured runoff data across the Mount Lofty Ranges.

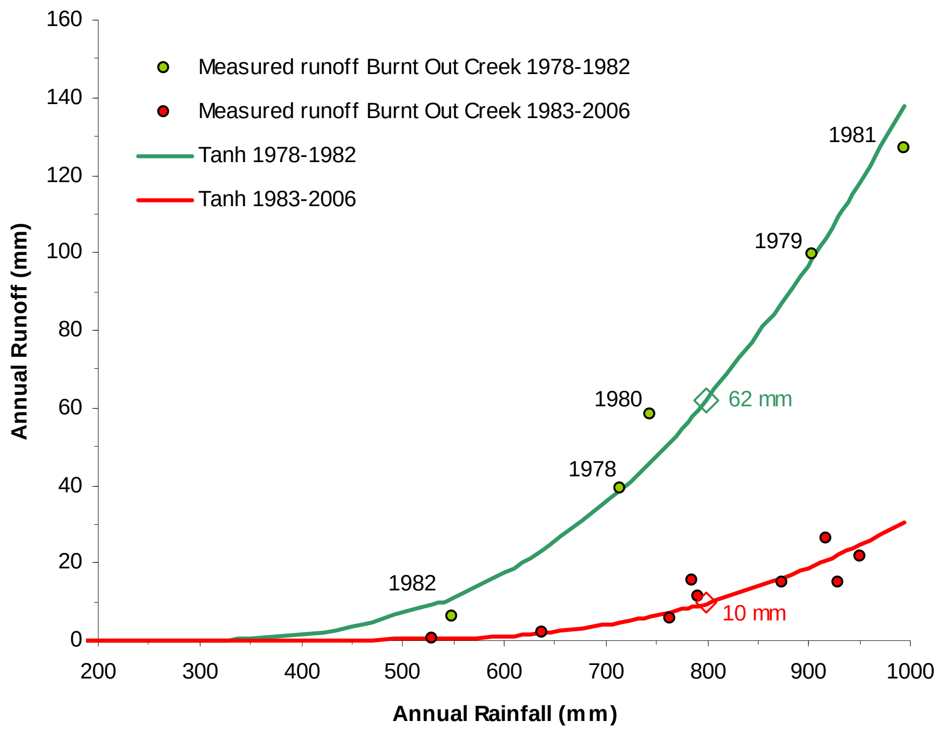


Figure 6. Burnt Out Creek rainfall-runoff relationships pre and post forest growth. Pre-forest data labelled with year.

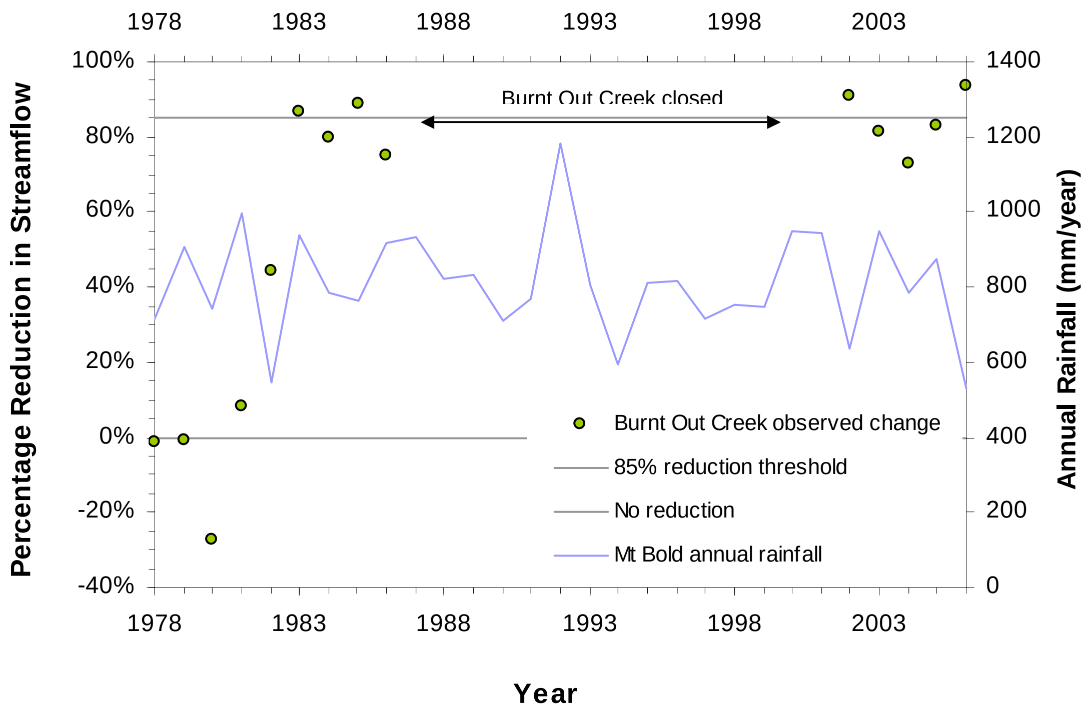


Figure 7. Decrease in measured Burnt Out Creek runoff compared to modelled pre-forest runoff.

The Burnt Out Creek data were then compared to models derived by Scott and Smith (1997) who also used measured runoff data (from paired catchment studies) in South Africa to develop relationships between the age of both pine and eucalyptus plantations and their impacts on annual streamflow. Figure 8 shows the Burnt Out Creek data overlain on the two Scott and Smith curves for pines (derived from data collected from both *P. radiata* and *P. patula* plantations). The dark blue curve was derived for *optimal* catchments, described as having deep soils and a sub-tropical climate; the red curve was derived for *sub-optimal* catchments with shallow soils and high altitude.

Both catchment types had mean annual rainfall in excess of 1000 mm/year and comparisons with local conditions should be made with care, however the Burnt Out Creek data showed strong accord with the Scott and Smith *optimal* curve in the first ten years of plantation growth, with a longer-term level of runoff reduction similar to that described by the *sub-optimal* curve. It is interesting to note that *sub-optimal* catchments were described by Scott and Smith (1997) as having shallow soil and less favourable, high altitude climate, while soils found around Burnt Out are also shallow (McKenzie *et al* 2005), but the climate is less favourable due to lower rainfall.

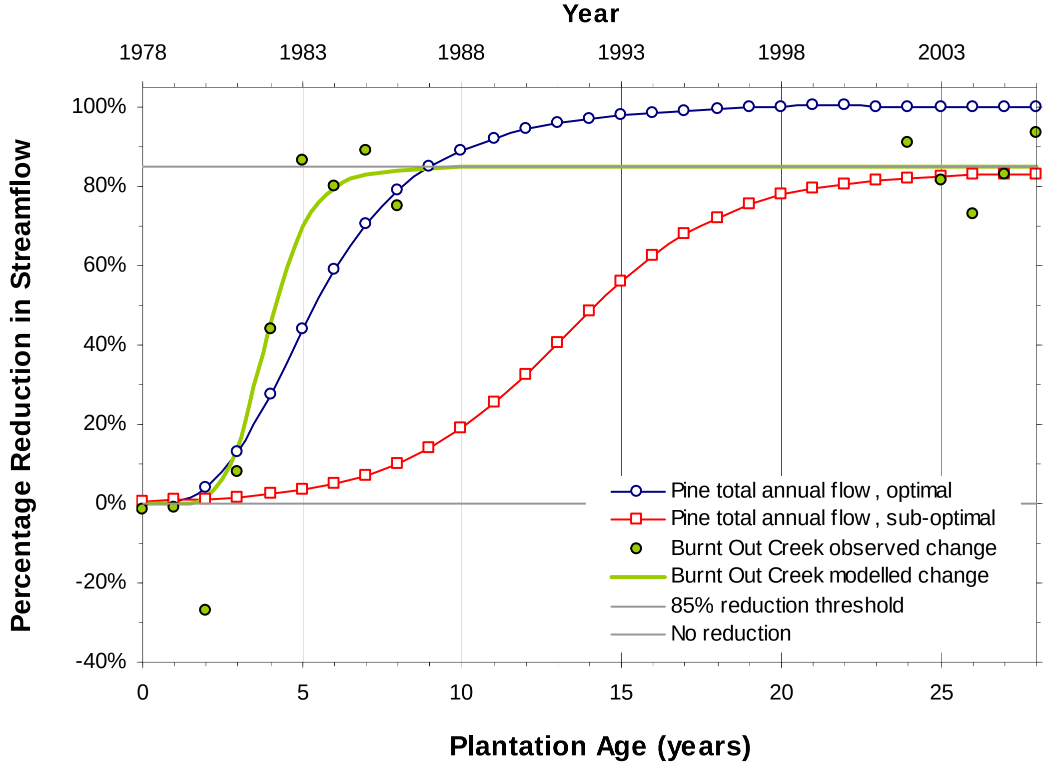


Figure 8. Burnt Out Creek runoff decrease compared to data from Scott and Smith (1997). Pine forest modelled.

Presenting the Burnt Out Creek data in this way stimulates the discussion of the respective similarities and differences between the South African data in terms of climatic and catchment influences, including the 1982 drought, soils and the remnant plantation in Burnt Out Creek. Further investigations in this area have the potential to assist in predicting the impacts of forestry on runoff under local conditions in the Mount Lofty Ranges and Kangaroo Island. More discussion of this issue is provided later.

The difference between the Tanh modelled pre- and post forest regrowth runoff datasets was calculated as a proportion of pre-forest runoff for a range of rainfall and compared to CSIRO data from Zhang *et al* (2007) (Figure 9). Data show that in the rainfall range from 500 to 1200 mm/year, which covers all the areas prospective for plantation forestry in the Mount Lofty Ranges, Fleurieu Peninsula and Kangaroo Island, the reduction in runoff can be expected to be between 70 and 100%, depending on annual rainfall. In years with annual rainfall of 800 mm, close to average for much of the area currently of interest to forestry developers in South Australia, reductions in runoff could be expected to be approximately 85%.

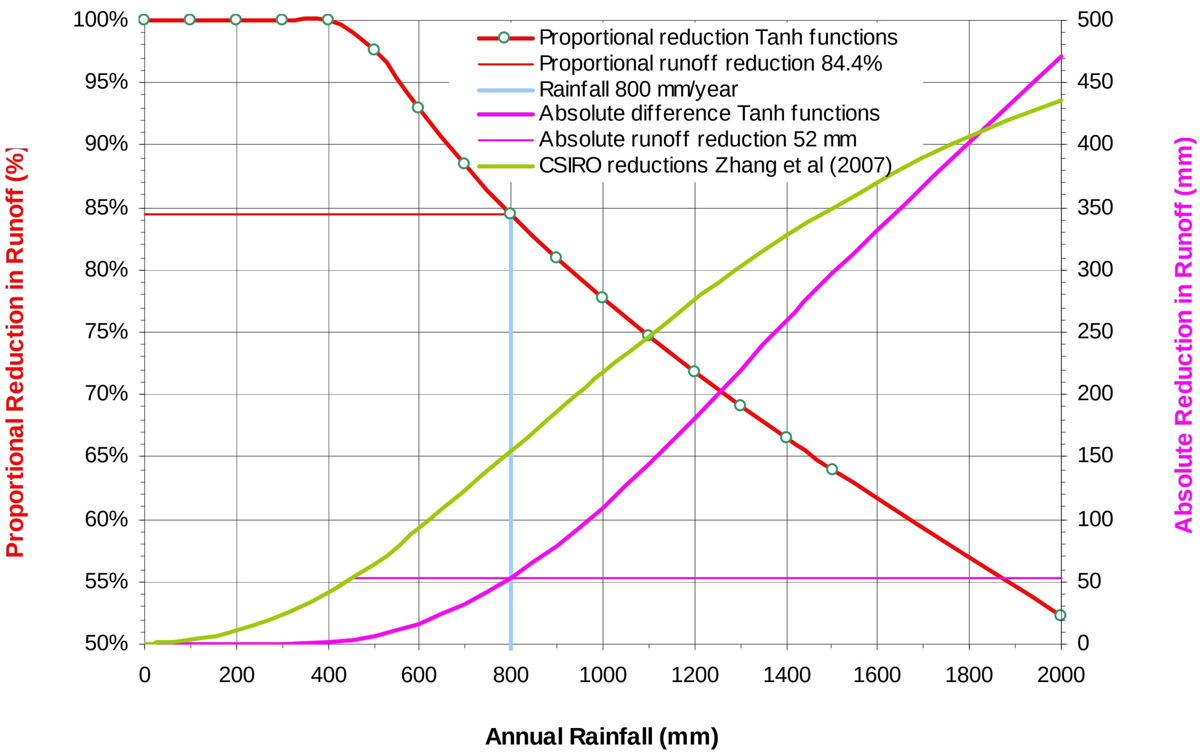


Figure 9. Change in Burnt Out Creek runoff with rainfall. CSIRO data from Figure 7 (p22) Zhang *et al* (2007).

Annual runoff reductions observed at Burnt Out Creek show a very similar trend to CSIRO data. Absolute reductions appear similar in very wet years but CSIRO data show much greater runoff reductions in areas with lower rainfall. Data from Burnt Out Creek indicate that when rainfall is 800 mm/year, runoff reductions due to forestry can be expected to be 50 mm, while CSIRO indicate reductions of 150 mm.

Burnt Out Creek was only two-thirds cleared. When adjusted to resemble a fully cleared catchment, the Tanh-modelled runoff of 62 mm runoff from Figure 6 could be expected to be around 95 mm/year. The CSIRO estimate of the expected runoff reduction due to forestry is actually greater than the total runoff available from a pastured catchment. On closer review the CSIRO data can be seen to generate very high levels of theoretical runoff, whereas Burnt Out Creek data are based closely on observations. More on this issue will be discussed later.

A striking aspect of the analysis is the way in which the Tanh modelled and observed Burnt Out Creek data show accord with international studies and independent modelling approaches.

DISCUSSION

MAGNITUDE OF REDUCTIONS IN RUNOFF

Proportional reductions in streamflow were observed to average 85% of pre-regrowth runoff after five years of forest regrowth. Reductions of this magnitude show close accord with Australian and international research.

Scott and Smith (1997) used observed data from paired catchment studies to derive empirical models that indicated maximum reductions in runoff due to pine trees of between 85 and 100% under sub-optimal and optimal growing conditions. Vertessy and Bessard (1999) developed a simple model to predict impacts of afforestation on mean annual runoff in 28 catchments of the Murrumbidgee Basin based on Holmes and Sinclair (1986) evapotranspiration-rainfall curves. Figure 4 in Vertessy and Bessard (1999) and later work by Vertessy (2001) and Vertessy *et al* (2002), indicated that if grassed catchments with mean annual rainfall of 800 mm/year and 210 mm mean annual runoff were planted to eucalypt forest, runoff maybe expected to reduce by 165 mm/year to 45 mm/year mean annual runoff (a 79% reduction) and 210 mm if planted to pines (a 100% reduction). While the initial estimates of runoff appear high (of which more will be said later), the expected proportional reduction in runoff of 80 to 100% are consistent with results from Burnt Out Creek.

Bradford *et al* (2001) and Zhang *et al* (2003) constructed theoretical forest and pasture runoff curves as the difference between theoretical mean annual evapotranspiration and rainfall. The proportional difference between mean annual pasture and forest runoff ranged from 60 to 85% of pasture runoff in areas with mean annual rainfall ranging up to 1000 mm. Concerns regarding the veracity of runoff estimates using this method are treated in greater detail below, particularly that runoff estimates attributed to forests are high and estimated impacts on runoff consequently low. Nonetheless, the proportional impacts of 60 to 85% accord with the high quality observed data from Burnt Out Creek.

The low flow frequency analysis of Lane *et al* (2003) showed pine plantation-induced decreases in runoff of 100% for flows with exceedances greater than 30%, 40% and 60% for their Group 1 catchments of Redhill, Stewarts Creek and Pine Creek respectively. Under wetter conditions reductions ranged between 50 and 95% (their Figure 5, p18).

A key aspect of the Burnt Out Creek data is the lack of a completely cleared pre-regrowth control period (or a paired catchment surrogate). In 1978 only 67% of the Burnt Out Creek catchment was cleared and re-planted. The 33% area of remnant plantation was planted between 1958 and 1965 (Figure 2), so that current runoff levels cannot be compared to *fully cleared* pre-forest conditions.

However the presence of some trees in an otherwise cleared catchment makes Burnt Out Creek more closely resemble and therefore more representative, of a wider range of mixed land-use catchments in the region. For example Middle River catchment on Kangaroo Island, an area currently receiving a lot of interest from forest developers, has an estimated 31% remnant native forest (Bren 2004).

The presence of the remnant plantation would have the effect of using water at plantation levels across a third of the Burnt Out Creek catchment area. The observed “pre-forest” runoff will be lower than what might be expected if it were completely cleared. If the 1978-1982 pre-forest runoff is assumed to be uniform and adjusted to have only been generated by the cleared 40 ha portion of the catchment, both modelled and observed average runoff increases from 66 mm/year to approximately 100 mm/year, for an average rainfall of 780 mm/year. Runoff reductions using these data as a pre-forest scenario results average 90%.

From this perspective, observed reductions of 85% are conservative and anywhere between 85 and 100% may be quite reasonable. Certainly some authors, such as Scott and Smith (1997), use a figure of 100% reduction in areas of higher rainfall and optimal growing conditions (See Figure 7). Vertessy (2001) and Vertessy *et al* (2002) reported 100% reductions in runoff when pasture was planted to pines (see discussion above). It may well be that forestry induced reductions in runoff in South Australia, where water resources are limited and soils shallow, are every bit as severe. More work is required.

TIMING OF REDUCTIONS IN RUNOFF

The 85% observed reduction in runoff at Burnt Out Creek occurred in the fifth year of plantation regrowth. A significant body of influential published literature suggests that the impacts of plantations on surface water resources are minor for the first five years and reach their peak at around 10 years, where they may stabilise or continue for up to 20 years.

> *"Runoff reductions are minor for the first five years after afforestation and are greatest 10-20 years after planting."* Zhang *et al* (2007) p 49.
>
> *"Where pasture is afforested, water yield declines progressively for about 11 years. The decline stabilises at about that age and persists until the plantation is thinned or harvested."* Keenan *et al* (2004a), p21.
>
> *"Water use is less in younger plantations and when plantations have been thinned. These effects should be considered in estimating plantation impacts on stream flow."* Keenan *et al* (2004b), p1.
>
> *Stream flow reductions tend to peak within 10–20 years of establishment, possibly later in drier environments.* Keenan *et al* (2004b), p4.
>
> *"Agreed Statement: The water yield impacts of plantations will be relatively low until canopy closure. Water yield reductions tend to peak at about 10–20 years, possibly later in drier environments... … In forest established on cleared farmland the impact will be measurable from canopy closure (typically 5-10yrs). From then on the yield will be dependent on stand density and management."* AG (2003) p2.
>
> *"In most situations the full hydrologic effect of plantations is not attained until the stand has reached about 8-15 years of age."* Vertessy *et al* 2003 p101.; *"…Evapotranspiration rates normally peak between stand ages 8 and 15 years. "* Vertessy *et al* (2002) p59.

Some of the literature suggests that faster impacts are possible. While rates of interception in a pine plantation can be expected to be low in the first three years of growth, they can increase rapidly between the fourth and ninth year (Putuhena and Cordery 2000). In an analysis of paired catchments in Tumut NSW Vertessy (2001) reported reductions in annual runoff of at least 100 mm/year occurring four years after Redhill catchment was afforested with 100% *P. radiata*. Impacts on low flows described by Lane *et al* (2003) reached their maximum in around five years.

Vertessy *et al* (2003) used modelling to demonstrate the relatively swift response of surface water to afforestation compared to that of groundwater (see Figure 10, below). These findings all point towards faster impacts by forests on smaller surface runoff events, typical of dry conditions or drought (see discussion below).

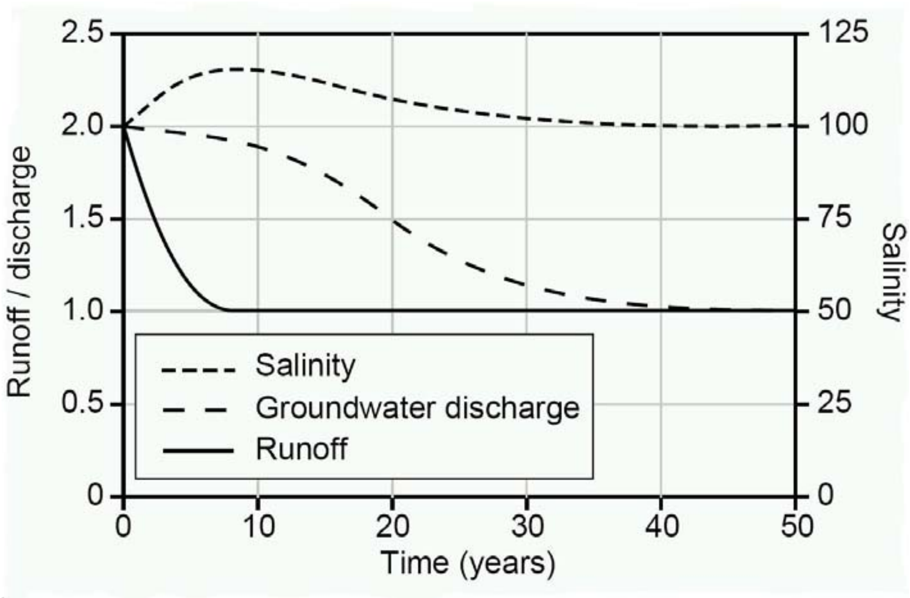


Figure 10. : Response of surface and groundwater to afforestation. Source: Vertessy *et al* (2003).

The presence of remnant forest in Burnt Out Creek means that it is not possible to gain an *unambiguous* picture of the sequential changes in forest hydrology at Burnt Out Creek during forest regrowth. The older trees would already have exerted an influence on pre-regrowth runoff at the time of replanting in 1978, which remained for the life of the study period. The discussion above indicated that the outcome of this effect is likely to be a conservative estimate of the maximum impacts on runoff.

It is also possible that the remnant forest may have biased the timing of the impacts on runoff. Despite some support from literature, an expectation of maximum impacts in five years appears relatively early. This time frame may well be realistic in specific catchments, under specific climatic conditions as will be discussed below. The effect of the remnant forest on the timing of impacts was explored further by attempting to estimate the average age of the remnant forest across Burnt Out Creek at the time of replanting, and extrapolating observed impacts from the adjusted age to compare with published observations.

When Burnt Out Creek was replanted in 1978, approximately 20 ha of mature pine plantation remained; 3.7 ha were 20 years old; 15.5 ha were 17 years old and approximately 0.5 ha were 13 years old (Figure 2). The areal weighted average age of the plantation was approximately 6 years. If Burnt Out Creek data were simply shifted by this period along the Scott and Smith (1997) age axis in Figure 8, the maximum reduction in runoff would have been achieved in an equivalent of 11 years, consistent with published data (Zhang *et al* 2007 and others cited above) (Figure 11 below).

This discussion has a conceptual character, but pursuing it further presents opportunities for additional insight into forestry impacts on runoff and further work. With mean annual rainfall ranging from 1100 to over 1600 mm/year, the Scott and Smith (1997) catchments were much wetter than the Mount Lofty Ranges. The Burnt Out Creek data were also subject to an intense drought in 1982, which in Figure 11 can be seen to define the steep part of the Burnt Out Creek Scott and Smith-type curve. If more surface water were available it is likely that more would have runoff through the forest and the proportional reduction in Burnt Out runoff would have been less. This may well have had the effect of delaying maximum impacts by retaining more moisture in the landscape. The resulting slope of the Burnt Out Creek curve may well have been closer to the Scott and Smith (1997) sub-optimal curve.

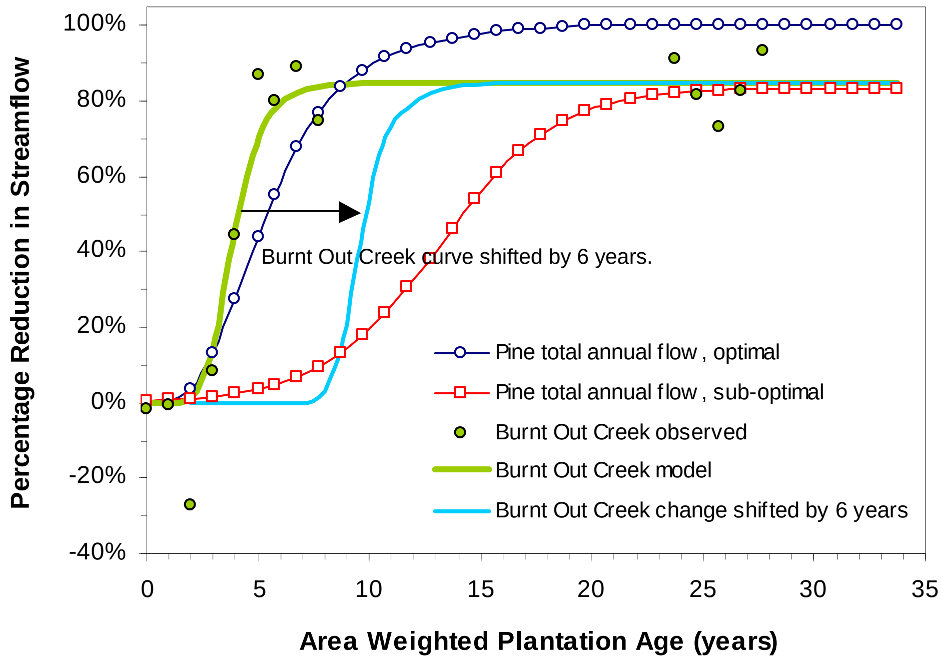


Figure 11. Decrease in measured Burnt Out Creek runoff compared to Tanh modelled pre-forest runoff. Pine forest modelled data from Scott and Smith (1997).

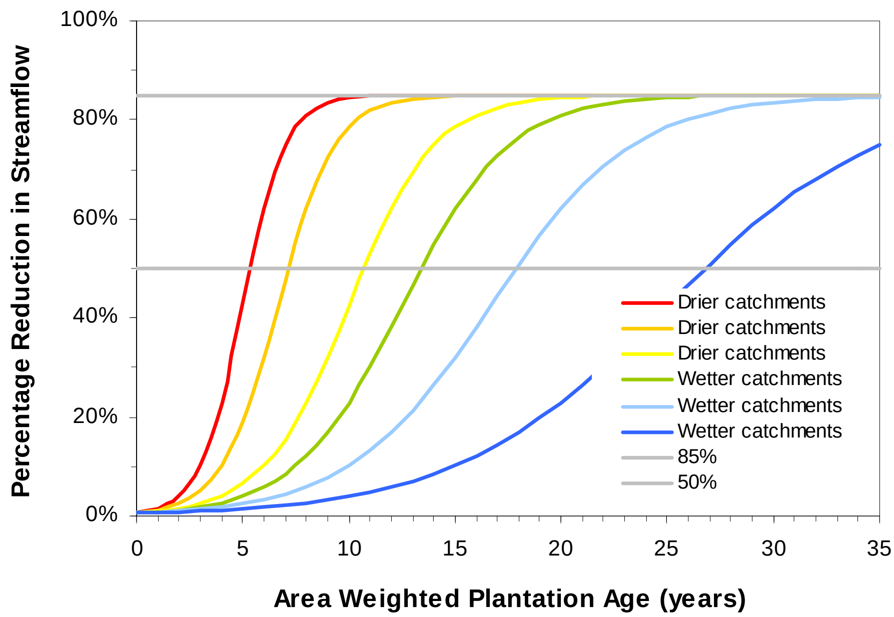


Figure 12. Conceptual forest age – runoff impact curves for different catchments after Scott and Smith (1997).

It is conceivable that a family of curves may be defined for a range of climatic and catchment conditions that can be used to estimate forest impacts on runoff (Figure 12). Initial parameters may include an observed maximum impact asymptote, such as observed at Burnt Out Creek. More immediate impacts may be predicted for drier catchments and delayed impacts for wetter ones. Application would be found in hydrological assessments, water resources management and policy development. More work is required.

Effect of drought

In terms of short-term rainfall deficiencies and their overall impact, the 1982 drought may be considered the worst drought in the 20th Century (BOM 2007). As the drought took effect in the summer of 1982 the pine forest at Burnt Out Creek was approximately four years of age (Plates 9 to 10a,b,c, , Appendix D). Data from both Scott Creek and Burnt Out Creek in Figure 3 (above) show the effect of the drought in reducing runoff to 23 mm (long term mean 140 mm) and 39 mm (pre 1982 mean 108 mm) respectively.

In 1982 the annual rainfall was 548 mm. In 1983 rainfall was 938 mm, nearly twice that of 1982. The return of wetter conditions saw Scott Creek runoff making a four-fold recovery, increasing in runoff from 23 to 98 mm, while the post-drought increase in Burnt Out Creek runoff was much more modest, from 6 to 15 mm.

The number of studies into the impact of forestry in dry conditions is limited. Some influential industry publications discount their impact in areas of low rainfall (Keenan *et al* 2006, Keenan *et al* 2004a,b, Vertessy *et al* 2003, see later discussion). Vertessy (2001) described a paired catchment study in the Tumut catchment in NSW which revealed significant changes in the duration of daily flows of all magnitudes. The pine planted test catchment (Redhill) ceased to flow for almost 40% of the time, compared with the pasture-covered control catchment (Kileys Run), which continued to flow all year round (Figure 13).

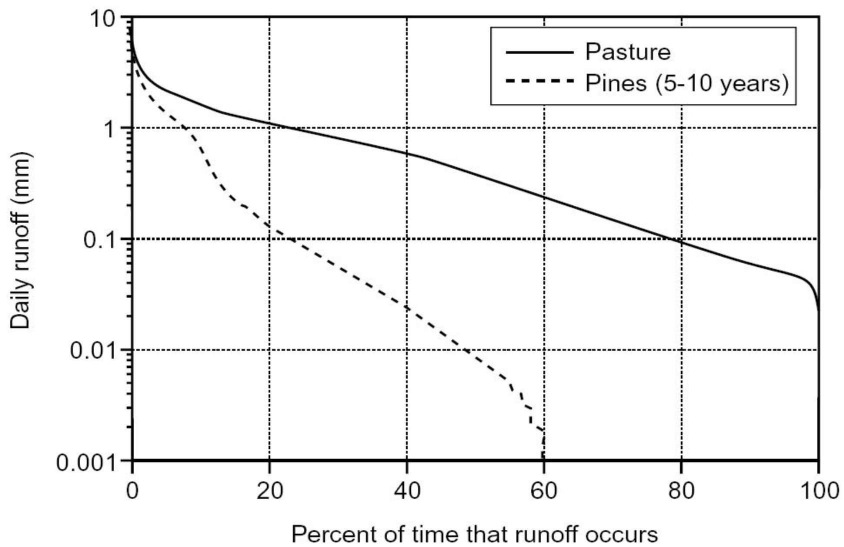


Figure 13. Increase in frequency of flow cessation due to forestry. Source: Vertessy (2001)

Lane *et al* (2003) showed that establishment of pine plantations significantly increased the number of days with zero flow and gave rise to a proportionally larger reduction in low flows compared to high flows. Their Pine Creek data from a catchment larger than Burnt Out Creek at 320 ha, but with a similar mean annual rainfall of 775 mm/year, shallow soil and 100% planted to *P. radiata*, showed that impacts reached a peak in around five years, increasing markedly after three years (Figure 14, below).

The drying effect of 1982 on Burnt Out Creek is evident in the low measured runoff data presented in Figure 3. After 1982, regional groundwater stores across the Mount Lofty Ranges showed declining trends to around 1986 (Barnett *pers comm*.) Plates 9 and 10a,b,c (Appendix D) show the opulent canopy development established in the same year.

Burnt Out Creek runoff probably relies heavily on shallow perched groundwater saturation (Barnett *pers comm.,* see discussion below). The depletion of soil and perched groundwater resources appears to have coincided with the maturing pine trees attaining canopy closure. The increased evapotranspiration and interception probably contributed to keeping soils dry and reducing recharge of perched groundwater, culminating in a sudden, large impact at a relatively early stage of growth in the replanted section of forest.

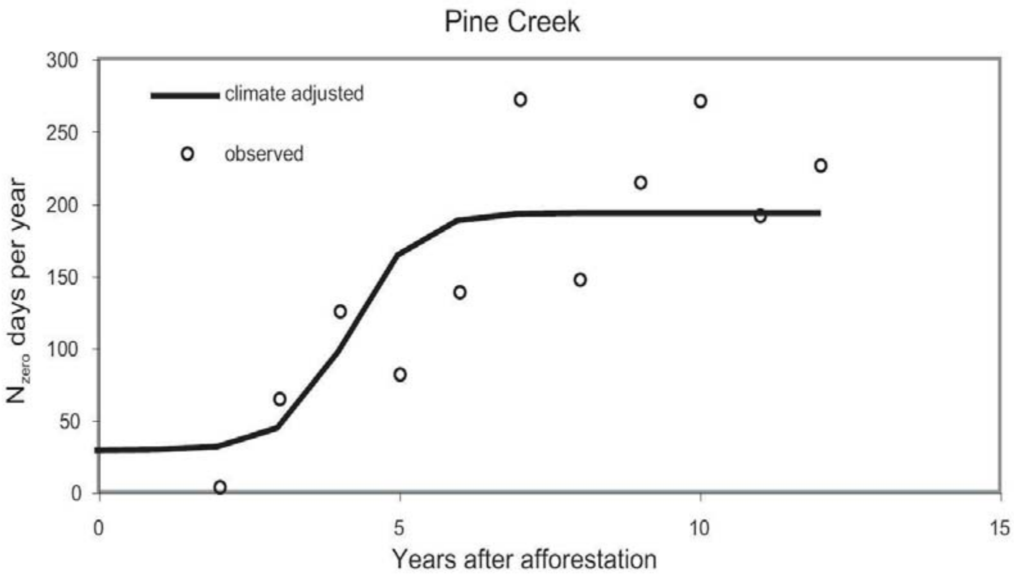


Figure 14. Maximum impacts of forestry on runoff shortly after five years. Source: Lane *et al* (2003)

Catchment Characteristics

Dry conditions may be a key consideration in the timing of surface water impacts but catchment characteristics are also likely to be important. Burnt Out Creek is known for its fast runoff response (GSA 2007a). This is due to its small size, shallow soils and moderately steep hills (15 to 30% gradient, McKenzie *et al* 2005).

Typical of the Mount Lofty Ranges' warm Mediterranean climate, it also has a short wet season. Over half the total annual rain falls in the period June to September, resulting in flashy ephemeral flow events. This is shown in Figure 15 (below). Runoff is highly episodic with a spikey hydrograph that lacks persistent baseflow recessions, decaying over a period of weeks, even following months of persistent seasonal rain.

From the perspective of surface-groundwater interactions, once soil and perched groundwater stores are saturated, runoff can occur. But where they are shallow and subject to high rates of evapotranspiration, may be prone to ceasing abruptly as soils and shallow groundwater stores can dry quickly. Under these conditions interception would play a significant role in controlling runoff by controlling recharge. Canopy closure, even in young trees, especially densely planted trees, would be capable of causing significant reductions in runoff.

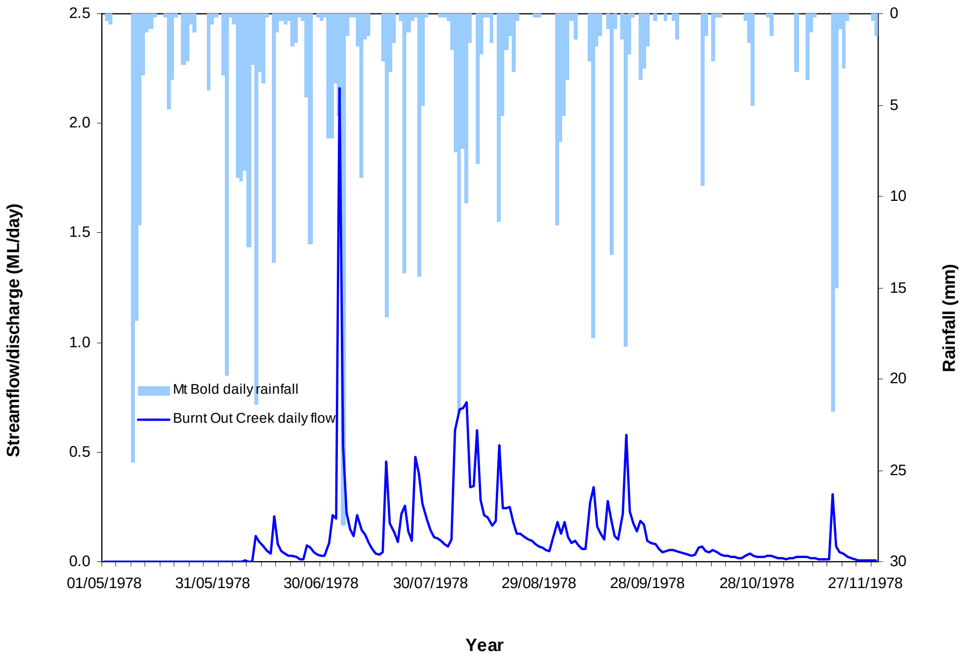


Figure 15. Burnt Out Creek daily streamflow May to end November 1980.

The sequence of growth recorded in Plates 8 to 12 (Appendix D) illustrates the development of the young canopy. Plates 8a,b show it as relatively open in 1980, two years after replanting. Plates 9 to 10a,b,c show a dramatic increase in canopy density in 1982 to a state of almost complete closure. By 1984 canopy growth was very thick (Plate 11) and remained so over the duration of the study period, as seen in Plates 12a,b which show the forest at 10 years of age in 1988.

IMPACTS IN LOW RAINFALL AREAS

Given the discussion on the effect of drought above, it is interesting to review some of the comments and recommendations found in published literature that appear to discount the impacts forestry has on runoff in low rainfall areas. Particularly as reputable sources may influence the decisions of developers to target areas where forestry is simply unsustainable due to limited water availability.

> *"In low rainfall zones where potential evaporation exceeds annual rainfall, differences in catchment water yield diminish or disappear, because all vegetation types consume water at rates that cannot be matched by rainfall.".* Keenan *et al* (2004a), p22*.*
>
> *"Run-off reduction increases with increasing rainfall. It is estimated to be less than 80–100 mm where rainfall is 500 mm/year and increases to more than 300 mm where rainfall is 1500 mm/year. Stream flow from small catchments may become more intermittent after reforestation."* Keenan *et al* (2004b), p1*;* Key Point 2 Keenan *et al* (2006), p1*.*
>
> *"The effect of plantations on water yield can potentially also be minimised by…targeting new plantation establishment in lower rainfall areas (<800 mm/year) where reductions in water yields are smaller;"* Keenan *et al (2004b),* p5.
>
> *"Plant in regions with less than 800 mm/year annual rainfall, where yield reductions are lower and salinity is more of a problem. "* Vertessy *et al* (2003) p59.

Anyone who suggests that the impacts of water affecting activities on surface water resources can be reduced by ensuring they are developed in low rainfall areas obviously doesn't live in one. Assessments presented in this work show that reductions in runoff due to plantation forestry in years where rainfall is 800 mm/year or less can be expected to range between 85 and 100% (Figure 9, above). Where there is less rainfall and runoff, a greater proportion of it is used by plantation forests.

Most of the catchments in the Mount Lofty Ranges, Fleurieu Peninsula and Kangaroo Island have a mean annual rainfall of 800 mm or less and the Mediterranean climate and shallow soil means that wet seasons are generally short, and runoff is episodic. Consequently runoff is modest and surface water resources are limited. In years with rainfall of 800 mm, measured data from a number of catchments across the region indicate that runoff may range between 50 to 150 mm/year (see Figure 16, with data from Teoh 2003 and Tomlinson 1996). In years where rainfall is 500 mm annual runoff is less than 50 mm.

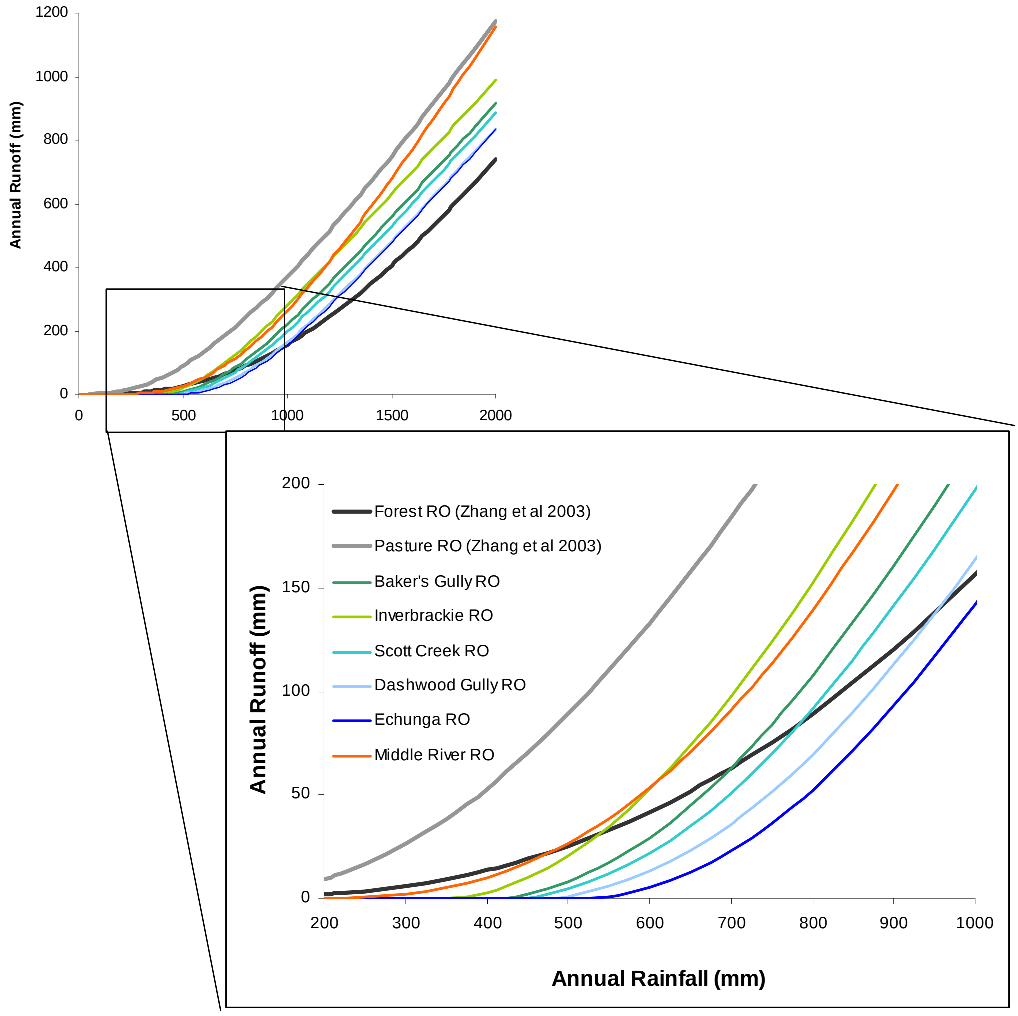


Figure 16. Figure 3: South Australian rainfall-runoff curves based on measured data (Teoh 2003; Tomlinson 1996) and theoretical relationships after Zhang *et al* (2003).

Most of the statements above are at odds with findings from Burnt Out Creek and similar assessments of forestry impacts based on measured data. They have their basis in the use of the Holmes and Sinclair (1986) and Zhang curves (Zhang *et al* 1999, 2001), which were derived to illustrate the difference in evapotranspiration between pasture and forests in high rainfall areas.

From these data a number of authors have estimated annual runoff as the difference between mean annual rainfall and mean annual evapotranspiration, including Vertessy and Bessard (1999), Vertessy (2001), Zhang *et al* (2003) and Bren (2004). The statements above suggest that the use of Zhang curves must be undertaken with appropriate consideration of the data on which they were based and their consequent limitations.

LIMITATIONS OF ACCEPTED FORESTRY IMPACT ASSESSMENT METHODS

In the context of measured South Australian data, statements like those of Keenan *et al* (2004a) above, that runoff is reduced by *less than 80–100 mm where rainfall is 500 mm/year*, should be challenged. In the Mount Lofty Ranges and Kangaroo Island runoff can be expected to reach a maximum of around 30 mm in years with 500 mm/year rainfall (Figure 16), making it difficult to reconcile published statements with field observations.

It was possible that the South Australian runoff data were the result of local runoff conditions. This appeared to be the case when theoretical Zhang pasture and forest runoff curves were plotted with rainfall-runoff curves based on observed data from Teoh (2003) and Tomlinson (1996) (Figure 17).

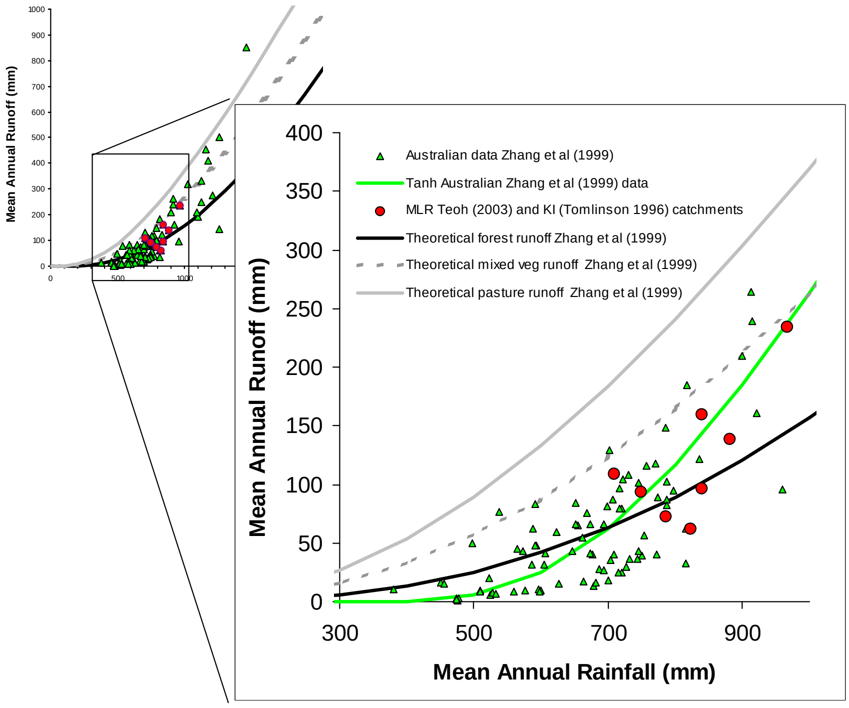


Figure 17. Measured Australian runoff data from Zhang *et al* (1999), Zhang runoff curves and measured South Australian runoff data.

Note that the Zhang curves represent the mean annual runoff generated from areas with a given mean annual rainfall, whereas the South Australian runoff data are Tanh functions based on annual time series. The Zhang data do not represent inter-annual behaviour whereas the South Australian data are derived from inter-annual behaviour. However a number of authors have used the Zhang approach to explore inter-annual behaviour (Bradford *et al* 2001 and Zhang *et al* 2003).

To clarify this issue all the observed Australian data used in Zhang *et al* (1999, 2001) were plotted with the theoretical Zhang runoff curves, along with the South Australian mean annual data

(Figure 17). The Zhang curves did not provide a good representation of any Australian data in areas of low rainfall whereas the South Australian data plotted amongst the other measured observations.

Furthermore the approach seemed to significantly overestimate runoff from low rainfall catchments. Approximately 90% of the Australian Zhang data were from catchments classified as *pasture* or *mixed vegetation* and approximately half of these had runoff below that expected from a theoretical Zhang forest runoff curve.

A number of significant issues arise:

- When mean annual data is used to describe inter-annual behaviour the inherent bias in skewed hydro-climatological time series will result in over-estimation of water resources and will be unable to represent the fundamental variability that characterises Australian hydrology (McMahon *et al* 1992).
- When runoff is overestimated the impacts of any water affecting activity on the available resources are underestimated.

Review of Holmes and Sinclair (1986) and Zhang *et al* (1999) identified that their approaches were unsuitable for catchments drier than about 900 mm/year (p218, Holmes and Sinclair 1986) and their model was based on long term averages and not designed for exploring inter- or intra-annual variability (p22, Zhang *et al* 1999). .

If theoretical Zhang-type runoff curves were used in accordance with stated limitations then the advice provided in published literature would be far more robust. When used out of context, runoff estimates based on Zhang-type curves tend to be unrealistically high, resulting in some authors modifying theoretical rainfall-runoff models by developing regression relationships with limited data (Bren 2004). This highlights the value of using even limited observed data as opposed to a poorly founded model, especially when inter-annual variability is an important consideration. The limits of application of Zhang curves will be the subject of a separate technical note.

Assessment techniques

> *"Agreed Statement: To calculate the water yield impacts of plantations in large catchments:…Divide the catchment in to small spatial units (ideally no larger than 1km^2 or 100ha) and calculate the mean annual water yield for each of these units using established relationships (eg. Zhang et al 2001),…"* AG (2003) p2.
>
> *"The Zhang curves provide a very good guide to runoff- the difference between rainfall and evapotranspiration – that can be expected under different vegetation types."* Zhang *et al* (2007) p22.

Following on from the preceding discussion on Zhang curves, caution should be exercised when using these *established relationships* for Australian conditions. Absolute quantities of runoff and runoff reduction are likely to be significantly overestimated.

However *proportional* reductions in runoff based on theoretical Zhang *et al* (1999, 2001) curves, as seen in Bradford *et al* (2001) and Zhang *et al* (2003) are closer to observations at Burnt Out Creek, while those based on Holmes and Sinclair (1986) curves, including Vertessy and Bessard (1999), Vertessy (2001) and Vertessy *et al* (2002) are in close accord. More work is planned to define the applicability of this approach in the near future.

APPLICATION IN WATER RESOURCES MANAGEMENT

The Burnt Out Creek findings have the potential to use pre-forest rainfall-runoff curves to generate post-forest rainfall-runoff curves using the rainfall dependent reductions shown in Figure 9, and explore the likely maximum inter-annual impacts of forestry using observed annual rainfall.

Once a rainfall-runoff curve is developed for a given catchment, preferably from observed or robust modelled catchment yield data (see Figure 6), then a theoretical post-forest rainfall-runoff curve may be derived from the pre-forest curve and the expected reductions shown in Figure 9.

Given a proposed scenario of a proportion of forest in a catchment, the pre- and post-forest rainfall-runoff functions can be apportioned to the relative areas of proposed forest and the remainder to generate a new rainfall-runoff function. Observed annual rainfall data can then be loaded into the new rainfall-runoff scenario model to explore the inter-annual impacts of forestry on runoff.

This approach is actually similar to that of Zhang *et al* (1999) and Bradford *et al* (2001) where forest and pasture evapotranspiration is apportioned across a catchment according to respective areas (Equation 1), where the parameter *f* is the proportion of forest cover in the catchment.

$$ET = f\,ET_f + (1-f)ET_h \qquad (1)$$

Here it is recommended that initial estimates of runoff be more robust than theoretical Zhang curves and post-forest runoff be estimated using the Burnt Out Creek adjustments. This modification to the Zhang type approach has the benefits of being based on observed data, including low rainfall years and can be used with extended annual rainfall time series to explore inter-annual variability.

POLICY CONTEXT

The findings of this review are relevant to a number of major state and commonwealth government water resources management initiatives.

South Australia

On 8 September 2005 the Eastern Mount Lofty Ranges became a Prescribed Area under the *State NRM Act 2004*, while the Western Mount Lofty Ranges were prescribed shortly thereafter on 20 October 2005. Both regions are currently under a Notice of Prohibition, which is a temporary moratorium on further water resources development triggered by concerns of the Government of South Australia that water resources may not meet future demand.

The entire Mount Lofty Ranges region is now the subject of a major water resources assessment program, which will support the development of water allocation plans (WAPs) by regional NRM Boards and define the amount of water that can be used. In defining water use limits, WAPs must consider:

- the water resource's capacity and limit the demands on a water resource; and,
- the needs of both the environment and consumptive water uses (see DWLBC undated and AMLRNRM 2006).

The NRM Boards in the region are currently consulting on how forestry water use should be accounted for in the water allocation plan.

25% use limit guideline

In the interim DWLBC have taken the position that the assessment of forestry development sustainability should be undertaken in the context of the *25% use limit guideline* (see Box 1), which is used for assessing the sustainability of all other water affecting activities. Invoking the 25% rule for forestry developments provides a transparent, equitable and convenient way by which accepted volumetric water use limits can be translated into areal extent of forestry and vice-versa.

> *Box 1: Government of South Australia 25% rule*
>
> *2. Outside prescribed areas, and until there is additional information, 25% of median annual adjusted catchment yield should be used as an indicator of the sustainable limit of the catchment surface water and watercourse water use. 'Adjusted' is defined as the annual catchment discharge with the impact of dam storage removed.*
>
> *GSA (2006) – Appendix B*

Farm dams or different irrigation practices can be retired in favour of areas of forestry. Adoption of this approach should prove a useful starting point in meeting objectives of sustainable resource management articulated in State and Regional NRM plans and the implementation of the Australian Government National Water Initiative (NWI).

A key consideration in applying the 25% rule is to maintain consistency with the prescription process and provide equity of access to developers, in spite of the historic legacy of any development in excess of the 25% rule allocation.

Since the overarching goal is to preserve the 25% use limit guideline at a catchment scale, some sub-catchments may already be over-allocated, which means others remain under allocated to remain within the 25% rule allocation at a catchment scale. This has implications for DWLBC policy development, which cannot be addressed by technical advice alone.

Maximum permitted area of forestry

In recent times, South Australia has taken a precautionary approach in applying the 25% rule based on the best available information. The impacts of forestry on surface water are assessed by assuming that plantations will exert their maximum expected impact on runoff.

This ensures downstream users have access to a reliable water supply, no matter what stage of growth a plantation attains before harvesting and water resources are managed in a way that meets the objectives and principles of the South Australian *Natural Resources Management (NRM) Act 2004* (Appendix G, GSA 2006a); the objectives of the State Strategic Plan (Objective 3 Attaining Sustainability, GSA 2007b) and water allocation levels in accordance with state

> *Box 2: Max forestry area using maximum impact and 25% rule*
>
> *1. Available resource = total development demand x available area.*
>
> *2. Available resource = forest demand x maximum forested area.*
>
> *3. 25% cleared runoff = 85% cleared runoff x maximum forested area.*
>
> *4. Maximum forested area = 25% cleared runoff / 85% cleared runoff = 30%.*

obligations under the NWI (s57, AG 2004).

When the impact of forestry on runoff is managed at a maximum reduction of 85%, then the fraction of total catchment that can be planted to forest, in the absence of farm dam development or other use, can be calculated by the procedure described below (see also Box 2).

1. The demand created by any development in the catchment must not exceed the sustainable limit.
2. When considering forestry, the total demand is determined by the expected reduction in runoff and the area of forestry.
3. Here, the permissible available resource is set at 25% cleared runoff and the effective forest demand is 85% of the cleared runoff; and,
4. Solving for the maximum area of forestry, the equation in Box 2 limits the maximum forest area to 30%. It indicates that trees would use more water if more water is available, which is probably the case in low rainfall areas like South Australia.

If farm dam development or other water uses are in place then the permissible available resource would be reduced by that amount resulting in a maximum-forested area of less than 30%.

Maximum versus average impacts

The results of this assessment tend to confirm the findings of published literature that impacts of forestry on runoff commence after canopy closure in 5 years (AG 2003) and in most situations the maximum hydrological impacts can be expected between 8 to 15 years (Vertessy *et al* 2003). Impacts may be accelerated by climate, catchment conditions and plantation management.

If a forest has a maximum impact of reducing surface water resources by 85% over ten years, it is reasonable to state that on average the forest has used less than that amount. Forest proponents may take the view that over a ten-year rotation the total surface water resources used in that period may have been closer to say 50% of the total streamflow (see Figures 8 and 14, above).

Notwithstanding the 25% rule, if resource managers allocate water for forestry at the level of 50%, then depending on the extent of the development, the resource runs the risk of over-allocation for a significant portion of the forest rotation. This may have impacts on downstream users, including the environment, who require a secure allocation every year.

This has implications for the State Government and Regional NRM Boards in meeting:

- the objectives of the State Strategic Plan (Objective 3 Attaining Sustainability) in ensuring South Australia’s water resources are managed within sustainable limits (Target 3.9);
- the goals of the State NRM Plan 2006 in establishing a more deliberate approach in providing secure, long-term access to key natural resources (Goal 2, p41); and certainty to consumptive users (Goal 2, p44);
- the requirements of water allocation plans in providing for the equitable allocation and use of water so that the rate of use of the water is sustainable; and take into account the present and future needs of the occupiers of land in relation to the existing requirements and future capacity of the land (*NRM Act 2004*, s76(4)); and,
- the objectives of the NWI in providing secure water access entitlements (s23(i)) and the return of all over-allocated or overused systems to environmentally-sustainable levels of extraction (s23(iv)).

Land management versus water resources management

Management practices described in industry guidelines currently address land-based issues (ForestrySA 1997). The guidelines ensure among other things, that parts of the plantations and infrastructure are accessible. From a water resources perspective it is important that the shared portion of runoff from a property is protected and accessible to downstream users. To this end a number of principles have been adopted to assess development applications, which it is hoped would form the basis of water resources appropriate plantation design guidelines.

The shared portion of property runoff must be free to pass downstream. Areas completely surrounded by forestry prohibit runoff and must be considered part of the forestry development. This requires a gross area approach be taken to assess the total size of forestry developments. Isolated areas that accommodate non-forest purposes such as native vegetation buffers can not be regarded as separate from the proposed development area. This issue should be addressed to a significant degree by buffering all areas with significant hydraulic connectivity to downstream systems (see below).

Buffers should be established to manage the impact of forestry on the downstream water users, including the environment. A minimum 50 m buffer should be established around all significant wetlands and streams as depicted on the DWLBC ordered stream GIS. The width has been set as a minimum interstate (GWA 2000) and is considered sufficient by DWLBC to manage uptake from watercourses and wetlands by lateral root growth (Knight 1997) and water table lowering (Vertessy *et al* 2000). A 5 m buffer should also be established around all unmarked drainage lines to ensure hydraulic connectivity can be maintained with significant ephemeral tributaries. The drainage lines and streams should not be used as roads or ripped or interfered with in any way to ensure the allocated shared portion of runoff passes to downstream users.

Commonwealth

Forestry has been recognised as one of the six risks to the shared resources of the Murray-Darling Basin (MDBC 2007, EarthTech 2003) and as a risk to the future integrity of water access entitlements and the achievement of environmental objectives for water systems under the NWI Water Access Entitlements and Planning Framework (AG 2004, s 25 to 57).

NWI Interception Activities

The NWI has recognised that forestry and a number of other land use change activities including farm dams development and harvesting overland flow, have the potential to intercept significant volumes of surface and/or groundwater now and in the future (s55, AG 2004) and that if these activities are not subject to some form of planning and regulation, they present a risk to the future integrity of water access entitlements (s56, AG 2004). It is intended that assessments of these activities be based on an understanding of the total water cycle, the economic and environmental costs and benefits of the activities of concern, and where necessary apply appropriate measures to protect the integrity of the water access entitlements and the achievement of environmental objectives (s56, AG 2004).

Accordingly, the Government of South Australia has agreed to implement measures on a priority basis, no later than 2011 that (s57):

i) in water systems that are fully allocated, overallocated, or approaching full allocation:-

  a) interception activities that are assessed as being significant should be recorded (for example, through a *licensing system*);

b) any proposals for additional interception activities above an agreed threshold size, will require a *water access entitlement;* and,

c) a robust compliance monitoring regime will be implemented; and

ii) in water systems that are not yet fully allocated, or approaching full allocation:-

a) significant interception activities should be identified and estimates made of the amount of water likely to be intercepted by those activities over the life of the relevant water plan;

b) an appropriate threshold level will be calculated of water interception by the significant interception activities that is allowable without a water access entitlement across the entire water system covered by the plan; and,

c) progress of the catchment or aquifer towards either full allocation or the threshold level of interception should be regularly monitored and publicly reported.

These stipulations will no doubt be of great interest to Regional NRM Boards that are currently in the process of developing water allocation plans for water affecting activities in the Mount Lofty Ranges.

Environmental Objectives

South Australia doesn't currently have a system for identifying high value water-dependent ecosystems. Controls on developments rest with councils and their principles of development control under the *Development Act 1993*, unless or until the Minister responsible for the *NRM Act 2004* declares that there is a risk of *inadequate supply or overuse of water* and enacts provision of the act to control water affecting activities. This process triggers rigorous process of water resources assessment, which culminates in the development of a water allocation plan and takes the needs of water-dependent ecosystems into account.

The NWI seeks to fill this gap. An outcome of the Water Access Entitlements and Planning Framework states that the Parties will (s25x): *identify and acknowledge surface and groundwater systems of high conservation values, and manage these systems to protect and enhance those values*.

In the interim some NWI environmental objectives are captured by commonwealth legislation. These include the protection of the *Swamps of the Fleurieu Peninsula*, which since 21 March 2003, have been listed as *Critically Endangered, Threatened Ecological Communities* under the Environment Protection and Biodiversity Conservation (EPBC) Act 1999 (AG 2006). Wetlands on the Fleurieu Peninsula, including Swamps of the Fleurieu Peninsula, are known to support 85 animal and plant species of state conservation significance, 9 species of national conservation significance, and 3 species protected by international conventions.

In the last two years forestry has become a contentious issue, particularly in the context of *Swamps of the Fleurieu Peninsula*. A joint DWLBC, DEH and PIRSA process has progressed to an inter-Departmental accord reached on 22 February 2007, requiring that forestry developments in the Mount Lofty Ranges and Fleurieu Peninsula be assessed according to the Water Allocation and Management Guidelines of the State NRM Plan 2006 (GSA 2006) and that specific water requirements of significant wetlands where they exist, be determined using a water balance approach as endorsed by Casanova and Zhang (2006).

The water balance approach will be developed as part of the DWLBC NWI project to collect biophysical data and develop hydrological models for use in the assessment of forestry impacts and the implications for downstream users, including important water dependent ecosystems (GSA 2006a). The project is due for completion in December 2008.

CONCLUSIONS

In early 1977 approximately 67% of the pine plantation in the Burnt Out Creek catchment was cleared (Plates 1 to 2, Appendix D). Collection of streamflow data began at the Burnt Out Creek hydrometric weir in January 1978 (Plates 3 to 6). Replanting was completed by November 1978. During the period 1978 to 1982 runoff averaged 66 mm/year.

In 1983 when the forest was five years of age, runoff suffered a significant and abrupt reduction, averaging 15 mm/year from 1983 to 1986 and 14 mm/year from 2002 to 2005. Runoff from other catchments in the region, without intensive forestry development, remained at expected levels. Despite the considerable break in the hydrometric record it is reasonable to conclude runoff has averaged approximately 15 mm/year for over 20 years.

Analytical rainfall-runoff relationships derived using data from Burnt Out Creek indicated that *P. radiata* plantation forestry was likely to reduce catchment water yield by between 70 and 100% depending on the annual rainfall, consistent with the findings of Australian and international studies.

The data may be used in the assessment of forestry impacts on catchment runoff by aerially adjusting pre-forest rainfall-runoff relationships. The approach is similar to that used by CSIRO and CRC researchers but is based on more robust estimates of pre- and post-forest runoff and has applicability for exploring inter-annual variability.

A convenient threshold of 85% may be adopted for estimating the maximum impacts of forestry in the Mount Lofty Ranges and Kangaroo Island for planning purposes. The figure is based on measured data from a single, small catchment, but has greater applicability than weakly based theoretical approaches published in Australian scientific literature.

The sudden nature of the change in runoff at Burnt Out Creek and its relatively early onset was probably a function of the runoff characteristics in a catchment highly dependent on soil and shallow perched groundwater stores in generating runoff, combined with a coincidence of extremely dry conditions and a young, dense forest achieving canopy closure and beginning to significantly increase levels of evapotranspiration and interception. From this perspective dry conditions can be seen as hastening the impact of forestry on runoff, rather than delaying them as described in some published literature.

The remanent stand of forest in the catchment may also have had an effect. It is likely that pre-regrowth runoff from Burnt Out Creek was not at true cleared or pasture levels, but was already effectively reduced by the surviving plantation. The result may have been a runoff response closer to a mixed vegetation catchment, typical of a wider area of the Mount Lofty Ranges and Kangaroo Island. In any case reductions in runoff relative to pre-regrowth runoff are likely to be conservative if applied to a completely cleared catchment.

Despite distinct site-specific climatic and catchment influences over the course of the data collection period, the long-term patterns of runoff reduction at Burnt Out Creek follow those predicted by modelling for catchments with shallow soils in South Africa, providing an indication of how applicable Burnt Out Creek data may be to local catchments. The Tanh approach produced results that were consistent with independently derived empirical models and where differences existed, the data showed the potential to provide additional insight into the likely response of forested catchments under local conditions.

RECOMMENDATIONS

- A precautionary approach is recommended in the management of forestry development to meet the objectives of current and future of water reforms including State and Regional NRM planning and South Australia's commitments to the NWI.
- Management prescriptions should be based on maximum impacts to ensure annual entitlements are secure for all users over the life of any development. Otherwise the shared water resource would run the risk of over-commitment when long-term developments mature.
- For simplicity and convenience of application and until additional information is collected, a policy be adopted whereby impacts of plantation forestry on runoff be estimated at 85% the pre-forest, cleared or mixed pasture runoff.
- To remain within sustainable limits of water resources development, plantation forestry should be limited to 30% of the area of any property in the Mount Lofty Ranges, Fleurieu Peninsula and Kangaroo Island. If farm dams are present on the property the area will need to be reduced accordingly.
- Unlike current forestry plantation design guidelines the area of the development should be considered gross area. Isolated exclusion zones around buildings or pockets of remnant bush must be considered part of the forestry development if they are isolated from watercourses and drainage lines. Exclusion zones should be connected to watercourses and drainage lines to ensure they pass allocated runoff downstream. Once these areas are surrounded by forestry they cannot contribute to catchment runoff and cannot contribute to the sharing of water resources with downstream users, including the environment.
- Pre-forest, cleared or mixed pasture runoff should be estimated using robust rainfall-runoff modelling that show strong accord with Departmental assessments and data. Post forest rainfall-runoff relationships can be constructed using the Burnt Out Creek information to assess maximum impacts. Runoff for the entire catchment may then be estimated by combining modelled runoff from the relative areas of mixed land-use and forest, similar to the Zhang *et al* (1999) approach.
- Runoff should not be estimated using Holmes and Sinclair or Zhang curves without close scrutiny. If Zhang curves must be used, they should be constructed in a way that ensures the outputs accord with measured runoff data in the region.

BIBLIOGRAPHY

Adelaide and Mount Lofty Ranges Natural Resources Management Board, AMLRNRM (2006) Developing a Water Allocation Plan for the Western Mount Lofty Ranges, May. http://www.amlrnrm.sa.gov.au/board_plans/wmlr/amlr_wmlr_info_april06.pdf

Australian Government, AG (2003) The Impact of Forest Plantations on Water Yield, Bureau of Rural Sciences, CSIRO Land and Water, CSIRO Forestry and Forest Products, Murray Darling Basin Commission and CRC for Catchment Hydrology, October.

Australian Government, AG (2004) Intergovernmental Agreement on a National Water Initiative between the Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory. Council of Australian Governments, Department of the Prime Minister and Cabinet, June. http://www.coag.gov.au/meetings/250604/iga_national_water_initiative.pdf

Bradford A, Zhang L and Hairsine P (2001) Implementation of a Mean Annual Water Balance Model within a GIS Framework and Application to the Murray-Darling Basin. CRC for Catchment Hydrology Technical Report 01/8, September.

Bren L (2004) Impacts of Plantation Development on the Water Resources of the Middle River Catchment, Kangaroo Island, unpublished report to Private Forestry Kangaroo Island, November.

Brown A E, Hairsine P B and Freebairn A (2006) The development of the Tasmanian Land Use Change and Stream Flow (TasLUCaS) tool. Report to the Tasmanian Natural Resource Management Committees, CSIRO Land and Water Science Report 54/06, July.

Bureau of Meteorology, BOM (2007) Short but sharp - The 1982-83 droughts, http://www.bom.gov.au/lam/climate/levelthree/c20thc/drought4.htm

Casanova M and Zhang L (2006) Fleurieu Peninsula Swamp Ecology, Swamp Hydrology and Hydrological Buffers. Report to the Steering Committee for the Independent Assessment and Recommendation of Buffers to Apply in Relation to Fleurieu Swamps. Charophyte Services and CSIRO Land and Water.

Dawes W R, Gilfedder M, Walker G, Evans R, Stenson M, Dowling T, Austin J and Best A (2004) BC2C Technical Documentation, CLW Technical Report 36/04, CSIRO Land and Water, Canberra.

Department of Water, Land and Biodiversity Conservation, DWLBC (undated) Prescription of Water Resources, Fact Sheet 26, http://www.dwlbc.sa.gov.au/assets/files/FS-No-26-prescription.pdf, assessed 21 March 2007.

Earth Tech (2003) Preliminary review of selected factors that may change future flow patterns in the River Murray System. Murray-Darling Basin Commission Publication No. 01/07, September. ISBN 1 921 257 11 3. http://www.mdbc.gov.au/__data/page/1503/Earthech_report_for_web.pdf.

ForestrySA (1997) Environmental Management Guidelines for Plantation Forestry in South Australia. ISBN 0 7308 7400 1 December. http://www.forestry.sa.gov.au/enviro.stm.

Freebairn A C, Brown A E and Hairsine PB (2006) taslucas, Tasmania land use change and stream flow, user manual. revision 1.0.1b, 31/07/2006, CSIRO Land and Water, Australia. www.toolkit.net.au/taslucas

Gilfedder M, Stenson M, Walker G, Dawes W and Evans R (2006) bc2c biophysical capacity to change, user manual, CRC for Catchment Hydrology, Australia, revision 1.0.3, 23/08/2006, www.toolkit.net.au/bc2c.

Government of South Australia, GSA (2006) State Natural Resources Management Plan 2006, Department of Water, Land and Biodiversity Conservation, January. ISBN 0-9758473-0-9. http://www.dwlbc.sa.gov.au/

Government of South Australia, GSA (2006a) National Water Initiative – South Australian Implementation Plan, unpublished report to the National Water Commission, Department of Water, Land and Biodiversity Conservation, January.

Government of South Australia, GSA (2006b) e-nrims Natural Resources Management System, A5030529: BURNT OUT CK @ U/S Mount Bold Res. DWLBC Water monitoring Data, Department of Water, Land and Biodiversity Conservation, http://e-nrims.dwlbc.sa.gov.au/sitedata/A5030529/A5030529.htm

Government of South Australia, GSA (2007a) Burnt Out Creek hydrometric base file, unpublished technical reference information, Department of Water, Land and Biodiversity Conservation.

Government of South Australia, GSA (2007b) South Australia's Strategic Plan 2007, January. http://www.stateplan.sa.gov.au/.

Government of West Australia, GWA (2000) Water Notes: Advisory Notes for Land Managers on River and Wetland Restoration. Water and Rivers Commission, WN4 Wetland Buffers. January. ISSN 1442-6900. http://portal.environment.wa.gov.au/pls/portal/docs/PAGE/DOE_ADMIN/FACT_SHEET_REPOSITORY/TAB1144247/WRCWN04.PDF

Grayson R B, Argent R M, Nathan R J, McMahon T A and Mein R G (1996) Hydrological Recipes: Estimation Techniques in Australian Hydrology. Cooperative Research Centre for Catchment Hydrology, Melbourne, Victoria.

Holmes J W and Sinclair J A (1986) Streamflow from some afforested catchments in Victoria. Hydrology and Water Resources Symposium Griffith University, Brisbane, 25-27, November. The Institute of Engineers, Australia, Preprints of papers: 214-218.

Jolly I D, Dowling T I, Zhang L, Williamson D R and Walker G R (1997) Water and salt balances of the catchments of the Murray–Darling Basin. CSIRO Land and Water Technical Report 37/97, November.

Keenan R J, Parsons M, Gerrand A, O'Loughlin E, Beavis S, Gunawardana D, Gavran M and Bugg A (2004a). Plantations and water use: a review prepared for the Forest and Wood Products, Research and Development Corporation. Bureau of Rural Sciences, Canberra, March, ISBN 1 920 88306 1.

Keenan R J, Gerrand A, Nambiar S and Parsons M (2004b) Plantations and Water, Plantation impacts on stream flow, Bureau of Rural Science, Science for Decision Makers series, Australian Government, June.

Keenan R J, Gerrand A, Nambiar S and Parsons M (2006) Plantations and Water, Plantation impacts on stream flow, Bureau of Rural Science, Science for Decision Makers series, Australian Government, February.

Knight J H (1999). Root distributions and water uptake patterns in Eucalypts and other species. In: Landsberg, J J (Ed), The Ways Trees use Water. Water and Salinity Issues in Agroforestry No. 5. Rural Industries Research and Development Corporation Publication Number 99/37, RIRDC Project No. CSI-3A. ISBN 0 642 57811 7. ISSN 1440-6845. Barton, ACT, pp. 55–85.

Lane P, Best A, Hickel K and Zhang L (2003) The Effect of Afforestation on Flow Duration Curves Technical Report 0./13, Cooperative Research Centre for Catchment Hydrology, Melbourne, Victoria, November, ISBN 1 920813 03 9.

McKenzie N J, Jacquier D W, Maschmedt D J, Griffin E A and Brough D M (2005) The Australian Soil Resource Information System, Australian Collaborative Land Evaluation Program, on behalf of the National Committee on Soil and Terrain Information, version 1.5, October. http://www.asris.csiro.au.

McMahon T A, Finlayson B L, Haines A T and Srikanthan R (1992) Global Runoff - Continental Comparisons of Annual Flows and Peak Discharges, Catena-Verlag, Cremlingen-Destedt, Germany.

Murray Darling Basin Commission, MDBC (2007) Natural Resources Management. Risks to Shared Water Resources, Program Overview. http://www.mdbc.gov.au/nrm/risks_to_shared_water_resources#Risks, last updated 8 Feb 11:43.

O'Loughlin E and Nambiar E K S (2001) Plantations, Farm Forestry and Water. A Discussion Paper. Water and Salinity Issues in Agroforestry No. 8 Rural Industries Research and Development Corporation. Publication No 01/137.

Podger G (2005) fcfc forest cover flow change, user manual. revision 1.0.0b 20/05/2005, CRC for Catchment Hydrology, Australia, www.toolkit.net.au.

Press W H, Teukolsky S A, Vetterling W T and Flannery B P (1992) Numerical Recipes in Fortran, The Art of Scientific Computing, Second Edition, Cambridge University Press. ISBN 0 521 43064 X.

Putuhena W M and Cordery I (2000) Some hydrological effects of changing forest cover from eucalypts to Pinus radiata, Agricultural and Forest Meteorology 100: 59-72.

SA Water (2007) Water Storage (Reservoirs). SA Water Corporation website. Last updated 7 May, 2007 http://www.sawater.com.au/SAWater/Education/OurWaterSystems/Water+Storage+(Reservoirs).htm

Scott DF and Smith RE (1997) Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. Water South Africa 23, 135-140.

Teoh K S (2003) Estimating the Impact of Farm Dams Development on Surface Water Resources of the Onkaparinga River Catchment. Department of Water, Land and Biodiversity Conservation report no 2002/22, in collaboration with the Onkaparinga Catchment Management Board and SA Water Corporation, October.

Tomlinson G W (1996) Catchment Yield Analysis for South Australian Reservoirs Volume 1, Department of Environment and Natural Resources, Water Information Unit, Water Resources Group, February.

Turner K M (1991) Annual evapotranspiration of native vegetation in a Mediterranean-type climate. Water Resources Bulletin, 27, 1-6. in Zhang *et al* (1999).

van Dijk A, Evans R, Hairsine P, Khan S, Nathan R, Paydar Z, Viney N and Zhang L (2006) Risks to the Shared Water Resources of the Murray-Darling Basin, Murray-Darling Basin Commission, Canberra MDBC Publication No. 22/06, ISBN 1 921038 88 8.

Vertessy R A and Bessard Y (1999) Anticipating the negative hydrologic effects of plantation expansion: Results from a GIS-based analysis on the Murrumbidgee Basin. In Coke J and Lane P (eds) Forest Management for the Protection of Water Quality and Quantity. Proceedings of the 2nd Erosion in Forests Meeting , Warburton 4-6 May 199. Cooperative Research Centre for Catchment Hydrology, Report 99/6, Canberra.

Vertessy R A (2001) Impacts of plantation forestry on catchment runoff. Proceedings of National Workshop, July 2000. Water and Salinity Issues in Agroforestry No. 7 Rural Industries Research and Development Corporation. Publication No 01/20.

Vertessy R, Connell L, Morris J, Silberstein R, Heuperman A, Feikema P, Mann L, Komarzynski M, Collopy J and Stackpole D (2000) Sustainable Hardwood Production in Shallow Watertable Areas. A report for the RIRDC/ LWRRDC/ FWPRDC Joint Venture Agroforestry Program Water and Salinity Issues in Agroforestry No. 6. Rural Industries Research and Development Corporation Publication No. 00/163, RIRDC Project No. CSI- 3A. ISBN 0 642 58193 2. ISSN 1440-6845. http://www.rirdc.gov.au/reports/AFT/00-163.pdf

Vertessy R A, Zhang L and Dawes W R (2002) Plantations, river flows and river salinity. In Gerrand A (ed), Proceedings of the Prospects for Australian Forest Plantations 2002 conference, 20-21 August 2002 Canberra, Australia. Bureau of Rural Sciences, Australia, pp97-109.

Vertessy R A, Zhang L and Dawes W R (2003) Plantations, river flows and river salinity. Australian Forestry 66(1): 55-61.

Walker D (2002) What is Possible: Hydrology and Morphology in Goodwin N and Bennett S (eds) The Murray Mouth, Exploring the implications of closure or restricted flow, Murray Darling Basin Commission and the Department of Water, Land and Biodiversity Conservation, South Australia, July. http://www.dwlbc.sa.gov.au/assets/files/murray_mouth_exploring_implications.pdf

Zhang L (2004) Tree Planting and Catchment Water Yield. Heartlands, Towards Sustainable Land Use in the Murray-Darling Basin, Fact Sheet No 5. CSIRO and MDBC. www.clw.csiro.au/heartlands .

Zhang L, Dawes W R and Walker GR (1999) Predicting the effect of vegetation changes on catchment average water balance. Technical Report 99/12, Cooperative Research Centre for Catchment Hydrology, Clayton, Victoria, 35pp.

Zhang L, Dawes W R and Walker G R (2001) Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 37(3), pp701-708, March.

Zhang L, Dowling T, Hocking M., Morris J, Adams G, Hickel K, Best A and Vertessy R (2003) Predicting the effects of large-scale afforestation on annual flow regime and water allocation: an example for the Goulburn-Broken catchments. Technical Report 03/5, Cooperative Research Centre for Catchment Hydrology.

Zhang L, Vertessy R, Walker G, Gilfedder M and Hairsine P (2007) Afforestation in a catchment context: understanding the impacts on water yield and salinity. Industry report 1/07, eWater CRC, Melbourne, Australia. ISBN 1876810 09 2. © 2007, CSIRO and eWater Limited

Personal communications

Barnett S, Principal Hydrogeologist, Department of Water, Land and Biodiversity Conservation, 20 March 2007.

McGuire D, Manager Research, ForestrySA, 2 May 2007.

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APPENDICES

A. RAINFALL DATA

Year	Total (mm)	Days Missing	Year	Total (mm)	Days Missing	Year	Total (mm)	Days Missing	Year	Total (mm)	Days Missing
1938	193	212									
1939	774	0									
1940	584	0									
1941	548	0	1961	586	0	1981	994	0	2001	943	0
1942	828	0	1962	586	0	1982	549	0	2002	638	0
1943	682	0	1963	818	0	1983	930	0	2003	951	0
1944	542	0	1964	817	0	1984	791	0	2004	786	0
1945	687	0	1965	498	0	1985	763	0	2005	874	0
1946	864	0	1966	736	0	1986	917	0	2006	530	0
1947	760	0	1967	462	0	1987	936	0	2007	57	335
1948	628	0	1968	1094	0	1988	819	0			
1949	588	0	1969	739	0	1989	832	0			
1950	567	0	1970	796	0	1990	709	0			
1951	982	0	1971	1107	0	1991	770	0			
1952	778	0	1972	657	0	1992	1181	0			
1953	822	0	1973	944	0	1993	806	0			
1954	670	0	1974	921	0	1994	597	0			
1955	1008	0	1975	821	0	1995	809	0			
1956	1102	0	1976	629	0	1996	822	0			
1957	561	0	1977	642	0	1997	718	0			
1958	767	0	1978	715	0	1998	755	0			
1959	437	0	1979	904	0	1999	747	0			
1960	847	0	1980	744	0	2000	948	0			

DWLBC - HYANN V57 output 16/03/2007. Site M023734 MOUNT BOLD RESERVOIR BOM Meteorological Station. Variable 10.10 (rainfall in mm, daily read)

Statistics:

Min	437 mm	1959
Max	1181 mm	1992
Mean	770 mm/year	1939-2006
	811.9 mm/year	1978-1986
	812.3 mm/year	2002-2005
	755.6 mm/year	2002-2006

B. HYDROMETRIC SITE INFORMATION AND DATA SUMMARY

A5030529 - BURNT OUT CK @ U/S Mount Bold Reservoir.

SITE DESCRIPTION

Site:	A5030529
Site Name:	BURNT OUT CK @ U/S Mount Bold Res.
Site Commenced:	12-Jan-1978
Site Ceased:	
Map Name:	6627-4 (1:50,000)
Grid Reference:	Zone - 54 E - 290822.0 N - 6110378.0
Latitude:	35: 7:39S
Longitude:	138:42:15E
Elevation:	**246.558 m**
Map Datum:	GDA94

STATION DESCRIPTION

Stream Distance:	47.2
Gauge Datum:	AHD
Control:	Concrete 60 deg V notch weir
Cease to Flow:	1.000
Max gauged stage (m):	1.362 on 05-Jul-1978
Catchment Area:	**60.0 sq km**
Stream Distance:	47.2
Gauge Zero:	245.558

DWLBC -SWA Unit HYSITREP - Site Summary Report 16:08_29-Apr-2007

RATING TABLES

Variable From		Variable To		Date	Time	Site	Table
100	Level (m)	140	Discharge (m^3/s)	12-Jan-1978	13:30	A5030529	3

BURNT OUT CREEK PERIOD OF RECORD

Variable			Start Date	End Date	Num. Days	Data Type	Max Value	Date	Min Value	Date	Perc. Bad
10	Rainfall (mm)	Recording	21/08/1979	20/06/2007	10165	Daily total	69.11	24/06/1987			73.9
100	Level (m)	Recording	12/01/1978	20/06/2007	10751	Instantaneous	1.714	21/07/1979	0.765	15/04/2006	42.9
100.9	Level (m)	Field Reading	13/06/1978	17/11/1988	3810	Instantaneous	1.325	05/07/1978	1	27/05/1988	0
140	Discharge (m^3/s)	Recording	12/01/1978	15/11/2005	10169	Instantaneous	0.463	21/07/1979	0	12/01/1978	45.3
140.9	Discharge (m^3/s)	Field Reading	12/07/1985	06/10/1987	816	Instantaneous	0.093	24/09/1986	0.004	13/09/1985	0
141.9	Discharge (Ml/day)	Field Reading	13/06/1978	28/11/1983	1994	Instantaneous	0.065	05/07/1978	0.001	13/06/1978	0
450.9	Water Temp. (Deg.C)	Field Reading	13/06/1978	17/11/1988	3810	Instantaneous	30.8	17/01/1980	5	07/06/1982	0
800.91	TDS (mg/L)	Lab Result	13/06/1978	17/11/1988	3810	Instantaneous	815.852	02/12/1980	150.317	05/07/1978	0
806.9	pH	Field Reading	13/06/1978	17/11/1988	3810	Instantaneous	8.7	28/11/1983	5.6	12/07/1988	0
806.91	pH	Lab Result	13/06/1978	17/11/1988	3810	Instantaneous	8.6	06/07/1981	7.5	05/07/1978	0
807.9	Dissolved Oxygen %	Field Reading	23/07/1979	17/11/1988	3405	Instantaneous	13.8	07/06/1982	5.2	28/11/1984	0
821.9	EC corrected (uS/cm)	Field Reading	13/06/1978	17/11/1988	3810	Instantaneous	1720	07/05/1981	355	05/07/1978	0
821.91	EC corrected (uS/cm)	Lab Result	13/06/1978	17/11/1988	3810	Instantaneous	1480	02/12/1980	274	05/07/1978	0

DWLBC -SWA Unit 14:09_12/11/2007 Page 1; HYSITREP - Site Summary Report

BURNT OUT CREEK RUNOFF DATA

Year	Total (mm)	Days Missing	Year	Total (mm)	Days Missing	Year	Total (mm)	Days Missing
1978	39.2	12	1988	7.3	45	1998	closed	365
1979	99.7	0	1989	closed	365	1999	closed	365
1980	58.5	0	1990	closed	365	2000	closed	366
1981	126.9	0	1991	closed	365	2001	6.5	138
1982	6.1	0	1992	closed	366	2002	2.1	0
1983	15.0	0	1993	closed	365	2003	21.6	0
1984	11.4	0	1994	closed	365	2004	15.5	0
1985	5.7	0	1995	closed	365	2005	14.9	0
1986	26.1	0	1996	closed	366	2006	0.6	0
1987	26.6	44	1997	closed	365	2007	0.4	195

DWLBC -SWA Unit HYANN V59 Output 12/11/2007. Site A5030529 BURNT OUT CK @ U/S Mount Bold Res. Variable 142.00 Catchment Runoff in Millimetres, Recording.

Complete data years in green. Missing data in 1978 occurred in mid-January during which time only 1 mm of rainfall was recorded, so runoff record is considered complete.

Summary runoff statistics in complete data years 1978-1986 and 2002-2006

Statistic	1978-2006	Comments	1978-1986	Comments	2002-2006	Comments
Minimum (mm)	0.6	2006	5.7	1985	0.6	2006
Maximum (mm)	127	1981	127	1981	22	2003
Mean (mm/year)	32		43		11	
Median (mm/year)	15		26		15	

BURNT OUT CREEK DATA QUALITY SUMMARY

Quality		Subtotal	%	Data Reliability	
1	Good	16.49 years	56.04	**Duration**	16.93 years operation
30	Fair	106.99 days	1	**Reliable**[1]	16.80 years or 99.2%
34	Fair - Estimated	6.89 days	0.06	**Unreliable**[2]	0.13 years or 0.8%
91	Poor - Estimated	4.64 days	0.04		
151	Missing	42.96 days	0.4		
Gap	Closed	12.50 years	42.46		
Total		29.43 years	100		

SITE DATA QUALITY REPORT HYQUAL V42 Output 14/04/2007. Site: A5030529.A BURNT OUT CK @ U/S Mount Bold Res. Variable: 100.00 Water Level Recording. Report Period: 14:30_12/01/1978 to 13:24_20/06/2007 Duration 29.43 Years

[1] Codes 1, 30 and 34. [2] Codes 91 and 151.

BURNT OUT CREEK HYDROMETRIC SITE VISIT AND DATA QUALITY COMMENTS

Start	End	Duration	Quality	Comments
14:30_12/01/1978	07:50_22/02/1979	1.11 years	1	COMMENCEMENT OF RECORD.
07:50_22/02/1979	11:55_23/02/1979	1.17 days	76	POOL BEING DESILTED
11:55_23/02/1979	04:03_26/02/1979	2.67 days	76	POOL BEING DESILTED
04:03_26/02/1979	20:42_09/11/1981	2.7 years	1	
20:42_09/11/1981	10:54_10/11/1981	14.2 hours	76	DEBRIS ON CONTROL
10:54_10/11/1981	16:17_03/11/1983	1.98 years	1	
16:17_03/11/1983	03:07_06/11/1983	2.45 days	76	DEBRIS ON CONTROL!
03:07_06/11/1983	15:45_05/12/1986	3.08 years	1	
15:45_05/12/1986	07:03_10/12/1986	4.64 days	103	
07:03_10/12/1986	12:00_06/05/1987	147.21 days	1	
12:00_06/05/1987	11:00_18/06/1987	42.96 days	151	CLOCK STOPPED. MAX STAGE IN PERIOD 1.122 M
11:00_18/06/1987	10:10_17/11/1988	1.42 years	1	DRIVE COGS JAMMED
10:10_17/11/1988	11:39_18/05/2001	12.5 years	Gap	Station closed
11:39_18/05/2001	10:35_22/09/2004	3.35 years	1	Backup No.7586
				Station recommissioned start of record (18-05-01)
				Data AOK no adjustments required.
				Well flushed, spike rmoved. Creek below CTF
				Creek dry. End point changed to EDS value.
				Block adjusted. Data OK. Inserted logger value.
				Data Ok. Weir subject to debri buildup at low flow.
				Trace edited to suit. Archived by PB.
				End point keyed in. Checked/Archived by PB.
				Well pumped. Logger removed for reconfiguration.
				Pluvio installed at site. Logger reinstalled.
				Inlet maybe partially blocked - check next visit.
				Debris on weir - removed from trace.
10:35_22/09/2004	10:20_07/01/2005	106.99 days	30	End point added. Data adjusted to EDS value.
				Checked/Archived by PB. End point added.
				Block adjusted to EDS value. Checked/Archived by PB
10:20_07/01/2005	13:24_20/06/2007	2.45 years	1	End point added. Block adjust to EDS value
				Checked/Archived by PB.
13:05_15/11/2005	11:48_18/04/2006	153.95 days	2	Checked/Archived by PB. Data ok. Adjusted to on site check.
11:48_18/04/2006	13:35_04/07/2006	77.07 days	1	
13:35_04/07/2006	04:16_02/11/2006	120.61 days	2	Checked/Archived by PB. Backup X0000393.BAK
				04/07/2006 to 02/11/2006. Block smoothed, weir prone to debris buildup.
				Creek dry. MB. Points removed, suspect debris on weir. MB.
				Points removed, suspect debri on weir MB.

02/11/06	14/02/07	Creek and well dry - no EDS/SG values. No flow for block. Good, valid data. RJ Mt Bold Bushfire. At site visit weir barracaded with straw bales to Reduce ash flowing into reservoir from recent bushfire Backup X0000766.BAK
14/02/07	20/6/07	Logger on/off values compare well with check on/off values. CTF blocked with buildup of debris. Data verified with neighbouring water level and pluvio stations. Good, valid data. RJ Checked/Archived MB. Suspect debris on control from here. Data adjusted. End point adjusted for debris on control

A5030502 - SCOTT CREEK @ Scott Bottom

SITE DESCRIPTION

Site:	A5030502
Site Name:	SCOTT CREEK @ Scott Bottom
Site Commenced:	28-May-1964
Site Ceased:	
Map Name:	6627-4 (50k)
Grid Reference:	Zone - 54 E - 287895.0 N - 6113235.0
Latitude:	35: 6: 5S
Longitude:	138:40:23E
Elevation:	**205.448 m**
Map Datum:	GDA94

STATION DESCRIPTION

Stream Distance:	0
Gauge Zero:	204.448
Gauge Datum:	AHD
Control:	RECTANGULAR STEPPED WITH V STEEL EDGE
Cease to Flow:	1.000
Max gauged stage (m):	2.229 on 03-Jul-1981
QMIN:	1
TMIN:	4000
Catchment Area:	26.6 sq km

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RATING TABLES

Variable From		Variable To		Date	Time	Site	Table
100	Level (m)	140	Discharge (m^3/s)	29-May-1964	12:00	A5030502	1
100	Level (m)	140	Discharge (m^3/s)	19-Mar-1974	11:15	A5030502	2
100	Level (m)	140	Discharge (m^3/s)	30-Sep-1974	12:00	A5030502	3
100	Level (m)	140	Discharge (m^3/s)	22-Nov-1977	18:00	A5030502	4
100	Level (m)	140	Discharge (m^3/s)	06-Apr-1984	10:00	A5030502	5
821	EC corrected (µS/cm)	800	TDS (mg/L)	01-Jan-1900	0:00	EC2TDS	1

SCOTT CREEK PERIOD OF RECORD

Variable			Start Date	End Date	Num. Days	Data Type	Max Value	Date	Min Value	Date	Perc. Bad
10	Rainfall (mm)	Recording	08-Mar-1991	11-Jan-2007	5788	Daily total	65.59903	08-Jul-1993			0.4
100	Level (m)	Recording	27-Mar-1969	11-Jan-2007	13804	Instantaneous	2.67993	24-Jun-1987	-0.0454	09-Jan-1973	0
100.05	Level (m)	Unidata Logger	21-Jun-2005	11-Jan-2007	568	Instantaneous	5.229	21-Jun-2005	1.03333	20-Dec-2006	0
100.9	Level (m)	Field Reading	26-Jun-1972	16-Aug-1989	6260	Instantaneous	2.16003	03-Jul-1981	0.006	04-Dec-1972	0
140.9	Discharge (m^3/s)	Field Reading	07-Oct-1975	01-Oct-1987	4377	Instantaneous	1.10999	02-Oct-1979	0.001	08-Apr-1987	0
450.9	Water Temp. (Deg.C)	Field Reading	10-Apr-1973	03-Jan-2007	12321	Instantaneous	26	24-Jan-1985	6	05-Aug-1993	0
450.99	Water Temp. (Deg.C)	Composite Sampl	21-Apr-2004	03-Jan-2007	987	Instantaneous	26	08-Feb-2006	4.80005	14-Jun-2006	0.6
800.91	TDS (mg/L)	Lab Result	26-Nov-1976	19-Nov-1997	7663	Instantaneous	1260.85181	04-Mar-1985	81.61369	03-Jul-1981	0
800.93	TDS (mg/L)		16-Jan-1973	09-Dec-1980	2884	Instantaneous	3940	16-Jul-1974	161	06-Nov-1980	0
800.99	TDS (mg/L)	Composite Sampl	27-Nov-1996	20-Dec-2006	3674	Instantaneous	1400	19-Feb-2003	120	08-Sep-2000	0
801.99	TDS(mg/L)	Composite Sampl	23-Aug-1988	13-Nov-1996	3004	Instantaneous	1200	26-Feb-1992	100	18-Sep-1991	0
802.99	SS (mg/L)	Composite Sampl	03-Mar-1999	20-Dec-2006	2849	Instantaneous	387	04-Aug-2004	1	10-May-2000	0
806.91	pH	Lab Result	16-Jan-1973	14-Nov-1997	9068	Instantaneous	8.3999	10-Sep-1974	7	06-May-1980	0
821.9	EC corrected (uS/cm)	Field Reading	26-Jun-1972	16-Aug-1989	6260	Instantaneous	2500	26-Jun-1974	166	03-Jul-1981	0
821.91	EC corrected (uS/cm)	Lab Result	26-Nov-1976	19-Nov-1997	7663	Instantaneous	2280	04-Mar-1985	159	03-Jul-1981	0
821.99	EC corrected (uS/cm)	Composite Sampl	23-Aug-1988	20-Dec-2006	6692	Instantaneous	2500	19-Feb-2003	150	27-Oct-1992	0
824.99	P Total (mg/L)	Composite Sampl	23-Aug-1988	14-Dec-2006	6686	Instantaneous	0.59	27-Oct-1992	0.008	21-Jun-2006	0
825.99	P Soluble (mg/L)	Composite Sampl	23-Aug-1988	13-Nov-1996	3004	Instantaneous	0.1	27-Oct-1992	0.0025	28-Jul-1989	0
826.99	TKN (mg/L)	Composite Sampl	23-Aug-1988	14-Dec-2006	6686	Instantaneous	8.66992	21-Mar-1995	0.01501	27-Oct-1992	0

SCOTT CREEK PERIOD OF RECORD (cont'd)

Variable			Start Date	End Date	Num. Days	Data Type	Max Value	Date	Min Value	Date	Perc. Bad
827.99	NOx (mg/L)	Composite Sampl	23-Aug-1988	20-Dec-2006	6692	Instantaneous	0.47701	01-Jul-1997	0	05-Mar-1997	0
828.99	Reactive P (mg/L)	Composite Sampl	27-Nov-1996	20-Dec-2006	3674	Instantaneous	0.087	21-Jan-1998	0.0005	04-Oct-2006	0
829.99	Total N (mg/L)	Composite Sampl	29-Sep-2004	14-Dec-2006	806	Instantaneous	2.31995	09-Nov-2005	0.18	03-Nov-2004	0
843.99	Copper (mg/L)	Composite Sampl	06-Oct-2004	20-Dec-2006	805	Instantaneous	0.0762	20-Sep-2006	0.001	05-Jan-2006	0
844.99	Lead (mg/L)	Composite Sampl	06-Oct-2004	20-Dec-2006	805	Instantaneous	0.0105	09-Nov-2005	0.0005	01-Dec-2004	0
846.99	Zinc (mg/L)	Composite Sampl	06-Oct-2004	20-Dec-2006	805	Instantaneous	0.214	15-Nov-2005	0.003	05-Jan-2006	0

C. FITTING TANH RAINFALL-RUNOFF CURVES

Grayson *et al* (1996) describe the use of an analytical mathematical function to represent rainfall-runoff relationships based on observed data. The method has found application in international studies and is used in South Australia as a rapid assessment tool. The Tanh function is presented below.

Tanh Curve Runoff = a*[P - L] - b*[F*Tanh[(P - L)/F]

Q	runoff [mm]
P	rainfall [mm]
L	Notional or initial loss [mm]
F	Notional infiltration or continuing loss [mm]
a	Constant
b	Constant

The fitting parameters L and F are presented as having a physical basis, although local experience has highlighted the limitations of this perspective. While it is preferable that parameters should be physically reasonable, the method remains a curve fitting exercise. Some authors such as Teoh (2003) have used constant coefficients a and b to further improve the fit to data.

The method used to fit the Tanh curves to observed data in this work followed the recommendations of Grayson *et al* (1996) in optimising the parameters using a curve fitting technique and if required refining the final parameter set to improve the fit. This approach can result in the choice of a statistically less significant parameter set for one with the appearance of a more robust fit, as the example below demonstrates.

The procedure is considered defensible since the final choice of parameters is based on a balance of statistical significance and specialised hydrological knowledge. The final suite of parameters represent the most significant alternatives, which are considered against known hydrological characteristics, enabling the best choice to be made from limited data that, if analysed using statistics alone, may generate spurious or unreasonable results.

After reviewing the observed rainfall-runoff data to get an indication of initial loss (L), the steps taken to derive Tanh parameters comprised a simple iteration of:

1. Using MS Excel® Solver to generate an optimised continuing loss (F) using a robust statistic.
2. Repeating the process for a regular sequence of L values until an optimal combination of L and F parameters were identified.

If required the final optimal parameters were adjusted to achieve the best accord with the data. This was not required in the pre-forest Tanh model, but was in the post-forest model, which is presented as an example below.

Kolmogorov-Smirnov Statistic

The K-S statistic was used as a robust goodness of fit measure to compare the modelled Tanh modelled data with the observed data. A full description of the method is provided in Press *et al* (1992). Its key strength is in its non-parametric character, comparing the similarity or difference between probability distributions based on the data sets, rather than the raw data, which in hydrological time series are typically skewed by outliers and not well described by moments of central tendency.

The method involves data manipulation that is effectively the same as that required to perform frequency analyses, a conventional approach to assessing the character of hydrological data or the faithfulness of a model's depiction of observed data. The K-S statistic adds the power of a non-parametric significance test to a standard hydrological practice.

By minimising the K-S statistic generated from modelled and observed data sets, the probability of confirming a null hypothesis, that the two distributions were drawn from the same population is maximised. This results in the modelled distribution being fitted to the observed data to a degree where the statistical significance of the fit reaches an optimised maximum.

Post Forest Example

A reviewing of the observed post-forest rainfall-runoff data indicated that no runoff occurred when rainfall was less than 600 mm/year (Figure C1). Runoff could be expected to reach zero somewhere between annual rainfall of 0 and 600 mm/year. 500 mm/year was subsequently selected as the first choice of initial loss (L).

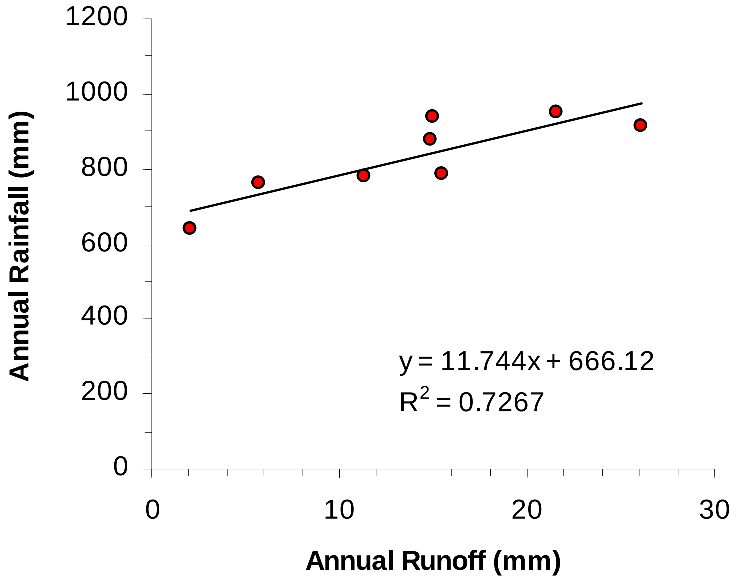

Figure C1. Burnt Out Creek post-forest observed rainfall-runoff data

The sequence of initial loss and optimised continuing loss parameters obtained using MS Excel® Solver is shown bin Table C1. Tanh curves obtained are shown in Figure C2 and optimised K-S statistics for each parameter combination in Figure C3.

Table C1. Optimised Tanh parameters

Min K-S	0.126	0.126	0.131	0.1342	0.136	**0.173**	0.155	0.156	0.157	0.160	0.162	0.157
L	500	450	425	410	400	**400**	400	395	390	370	350	300
F	1147	1336	1427	1482	1520	**1465**	1411	1429	1448	1525	1603	1815
a	1	1	1	1	1	**1**	1	1	1	1	1	1
b	1	1	1	1	1	**1**	1	1	1	1	1	1

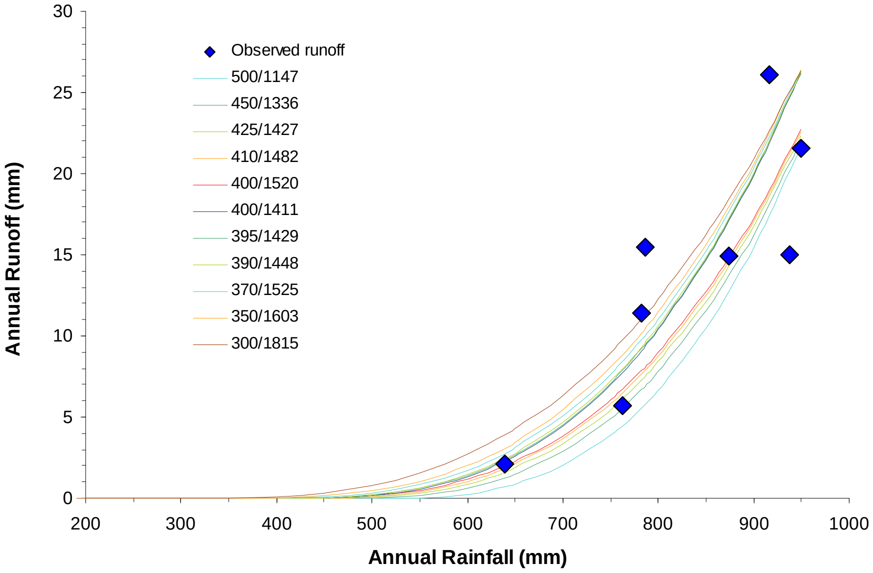

Figure C2. Burnt Out Creek post-forest Tanh rainfall-runoff relationships

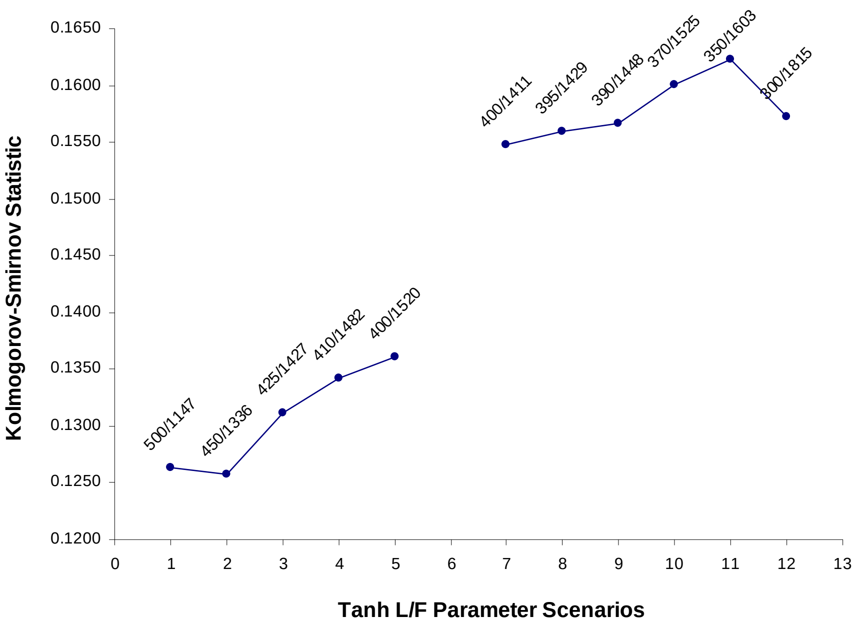

Figure C3. Burnt Out Creek post-forest optimised K-S statistics

The data showed a number of remarkable characteristics. Despite its attractively low K-S statistic, 500 mm/year over-estimated over half of the observed data. The optimised K-S statistic above and below L = 400 mm showed two discrete populations. The best fitting parameters appeared to be the two L = 400 mm parameters with F = 1411 and 1520. Either could arguably have been used, but the gap between the two optimised models actually appeared a better fit for the observed data.

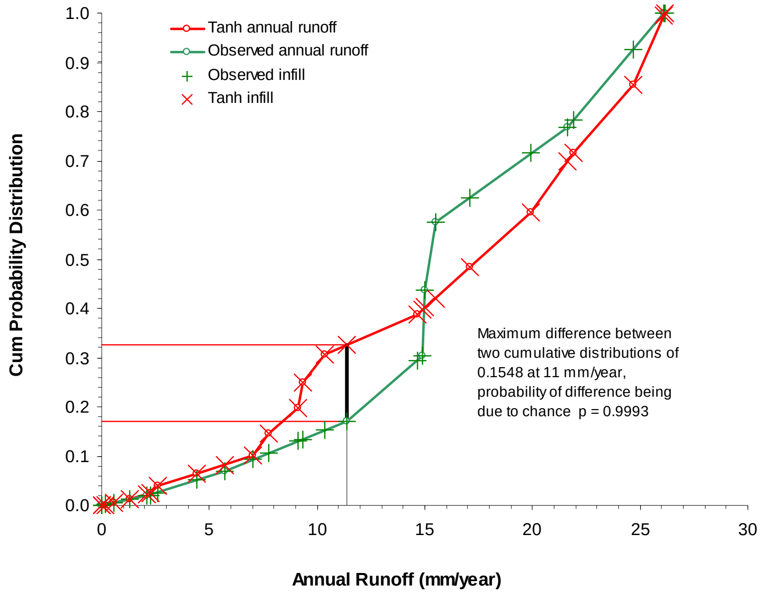

Figure C4. Burnt Out Creek post-forest rainfall-runoff K-S optimisation, L = 400; F = 1411

On closer examination of the results the partitioning of the Tanh runoff populations was due to the way the K-S probability distributions converged to unity. The procedure identified two sets of optimised parameters according to whether the cumulative modelled runoff probability was greater than the observed probability at higher values or less than the observed probability (Figures C4 and C5).

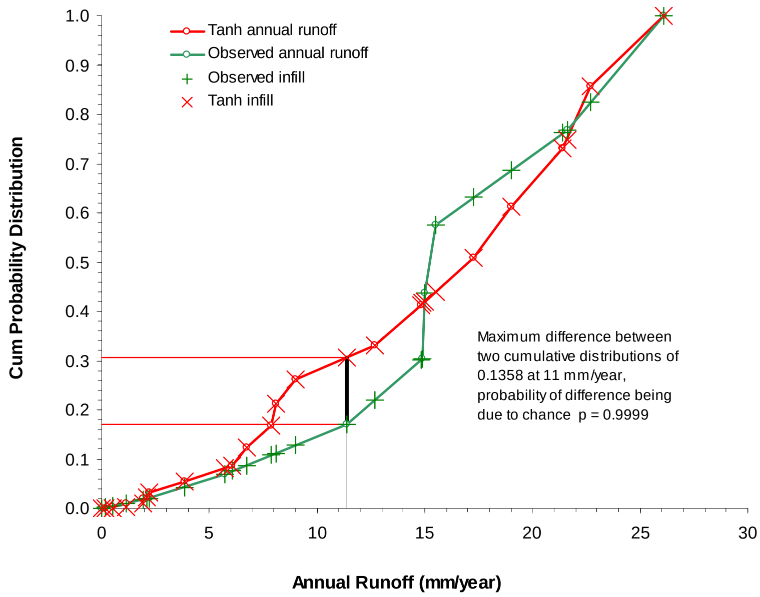

Figure C5. Burnt Out Creek post-forest rainfall-runoff K-S optimisation, L = 400; F =1520

The L = 400 and F = 1520 Tanh model appeared the better fit as indicated by the K-S statistic, however it provided a conservative estimate of post-forest runoff in higher rainfall years. This may be a reasonable depiction of reality but the limited data points and their relatively wide scatter presented a compelling case to compromise between the two 400 mm data sets, even though the difference in most years would be modest and despite a weaker K-S statistic (Figures C6 and C7). The final continuing loss F, was taken as 1465, the average between 1411 and 1520.

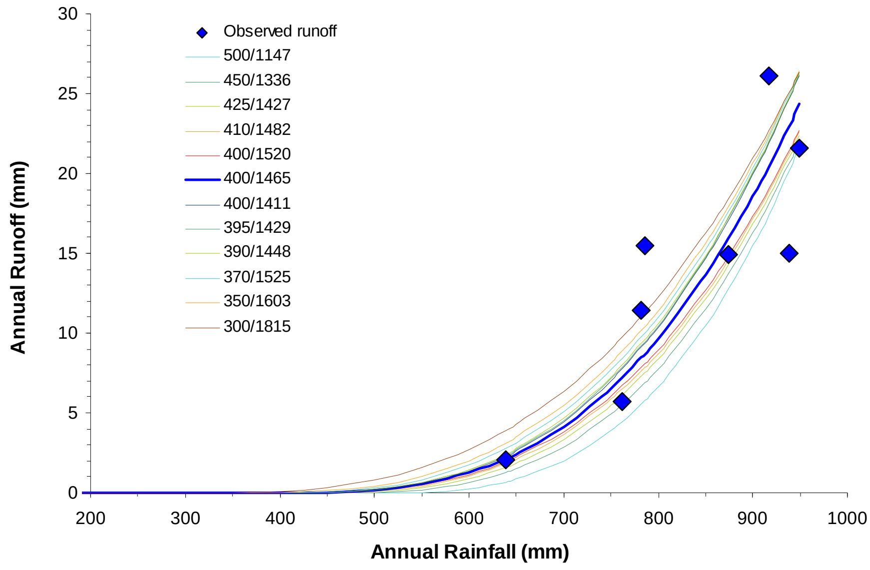

Figure C6.   **Burnt Out Creek post-forest Tanh rainfall-runoff relationships, with L = 400; F = 1465.**

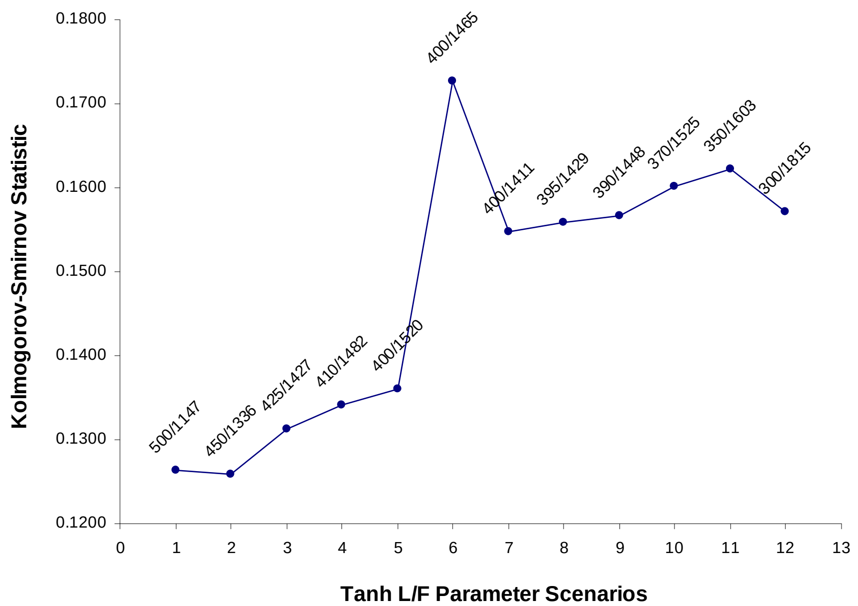

Figure C7   **Burnt Out Creek post-forest optimised K-S statistics, with L = 400; F = 1465.**

D. PLATES

Plate 1: Clearing burned pine trees at Burnt Out Creek, February 1977. Remnant unburned trees in back ground.

Plate 2: Clearing at Burnt Out Creek, 1 March 1977. Remnant unburned trees at right.

Plate 3: Burnt Out Creek gauging station construction site and cleared catchment, 22 July 1977.

Plate 4: Burnt Out Creek gauging station and cleared catchment, 4 December 1977. Remnant unburned trees at top of catchment.

Plate 5: Burnt Out Creek gauging station December 1977. Ripped lines in background.

Plate 6: Burnt Out Creek gauging station, 26 June 1978.

Plate 7: Upstream Burnt Out Creek gauging station, April 1979. Growth of seedlings on hill sides described as “considerable”.

Plate 8a: Upstream Burnt Out Creek gauging station, November 1980.

Plate 8b: Upstream Burnt Out Creek gauging station, November 1980.

Plate 9: Upstream Burnt Out Creek gauging station (bottom right corner), 14 April 1982.

Plate 10a: Upstream Burnt Out Creek gauging station (bottom left corner), 5 August 1982.

Plate 10b: Upstream Burnt Out Creek gauging station, 5 August 1982. Dense growth.

Plate 10c: Upstream Burnt Out Creek gauging station, 5 August 1982. Canopy closure.

Plate 11: West of Burnt Out Creek gauging station, 28 November 1984.

Plate 12a: Upstream Burnt Out Creek gauging station, 12 July 1988.

Plate 12b: Upstream Burnt Out Creek gauging station, 12 July 1988.

E. PEER REVIEW DR LU ZHANG CSIRO

Review of "The Impact of Plantation Forestry on Runoff in the Mount Lofty Ranges, Case Study: Burnt Out Creek"

Lu Zhang

Principal Research Scientist
CSIRO Land and Water
Christian Laboratory
Canberra, ACT

September 2007

General comments

This report describes a case study for assessing the impact of plantation forestry on runoff from a small catchment in South Australia. It showed that runoff was significantly reduced following plantation development and it provided direct evidence of plantation impact on runoff. The method used in the analysis is appropriate and the findings would help to develop local NRM plans.

Specific comments

P6. It would be useful to highlight Scott Creek on the map.

P9. How big is Scott Creek?

P10. Why not shown the 1987 and 1988 data?

P12. "*In 1983 the variance jumped to 87% …*". Do you mean percentage reduction in runoff? Are these the original curves of Scott and Smith (1997)? Which is the fitted curve using Burnt Out Creek data? You should provide more information on Figure 7. It seems to me that the data from Burnt Out Creek compared well with the Scott and Smith-type curve for optimal conditions, but with a lower relative reduction in runoff.

P14. I assume the 150 mm of runoff reduction is associated with 100% change in forest cover and this would not apply to Burnt Out Creek, where the initial forest cover was about 33%.

P16. "*If Burnt Out Creek were completely cleared and behaved as a 100% pasture catchment, a greater proportional reduction in runoff would be expected than indicated by the current data.*" Do you mean the runoff reduction would be greater if the forest cover were increased from 0 to 100%?

P16. Third paragraph, delete the word "*influential*"

P17. Delete *"Figure 1 shows the area of remaining plantation and its date of establishment."*

P18. Figure 11 is not referred at this point and should be moved to page 19.

P19. The absolute increase in runoff for Burnt Out Creek was small, but it was nearly a three-fold recovery compared with a four-fold recovery for Scott Creek. You might want to reword it.

P19. *Vertessy (2002),* should this be Vertessy (2001)?

P22. *"Anyone who suggests that the impacts of water affecting activities on surface water resources can be reduced by ensuring they are developed in low rainfall areas obviously doesn't live in one".* Planting trees in low rainfall area will reduce the impact on water resources because high rainfall areas are generally the headwater catchments for our water supply and they generate most of runoff. I agree with you that you would expect a greater proportion in runoff from low rainfall catchments and such changes may have more significant environmental impacts. The statements quoted above do not have their basis in the use of Holmes and Sinclair (1986) and Zhang et al. (2001). I do not think the data from Burnt Out Creek are very different from other catchments with similar vegetation history. Zhang et al. (2003) did not estimate **annual runoff** as the difference between mean annual rainfall and mean annual evapotranspiration.

P24. *"The Zhang data do not represent inter-annual behaviour whereas the South Australia data are derived from inter-annual behaviour. However, a number of authors have used the Zhang approach to explore inter-annual behaviour (Bradford et al., 2001 and Zhang et al., 2003)".* It is true that the method of Zhang *et al.* (2001) is for mean annual water balance and shout not be applied to inter-annual behaviour without further testing. I do think Bradford *et al*. (2001) and Zhang *et al.* (2003) applied the model to inter-annual behaviour.

P24. Second paragraph, should this be Figure 16?

Response to Dr Zhang's comments

p6 Scott Creek gauging station locality label placed in Figure 1.

p9 Area of Scott Creek, 26.6 sqkm incorporated into text.

p10 1987 and 1988 data incomplete as described in text, but included in Figure 4 with additional explanatory text.

p12 Additional figure and information provided.

p14 Amended in text.

p16 Amended in text.

p16 The word "influential" has not been deleted. A range of work generated by the cited authors has not only influenced but also encouraged consultants to use methods beyond their scope applicability.

p17 Deleted.

p18 Amended.

p19 Corrected

p22 In describing their water balance model, Zhang *et al* (2003) state (p6):

The water balance model used in this study was developed by Zhang et al (1999, 2001). It calculates mean annual evapotranspiration from mean annual rainfall and potential evapotranspiration (Figure 5). In estimating catchment average water yield, it is assumed that there is no net change in catchment water storage over a long period of time. ***As a result, catchment water yield can be calculated as the difference between long-term average rainfall and evapotranspiration****. The average relationships are shown in Figure 6 for grassland and forested catchments.*

No further comment.

p24 No comment required.

p24 Corrected.