COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

THE EFFECT OF AFFORESTATION ON FLOW DURATION CURVES

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The Effect of Afforestation on Flow Duration Curves

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Preface

Trees use more water than grass. This simple statement has important implications for managing dryland salinity and changes in river flows. Until recently the data analysis and predictive tools only permitted confidence in predictions concerning river flows on a mean annual basis. This has limited the use of the science in the day-to-day management of water resources and catchment planning. This report is part of a series that bridges the gap between the science of catchment water balances and the management of rivers for a range of outcomes by considering the impact of afforestation on flow distribution throughout the year. Afforestation and water will remain a contentious issue until the hydrologic impacts are clear for a complete range of environments and timescales.

This work has been conducted by the Cooperative Research Centre (CRC) for Catchment Hydrology's program concerning land-use impacts on rivers. The program is focused upon the impact of man's activities upon the land and stream environment upon the physical attributes of rivers. We are concerned about managing impacts for catchments ranging in size from a single hillslope to several thousands of square kilometres. The specific impacts we are considering are changes in streamflow, changes to in-stream habitat by the movement of coarse sediment and changes to water quality (sediment, nutrients and salt). If you wish to find out more about the program's research I invite you to first visit our website at http://www.catchment.crc.org.au/programs/projects/index.html.

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Abstract

The hydrologic effect of replacing pasture or other short crops with trees is reasonably well understood on a mean annual basis. However, recent work by Best *et al.,* (2003), Vertessy *et al.,* (2003) and Zhang *et al.,* (2003) highlights the need to improve our understanding of the impact of the afforestation on the flow duration curve (FDC). This study sought to quantify these changes in the FDC as a result of afforestation. The starting point for the analysis was the assumption that rainfall and vegetation age are the principal drivers of evapotranspiration. The aim was to remove the impact of rainfall variability on the percentile flows of the FDC, leaving changes in the FDC solely attributable to the change in evapotranspiration following afforestation. Data from ten catchments from Australia, South Africa and New Zealand were used, eight of which are paired-catchment experiments. A model was developed to firstly characterise changes in each flow decile over time, and then to construct FDCs adjusted for rainfall variability. The model was able to represent flow variation for the majority of deciles at eight of the ten catchments, particularly the 10^{th}-50^{th} percentiles. The adjusted FDCs revealed variable patterns in flow reductions with two types of responses (groups) being identified. Group 1 catchments show a substantial increase in the number of zero flow days, with low flows being more affected than high flows. Group 2 catchments show a more uniform reduction in flows across all percentiles. The modelled flow reductions were in accord with published results of paired catchment experiments. An additional analysis was performed to characterise the impact of afforestation on the number of zero flow days (N_{zero}) for the catchments in Group 1. This model performed particularly well, and when adjusted for climate, indicated a significant increase in N_{zero}. The zero flow day method could be used to determine change in the occurrence of any given flow in response to afforestation. The methods used in this study proved satisfactory in removing the effect of rainfall variability. This approach provides a methodology for understanding catchment response to afforestation where paired-catchment data is not available.

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1. Introduction

Experiments at the plot and catchment scales, and hydrologic analyses relating streamflow quantity to catchment vegetative cover have established that streamflow from forested catchments is lower than that from a grassland or cropland (Zhang *et al.,* 1999). The greater evapotranspiration (ET) for forests relative to grassland or short crops is the primary reason for the differences in water yield in catchments under different vegetation types. However, the complex interplay of climate, soils, catchment geometry and land-use can obscure the reasons for the observed hydrological response when catchment vegetation is altered. The physical processes driving this greater ET from forests relative to grassland are described in detail by Zhang *et al.,* (1999) and Vertessy and Bessard (1999), and can be summarised as differences in aerodynamic roughness, albedo, leaf area, rooting depth, and ability to extract soil water water. Using data from multiple catchments, Holmes and Sinclair (1986), Cornish (1989), Vertessy and Bessard (1999), and Zhang *et al.,* (1999, 2001) have all demonstrated the difference in the relationship between ET and rainfall for different vegetation types on a mean annual basis. Once mean annual rainfall exceeds 400-500 mm, there is an increasing divergence between forest and grassland ET. Figure 1 shows the generalised curves derived by Zhang *et al.,* (1999) for this relationship on a mean annual basis.

Widespread plantation establishment on agricultural land can significantly alter the hydrologic regime of a catchment. Research from South Africa in particular has demonstrated flow reduction following afforestation with both softwoods and hardwoods (Bosch, 1979; Van Lill *et al.*, 1980; van Wyk, 1987; Bosch and Van Gadow, 1990; Scott and Smith, 1997; Scott *et al.*, 2000). Prediction of the long-term hydrologic impact of afforestation is a prerequisite for wise planning of catchment land-use. For example, afforestation is widely held to be the prime biophyiscal tool for amelioration of dryland salinity through diminution of groundwater recharge. However, reduction of recharge and therefore streamflow may inhibit flushing of salinised catchments, decrease environmental flows, and

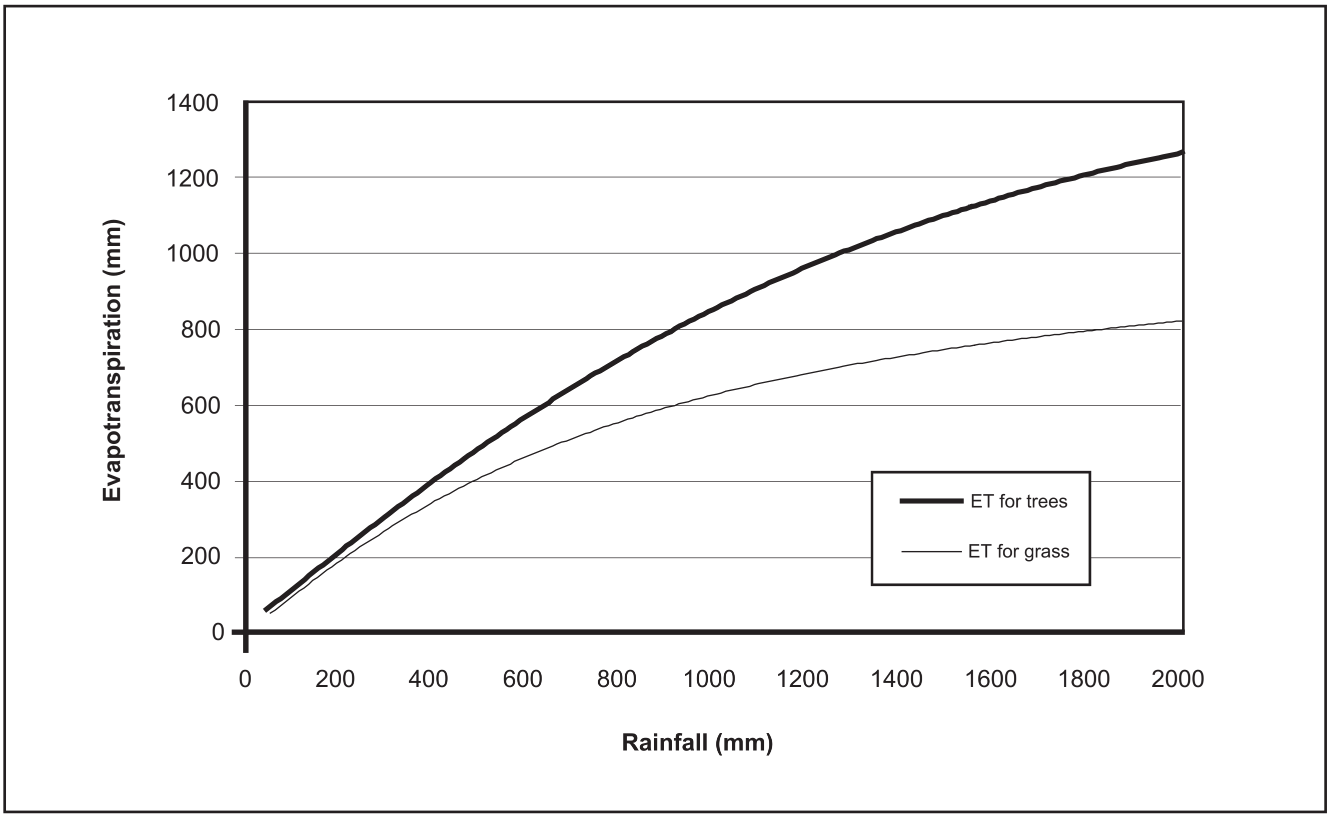

Figure 1. Relationship between Annual Evapotranspiration and Rainfall for Trees and Grass (after Zhang *et al.,* 1999).

threaten downstream water supplies. In South Africa there are legislative requirements to consider hydrologic impacts from land-use change, particularly afforestation. Hughes and Hannart (2003) and Hughes (2001) describe the development of modelling tools to quantify flows required to maintain streamflow to satisfy human and ecological needs. Such models require quantitative predictions of flow changes. Zhang *et al.,* (1999, 2001) and Munday *et al.,* (2001) have developed simple and easily parameterised models to predict changes in mean annual flows following afforestation. However, there is a need to consider the annual flow regime as the relative changes in high and low flows may have considerable site specific and downstream impacts. Sikka *et al.,* (2003) recently showed a change from grassland to *Eucalyptus globulus* plantations in India decreased the low flow index by a factor of 2 during the first rotation, and by 3.75 during the second rotation, with more subdued impact on peak flows. The index was defined as the 10 day average flow exceeded 95 percent of the time, obtained from analysis of 10-day flow duration curves over the period of record. Scott and Smith (1997) reported proportionally greater reductions in low flows (< 75th percentile) than annual flows from South African research catchments for conversion from grass to pine and eucalypt plantations, while Bosch (1979) found the greatest reduction in seasonal flow from the summer wet season. Theoretically, decreased dry season flows following afforestation could be expected because of higher transpiration and consequently higher soil moisture deficits, but the high infiltration rates and low surface runoff under forests could also lower soil moisture deficits (Calder, 1999). The generalisations that can be drawn from annual analyses where processes and hydrologic responses are to a certain extent integrated may not apply on a seasonal or shorter scale. This is particularly true where rainfall seasonality is pronounced.

In the past couple of years, much work has been undertaken within the Cooperative Research Centre (CRC) for Catchment Hydrology to improve our understanding of the impacts of vegetation changes on the annual water balance, flow regime, water allocation and water resource security. The work of Hickel and Zhang (2003) provides us with an improved understanding of the impact of seasonality on the mean annual water balance. A simple method for incorporating this seasonal impact into a mean annual water balance model was developed using readily available catchment data. Best *et al.,* (2003) provide a review of available paired catchment data assessing the impacts on broad scale vegetation changes on annual and seasonal water yield and on the distribution of daily flow (as represented by the flow duration curve, FDC). In summarising the results of paired catchment studies, Best *et al.,* (2003) noted that climatic influences made it difficult to determine the true impact on vegetation change on the FDC. Vertessy *et al.,* (2003) highlighted some of the impacts on plantation forestry of river flows and salinity, concluding that the formation of policy to manage plantation development which considers the water resources impacts, as well as the potential environmental benefits is required in Australia. The likely impacts of plantation forestry on water allocation and flow regime were assessed by Zhang *et al.,* (2003) for the Goulbourn Broken catchment. This work linked a mean annual water balance model, a plant growth model and a water allocation model to assess the impact of potential plantation on irrigation water security. Along with an impact on water security, an assessment was also made about the likely impact of plantation development on the FDC, based on results from a paired catchment study. The work of Best *et al.,* (2003), Vertessy *et al.,* (2003) and Zhang *et al.,* (2003) highlights the need to improve our understanding of the impact of plantation forestry on the FDC. This report improves the current understanding of the impacts of plantation forestry on the FDC by separating the climatic and vegetation signals using a simple additive model allowing the impact of afforestation on the FDC to be assessed.

To quantify the impact of vegetation change on the FDC, the variability in climate needs to be accounted for. Hydrologic response to land-use change may be assumed to be a function of the type and density of the vegetation, climate, and the physical properties of the catchment that influence soil and groundwater storage and response times. For individual catchments, these physical properties are considered invariant. However, different patterns in annual or seasonal rainfall result in different distributions of flow for the same vegetation type. Thus, the true impact of the vegetation change can be difficult to detect. If the impact of climate on the FDC is removed, the resultant changes in flow can then be attributed solely to the changes in vegetation. The time-tested solution to this problem is the paired-catchment experiment. The benefits to such studies are manifold: unambiguous measures of trends, insights into the processes driving those trends, excellent opportunities for model parameterisation and validation. Unfortunately the time and money required for the successful prosecution of long-term studies is rarely supported by funding bodies at present, particularly in Australia. Additionally, the current urgent demands for answers to questions posed by dynamic land-use change do not necessarily accord with experimental programs that require decades for fruition. Therefore techniques that account for climate variability in non-paired catchments are required.

The aim of this study is to separate the climate and vegetation impacts on the FDC following afforestation and thus characterise changes in annual flow regime due to plantation establishment, using readily available climate and catchment variables. A "top down" approach was adopted whereby whole of system responses are sought based on changes in the main driving variables (Klemes, 1983). A prime objective was to use as simple a model as possible. The approach adopted here is similar to the generalised additive model approach of Nathan *et al.,* (1999) used to estimate time trends in hydrologic time series data.

2. Methods

2.1 Characterisation of Flow Regime

Flow duration curves display the relationship between streamflow and the percentage of time the streamflow is exceeded as a cumulative density function. They can be constructed for any time period (daily, weekly, monthly, etc.) and provide a graphical view of historic streamflow variability in a single catchment or a comparison of inter-catchment flow regimes. Vogel and Fennessey (1994) and Smakhtin (1999, 2001) demonstrate the utility (and caveats) of FDCs in characterising, comparing and predicting flow regimes at varying temporal scales. An example of annual FDCs constructed from daily flows is shown in Figure 2. For the consideration of annual flow regime, daily flows are an appropriate time step for FDC construction.

FDCs were computed from the distribution of daily flows for each year of record based on water years (May-April). Each decile was extracted from the annual FDCs of each catchment to form the data sets for analysis. For the purpose of predicting changes in each of the deciles, it is assumed that the time series is a function of climate, catchment physical properties, and vegetation characteristics. Given rainfall is generally the most important factor affecting streamflow and the most easily accessed data, it is chosen to represent the climate. Catchment physical properties such as soil properties and topographic features are assumed to be time invariant and therefore their impact on runoff is considered constant throughout the analysis. The impact of vegetation characteristics on streamflow is mainly through evapotranspiration, which in part is a function of vegetation age. A simple model relating the time series of each decile with rainfall and vegetation characteristics can be expressed as:

$$Q_{\%} = f\,(P) + g(T) \qquad (1)$$

where $Q_{\%}$ is the percentile flow, $f(P)$ is a function of rainfall and $g(T)$ is a function of the age of the plantation. The choice of model form is dependent on selecting a function that describes relationship between forest age and ET. Scott and Smith (1997) demonstrated reductions in annual and low flows resulting from afforestation fitted a sigmoidal function, similar to forest growth functions.

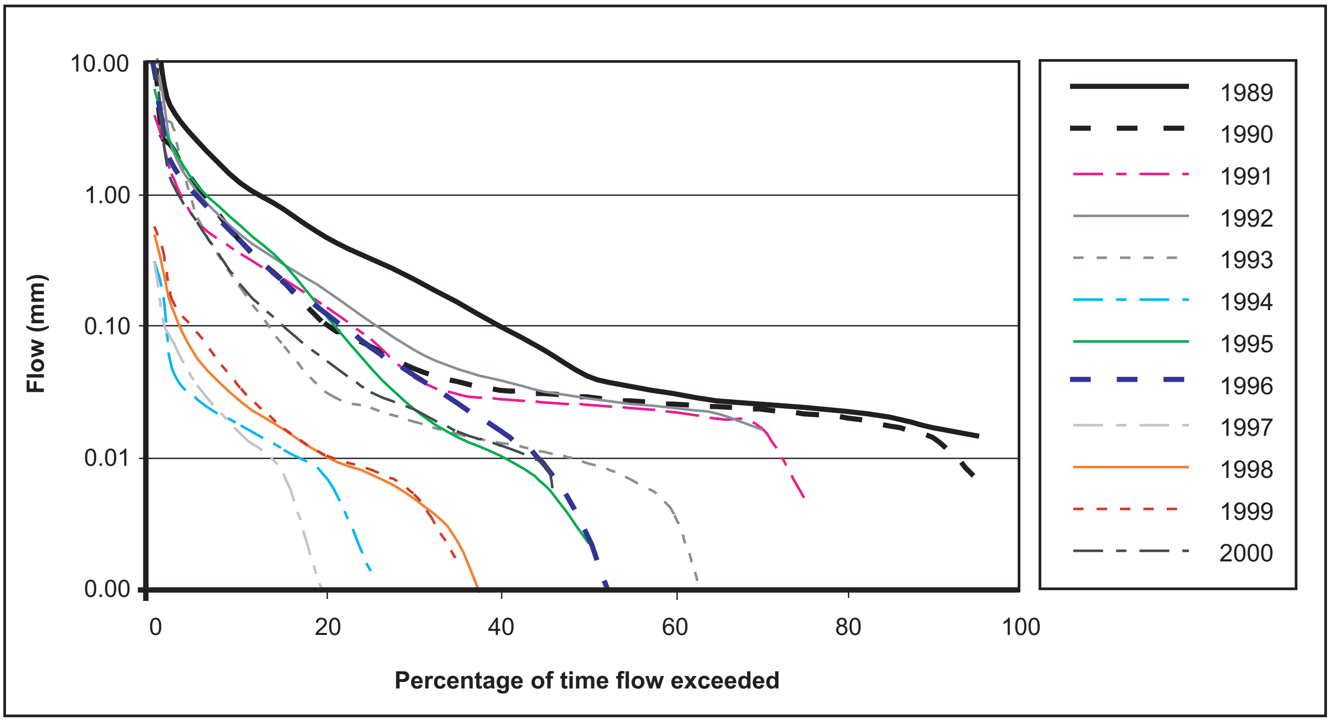

Figure 2. Annual Flow Duration Curves of Daily Flows from Pine Creek, 1989-2000.

Consequently, we used a sigmoidal function, similar to Scott and Smith (1997) to characterise the impact of plantation growth. Thus the model took the form:

$$Q_{\%} = a + b(\Delta P) + \frac{A_{sig}}{1+\exp\left(\frac{T - T_{half}}{N_{sig}}\right)} \qquad (2)$$

where $Q_{\%}$ is the percentile flow (i.e. Q_{50} is the 50th percentile flow), A_{sig}, and N_{sig} are coefficients of the sigmoidal term, ΔP is the deviation of annual rainfall from the period of record average, and T_{half} is the time in years at which half of the reduction in $Q_{\%}$ due to afforestation has taken place. For the average climate condition $\Delta P = 0$, a becomes the value of $Q_{\%}$ when the equilibrium under afforestation is reached. A_{sig} then gives the magnitude of change due to afforestation, and N_{sig} describes the shape of the response as shown in Figure 3. For the average pre-treatment condition $\Delta P = 0$ and $T = 0$, $Q_{\%}$ approximately equals $a + A_{sig}$.

a, b, A_{sig}, N_{sig} and T_{half} are all subject to physical constraints. a and b must be greater than or equal to zero. N_{sig} and A_{sig} must have the same sign to yield a decreasing sigmoidal function and could theoretically both be negative; however it was decided to constrain both to be positive. Conceptually, the reduction in year 0 from the time term should also be zero. However, this constraint can only be mathematically formulated as being close to zero, since the sigmoidal function approaches zero-reduction asymptotically. It was decided to limit the flow reduction at time zero to less than 5 percent of the total reduction thus yielding the constraint that $T_{half} \geq 3\ N_{sig}$. Sensitivity of this constraint was analysed using threshold values of 1, 2 and 10 percent of the total reduction.

2.2 Zero Flow Day Analysis

Studies have indicated that afforestation has a differential impact on flow regime, resulting greater relative reductions in low flows (Sikka *et al.,* 2003, Scott and Smith, 1997). Figure 2 is an example of annual flow duration curves following afforestation at Pine Creek, Central Victoria. One of the features to note is the significant reduction in the cease to flow percentile or the increases in number of zero flow days. A similar approach using the sigmoidal model, (Equation 2), was employed to assess the impact of

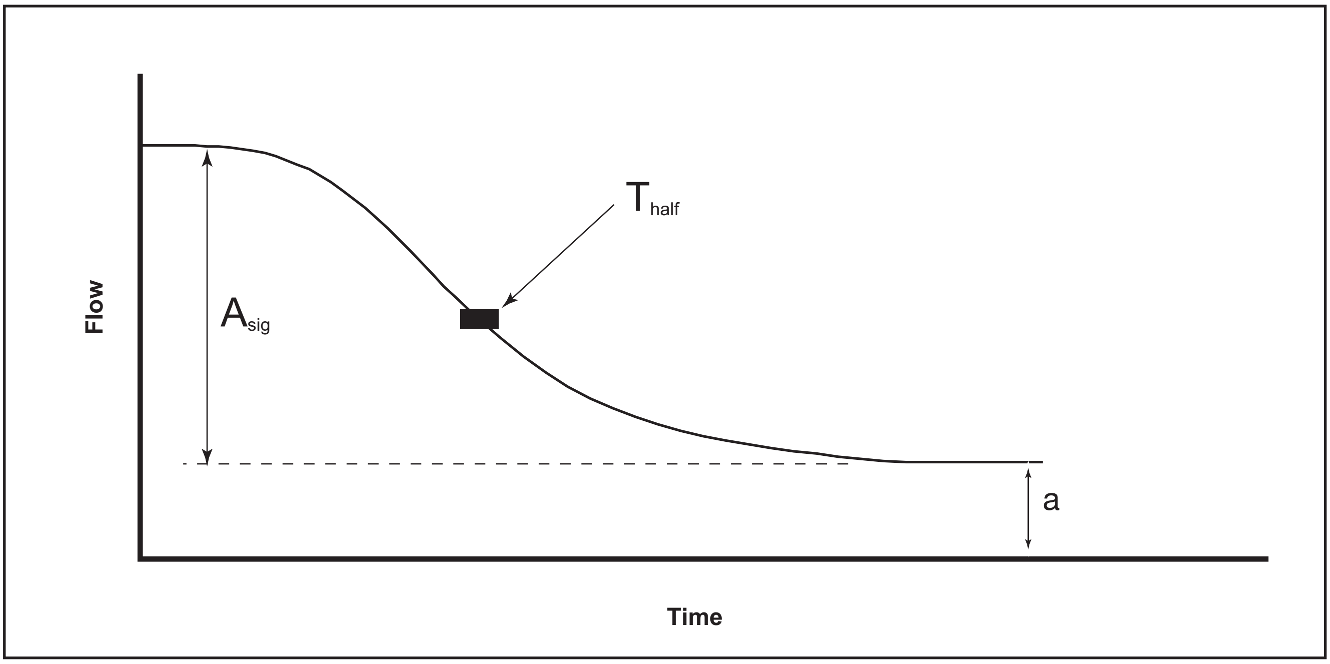

Figure 3. Generic Form of Equation 2, and Definition of Model Parameters.

afforestation on the number of zero flow days per year (N_{zero}). In this case, the left hand side of Equation 2 is replaced by N_{zero}

$$N_{zero} = a + b(\Delta P) + \frac{A_{sig}}{1 + \exp\left(\frac{T - T_{half}}{N_{sig}}\right)} \qquad (3)$$

For the average pre-treatment condition $\Delta P = 0$ and $T = 0$, N_{zero} approximately equals a. A_{sig} gives the magnitude of change in zero flow days due to afforestation, and N_{sig} describes the shape of the response. For the average climate condition $\Delta P = 0$, a+A_{sig} becomes the number of zero flow days when the equilibrium under afforestation is reached.

In the zero flow day analysis, *b* was constrained to be negative to represent the fact that the number of zero-flow days decreases as rainfall increases. Furthermore, N_{sig} was constrained to be negative to obtain a sigmoidal function that increases with time. All other constraints were the same as used in Equation 2.

2.3 Optimisation Procedure

For each decile of each catchment, optimal values for *a*, *b*, A_{sig}, N_{sig} and T_{half} are obtained using an algorithm developed for Visual Basic for Applications (VBA). *Solver,* a standard add-in for Excel has been used as the core of the optimisation algorithm. In the algorithm developed, the optimisation for each decile is started several times, each time with a different combination of initial values for *a*, *b*, A_{sig}, N_{sig} and T_{half}. Since *a*, *b* and A_{sig} decrease with higher exceedance probability (i.e. flow decreases), the initial values are estimated using power-functions of the current exceedance probability. N_{sig} and T_{half} on the other hand are independent of the magnitude of flows, so the optimisation is performed with three different starting values for each to increase the likelihood of finding the global optimum. Therefore, a total of nine optimisation runs are performed for each decile.

Each optimisation run involves a loop over two internal calls of the *Solver add-in*. Two calls were used to separate the optimisation of the rainfall and the time term. Using the least squares method, the first call optimises *b* which is part of the rainfall term; *a* and A_{sig} are also included to control the magnitude of predicted rainfall-adjusted percentile flow. The second call of *Solver* is intended to optimise the parameters of the time term, i.e. A_{sig}, N_{sig} and T_{half}. Parameter a is also included because changes in shape and magnitude of the time term affect this parameter. Having completed the second call of *Solver*, the algorithm uses the optimised parameter values of the completed run in an iterative process in which both calls are repeated up to 20 times or until the improvement in the sum of squared errors from the last step is less than 1 percent of the total sum of squared errors. This procedure is performed for each of the nine optimisation runs and after their completion the best solution is chosen on the basis of the smallest sum of squared residuals.

For the zero flow day analysis, estimation of the starting values for *a*, *b* and A_{sig} using the power function was replaced with the use of three initial values.

2.4 Statistical Analyses

The coefficient of efficiency (*E*) (Nash, 1970; Chiew and McMahon, 1993; Legates and McCabe, 1999) was used as the "goodness of fit" measure to evaluate the fit between observed and predicted flow deciles Equation 2 and zero flow days Equation 3. *E* is given by:

$$E = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i-1}^{N}(O_i - \overline{O})^2} \qquad (4)$$

where *O* are observed data, *P* are predicted values, and $\overline{O}$ is the mean for the entire period. *E* is unity minus the ratio of the mean square error to the variance in the observed data, and ranges from minus infinity to 1.0. Higher values indicate greater agreement between observed and predicted data as per the coefficient of determination (r^2). *E* is used in preference to r^2 in evaluating hydrologic modelling because it is a measure of the deviance from the 1:1 line. We consider $E > 0.7$ to indicate adequate model fits.

For both flow duration curve analysis and zero flow days analysis, a t-test was performed to assess the significance of the model parameters. This test was used as a measure of how successful the model had been in removing the rainfall variability. Due to the constraint that the rainfall and time term must be positive, a one tailed t-test was applied. The model was split into simplified forms where only the rainfall or time terms were included by optimising with either b = 0, as shown in Equation 5, or $A_{sig} = 0$ as shown in Equation 6, and tested against the complete model, Equation 2.

$$Q_{\%} = a + \frac{A_{sig}}{1 + \exp\left(\frac{T - T_{half}}{N_{sig}}\right)} \tag{5}$$

and

$$Q_{\%} = a + b\Delta P \tag{6}$$

The F-statistic was calculated as:

$$F = \frac{\left[(SSE_s - SSE_c)/(df_c - df_s)\right]}{SSE_c / df_c} \tag{7}$$

where SSE is the residual sum of the squared errors, df is degrees of freedom, and the subscripts s and c refer to the simplified model and complete model, respectively. The t-value can then be calculated as $F^{0.5}$, and compared with the critical value for significance at the 0.05 level (R. Morton, *pers. comm.*). Standard errors (SE) and confidence intervals (CI) were also calculated using standard techniques.

3. Data Sets

Streamflow data was obtained from ten catchment studies. The initial criteria for selection of these catchments were a known vegetation history and streamflow records of good quality. The ideal data sets were those with a lengthy pre- and post-treatment (plantation establishment) flow record with approximately 100 percent of the catchment converted from grassland or a crop equivalent to plantation. In reality all these criteria were not easy to satisfy. For example in Victoria the best data is from Stewarts Creek, a set of decommissioned research catchments with 9 years of pre-treatment data and 25 years of post-treatment. Here, though, the treatment was a conversion from native eucalypt forest to pine. Data from Victoria, NSW, New Zealand and South Africa were gathered. The South African data sets provided the best data quality as they are part of a series of long term research catchments that, unlike within Australia, have been funded for the decades necessary to establish hydrologic responses to land-use change over the appropriate temporal scales. Catchment details and treatments are given in Table 1.

All catchments excepting Traralgon Creek were afforested with pine species, predominantly *Pinus radiata*, with *P. patula* planted at the two Cathedral Peak catchments. Traralgon Creek has only 6 percent pine, with the remainder *eucalypts species,* most of which is Eucalyptus regnans. Data on soil

Table 1. Site Characteristics for all Catchments. For *rainfall distribution, U = uniform, W = winter dominated, S = summer dominated.

	Area (ha)	% Area Planted	Mean annual rainfall	*Rainfall Dist.	Forest Age (years)	Mean Soil Depth (m)	BFI	Key References
Traralgon Ck (Vic)	8700	~ 70	1472	U	19	2.0	0.37	
Redhill (NSW)	195	78	866	W	9	1.0	0.39	Hickel, 2001
Pine Ck (Vic)	320	100	775	W	11	< 1.0	0.26	
Stewarts Ck 5 (Vic)	18	100	1156	W	20	< 1.0	0.28	Nandakumar and Mein, 1993
Glendhu 2 (NZ)	310	67	1282	U	17	1.0	0.64	Fahey and Jackson, 1997
Cathedral Peak 2 (SA)	190	75	1436	S	20	1.5-2.0	0.66	Scott *et al.*, 2000
Cathedral Peak 3 (SA)	139	86	1504	S	17	1.5-2.0	0.75	Scott *et al.*, 2000
Lambrechtbos A (SA)	31	82	1134	W	19	1.5-2.0	0.78	Scott *et al.*, 2000
Lambrechtbos B (SA)	66	89	1088	W	20	1.5-2.0	0.87	Scott *et al.*, 2000
Biesievlei (SA)	27	98	1332	W	20	1.5-2.0	0.72	Scott *et al.*, 2000

characteristics have been obtained from published reports and personal communication with researchers, but is far from uniform, particularly regarding porosity. Consequently only an indication of mean depth is reported here. However, this does give some indication of the likely relative storage capacities of the catchments. To obtain insights into the pre-afforestation hydrologic characteristics a baseflow separation was performed on the daily flows from each catchment, using the digital filtering method of Lyne and Hollick (1979) with a filter coefficient of 0.925. The resultant average baseflow index (BFI) for the first 3 years following disturbance is given in Table 1. This condition was chosen as it may approximate the ET conditions of pasture or short crops. The Australian catchments display a notably lower BFI than the South African and New Zealand catchments. For Stewarts Creek, Pine Creek and Redhill the lower BFI may be explained by the shallow soils that occur in those catchments. Pre-treatment data is not available for all catchment in the data set, so it was decided for the sake of consistency in the analysis to start each of the data sets in the year of treatment. If data in the year of treatment was not available, the data set started in the first year of record.

4. Results

4.1 Comparison of Rainfall Statistics

Correlation between the flow deciles and various rainfall statistics were investigated for sample catchments. Rainfall statistics tested were mean daily rainfall for each year of record, median daily rainfall, rainfall percentiles, mean daily for highest and lowest 3 monthly rainfall and deviation of annual rainfall from the period of record average. The spread of r^2 across all deciles was used to assess the most robust rainfall statistic; ie. the rainfall statistic that returned the higher r^2 over all deciles was preferred to a rainfall statistic that was very highly correlated with some deciles but poorly correlated with others. Generally the deviation from the mean daily rainfall returned the best overall correlations with all flow percentiles, although the 20th rainfall percentile was superior for the Stewarts Creek data. However, the deviation of annual rainfall from the period of record average was used for all data sets. The use of an easily calculated statistic meets the aim of minimising complexity of parameterisation.

4.2 Model Evaluation

The fit of the complete model as given by equation (2) to the observed data was generally good. Table 2 gives the coefficient of efficiency (E) for each flow percentile at all the catchments. The majority of fits (77%) returned $E > 0.7$, with 60 percent 0.8 or better. The significance of the rainfall and time terms is given in Tables 3 and 4, respectively, for all deciles where solutions were found. There were not enough data to fit the model in 5 instances because of extended periods of zero flows. This problem is addressed to some extent in the zero flow analysis. If the rainfall signal is to be separated from the vegetation signal the rainfall terms must be significant. This term, b, was significant for 75 percent of the deciles at the 0.05 level, and a further 9 percent at the 0.10 level. The incidence of significance was greatest for the 10-50th percentiles at 45 of the 50 data sets at the 0.05 level. The time term, A_{sig}, returned similar results, with 80 percent of the deciles significant at 0.05 level. There were an additional 9 percent of deciles significant at the 0.10 level. The poorest E values were those from Lambrechtsbos A and B. The high E for 50-100th deciles at Biesievlei where b was not significant are notable. In general the model fits the higher flows (lower deciles) better, most of the poorer fits are in the 80-100 percentile range. This can be expected given the results of the significance tests for b. The optimised values of b and A_{sig} and the calculated confidence intervals are tabulated in Appendix 1. The results of the sensitivity analysis suggests that the E values for Glendhu 2 and for 10th and 20th percentiles from Cathedral Peak 3 may exaggerate the goodness of fit to the exact form of the model.

4.3 Adjusted FDCs - Magnitude of Flow Reductions

Assuming that the rainfall term accounts for climate signal the deciles of the FDC were adjusted for climate by setting (P to zero. The climate adjusted FDCs produce an estimation of the change in flow percentiles over time for each catchment due to afforestation that may be viewed in two forms: new FDCs, adjusted for climate, as depicted in Figure 4, and a comparison between all catchments of the maximum change in yield (given by A_{sig}) for each flow percentile from baseline flows (given by a + A_{sig}) as shown in Figure 5. Examples of observed and adjusted FDCs are shown in Figure 4 for three catchments; Traralgon Creek, Stewarts Creek 5 and Cathedral Peak 2. Where the new equilibrium is reached, the adjusted FDCs for individual years should be identical if rainfall variability has been accounted for. The new equilibrium is approximately reached for T=2T_{half}. Thalf values are given in Table 5. Figure 4 shows that for most deciles the adjusted FDCs are identical for 12 and 20 years after treatment at Cathedral Peak 2 and Stewarts Creek, and 18 and 19 years at Traralgon Creek. Differences in observed and climate adjusted FDCs for year 0 in Figure 4a and year 20 in Figure 4c clearly demonstrate the necessity to adjust the FDC for climate.

The relative net flow change due to afforestation is given by $A_{sig}/(A_{sig} + a)$, which represents the change from the old equilibrium condition to the new. This quantity is plotted for all catchments in Figure 5. Some deciles have been removed from the data set, the 10th and 50th percentile for Glendhu 2 and the 10th and

Table 2. Coefficient of Efficiency, E. ns indicates that no solution was found, and na denotes deciles with too few data points for analysis.

Site	**Percentile**									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Traralgon Ck.	0.82	0.85	0.81	0.81	0.83	0.78	0.80	0.77	0.65	0.56
Redhill	0.90	0.95	0.82	0.80	0.92	0.88	0.89	0.77	0.65	0.42
Pine Ck	0.56	0.76	0.88	0.99	0.99	0.99	0.71	0.99	na	na
Stewarts Ck 5	0.82	0.85	0.81	0.88	0.87	0.88	0.88	na	na	na
Glendhu 2	0.76	0.77	0.82	0.84	ns	0.87	0.89	0.90	0.86	0.76
Cathedral Peak 2	0.83	0.91	0.93	0.92	0.81	0.73	0.89	0.95	0.96	0.95
Cathedral Peak 3	0.68	0.75	0.78	0.91	0.96	0.95	0.94	0.81	0.84	0.79
Lambrechtsbos A	0.71	0.60	0.57	0.47	0.47	0.47	0.47	0.50	0.49	0.51
Lambrechtsbos B	0.82	0.76	0.70	0.66	0.65	0.65	0.62	0.59	0.58	0.58
Biesievlei	0.96	0.96	0.90	0.82	0.81	0.88	0.92	0.94	0.91	0.81

Table 3. Significance of the Rainfall Term. b, indicates that the rainfall term was significant at the 5 percent level, * represents significance at the 10 percent level, and na denotes too few data points for meaningful analysis.

Site	**Percentile**									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Traralgon Ck.	b	b	b	b	b	b	b	b	b	b
Redhill	b	b		*	b	b	b	b		
Pine Ck		b	b	b	b				na	na
Stewarts Ck 5	b	b	b	b	b	b	b	na	na	na
Glendhu 2	b	b	b	b	b	b	b	b	b	b
Cathedral Peak 2	b	b	b	b	b	*	b	b	b	
Cathedral Peak 3	b	b	b	b	b		b	b	b	
Lambrechtsbos A	b	b	b	b	*	*	*	*	*	
Lambrechtsbos B	b	b	b	b	b	b	b	b		
Biesievlei	b	b	b	b	*	*			b	b

20th percentiles from Cathedral Peak 3. The optimised value of a was zero or near zero for these cases, which in comparison to the subsequent flow percentiles is not conceptually possible, and illustrates the non-conformity to the conceptual model of certain deciles as identified by the sensitivity analysis discussed in section 4.5.

The changes shown in Figure 5 are variable. However, there are some commonalities between catchment responses. Two types of responses (groups) were identified. Group 1 catchments show a substantial increase in the number of zero flow days, with a greater proportional reduction in low flows than high flows. Group 2 catchments show a more uniform proportional reduction in flows across all percentiles. Catchments in group 2 can be broken up into group 2a and group 2b depending on the magnitude of the response reduction. The catchments in each group are:

Group 1:	Stewarts Creek, Pine Creek, and Redhill
Group 2a:	Cathedral Peak 2 and 3, and Lambrechtsbos B
Group 2b:	Lambrechtsbos A, Glendhu 2, Biesievlei and Traralgon Creek

Group 1 exhibit both the highest reduction of flows overall, and they show the largest proportional reduction at lower flows leading to a complete cessation of flow. Responses for the group 2a catchments are the most variable through the flow regime. Group 2b reductions are reasonably uniform through the percentile range. The interpretation of these results in hindered slightly by the range of afforestation at the catchments (Table 1). These results could be scaled up to 100 percent afforested if it is assumed there is a linear relationship between the area planted and flow reductions. As there is no evidence this is the case we have not presented scaled reductions here. Linear scaling has the effect of shifting the reduction curves upward for those catchments that are less than 100 percent afforested. This does not change our groupings.

Table 4. Significance of the Time Term. A indicates that the time term is significant at the 5 percent level, * represents significance at the 10 percent level, and na denotes too few data points for meaningful analysis.

Site	**Percentile**									
	10	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Traralgon Ck.		*					*			
Redhill	A	A	*	*	A	*	*	*	*	*
Pine Ck		A	A	A	A	A	A	A	na	na
Stewarts Ck 5	A	A	A	A	A	A	A	na	na	na
Glendhu 2		A	*	A	A	A	A	A	A	A
Cathedral Peak 2	A	A	A	A	A	A	A	A	A	A
Cathedral Peak 3	A	A	A	A	A	A	A	A	A	A
Lambrechtsbos A	A			A	A	A	A	A	A	A
Lambrechtsbos B	A	A	A	A	A	A	A	A	A	A
Biesievlei	A	A	A	A	A	A	A	A	A	A

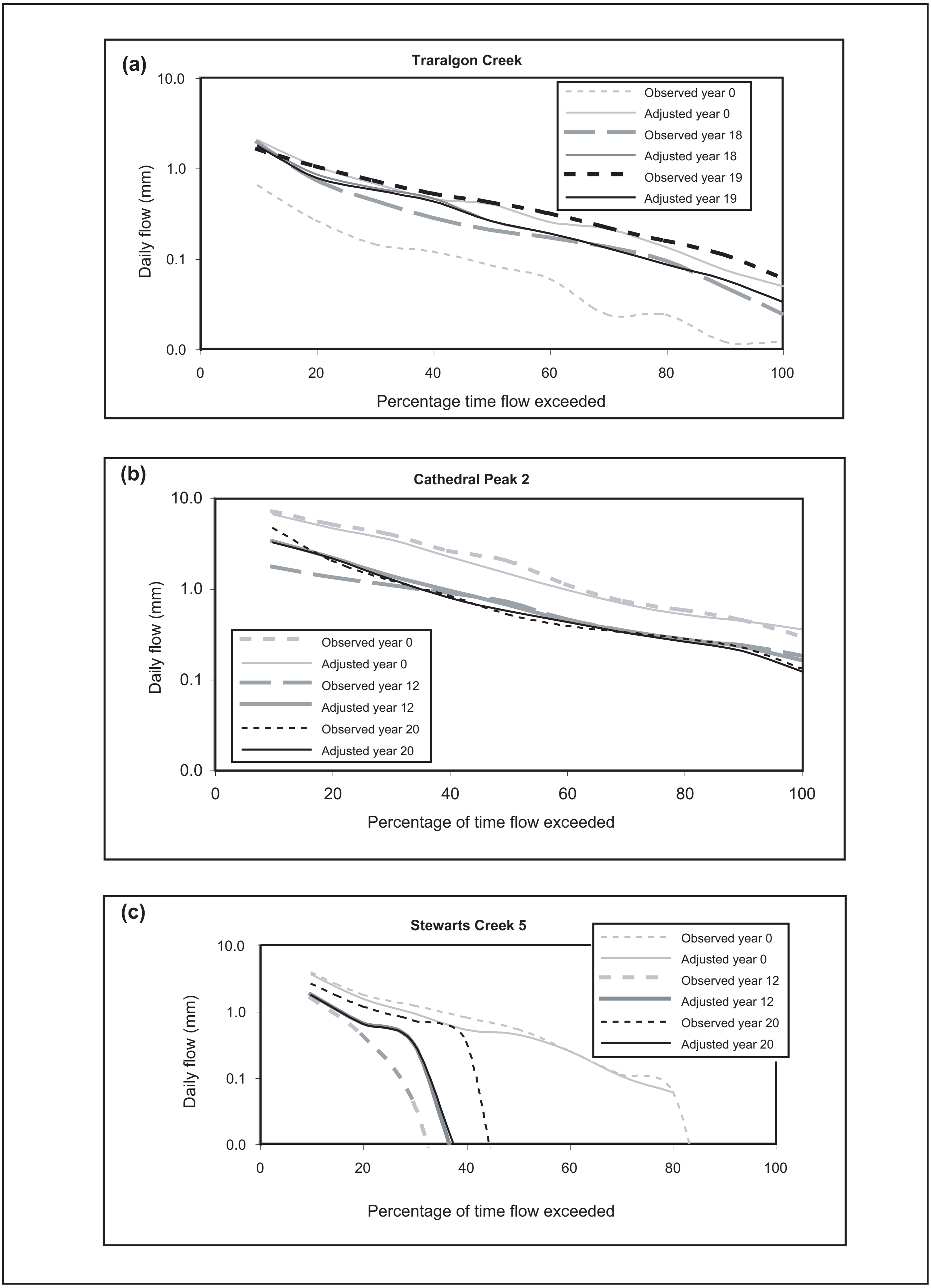

Figure 4. Examples of Observed and Adjusted Flow Duration Curves Years after Afforestation for (a) Traralgon Creek, (b) Cathedral Peak 2 and (c) Stewarts Creek 5.

4.4 Timing of Flow Reductions

The speed of flow responses to afforestation can be evaluated by examining the value of T_{half} (Table 5). There is substantial variation in response times both over the percentile spread in some individual catchments, and between the catchments. The majority of responses have a T_{half} value between 5 and 10 years. Pine Creek and Stewarts Creek, Redhill and Lambrechtsbos A exhibit the fastest responses, with Biesievlei showing the most uniformly slow response. T_{half} for the South African catchments display a good correspondence to published annual changes (Scott *et al.*, 2000, van Wyk, 1987), excepting the 10-20th deciles for both Cathedral Peak catchments and the lower deciles at Lambrechtsbos B. The T_{half} from Glendhu 2 appears to be substantially lower than other published data (Fahey and Jackson, 1997).

4.5 Sensitivity Analysis

The sensitivity of the model to the constraint that flow reduction at time zero is less than 5 percent of the total reduction (see section 2.1) was tested by investigation of how the relative reduction in flows given by $A_{sig}/(a+A_{sig})$ changed when constraints of 1, 2 or 10 percent were adopted. 72 percent of values of $A_{sig}/(a+A_{sig})$ were unchanged when the threshold constraint was altered from 5 to 1 percent, and a further 19 percent of deciles exhibited less than 10 percent change. The remaining 9 percent of solutions were scattered through several FDCs and exerted minimal impact on the overall results. There was a comparable result for a threshold of 10 percent and a lesser impact for 2 percent. The impact on the individual parameters, a and A_{sig}, were also similar, with 75 percent of deciles unchanged for a. There was a slightly greater effect on A_{sig}. (70 percent unchanged) This parameter varied most for the Glendhu 2 deciles, lower deciles at the 2 Cathedral Peak catchments and the deciles where model fits were poorest (Tables 2, 3 and 4), reflecting some departure of these data from the conceptual model.

4.6 Comparison with Paired Catchment Studies

A further check on the overall model performance is a comparison with published results of paired catchment studies. The data most appropriately compared with our results are presented in Table 6 and can be broadly compared with Figure 5. These data are reductions in years with near average annual rainfall, and at a time after treatment when maximum changes in streamflow have occurred. Table 6 also includes estimates on the total and low flow reductions calculated from this study. Results from Pine Creek and Traralgon Creek are not included in Table 5 as these catchments are not paired. Exact comparisons are impossible because of the rainfall variability, and lack of calibration period for Redhill. Despite this, Table 6 shows that total and low flow reductions estimated from our study are comparable to the results from paired catchment studies, indicating that our simple model has successfully removed the rainfall signal.

4.7 Zero Flow Days

As this analysis could only be applied where there was consistent drying up of streams, it was confined to Stewarts Creek, Pine Creek and Redhill catchments. The model returned values of E of 0.95, 0.99 and 0.99, respectively. The t-tests on b and A_{sig} returned significant results at the 0.05 level for both parameters at all three catchments, indicating that the rainfall term accounts for the climatic variability. The climate adjusted zero flow days are shown in Figure 6. Clearly the increases in zero flow days are substantial with flows confined to less than 50 percent of the year by year 8 at Stewarts Creek and Pine Creek and year 11 at Redhill. The latter has changed from an almost permanent to a highly intermittent stream. The curves are also in agreement with the flow reductions in Figure 5.

Table 5. T_{half} (years) for all Catchments. Note that no solution could be found for the 50th percentile for Glendhu indicted by the ns.

Site	Percentile									
	10	20	30	40	50	60	70	80	90	100
Traralgon Ck.	9.68	9.59	9.99	10.02	4.92	7.59	4.92	3.97	4.39	5.97
Redhill	6.13	6.07	5.99	5.99	6.07	6.04	6.79	6.81	6.02	6.00
Pine Ck	9.87	5.52	5.45	5.22	5.69	5.86	0.64	1.25	na	na
Stewarts Ck 5	6.49	6.41	6.09	5.96	3.89	3.03	2.31	na	na	na
Glendhu 2	19.59	2.67	2.24	2.08	ns	2.06	2.07	1.62	6.63	2.02
Cathedral Peak 2	4.96	3.92	5.78	7.68	8.64	8.95	9.26	9.08	8.93	9.47
Cathedral Peak 3	14.13	13.20	7.02	7.44	9.01	8.68	8.87	9.46	8.16	6.98
Lambrechtsbos A	6.89	6.87	6.93	6.89	6.88	6.97	6.94	6.93	6.94	6.97
Lambrechtsbos B	14.52	14.84	14.89	10.98	6.89	5.69	5.55	6.01	6.23	6.29
Biesievlei	9.36	9.17	9.59	10.32	10.78	10.46	10.06	10.08	10	10.10

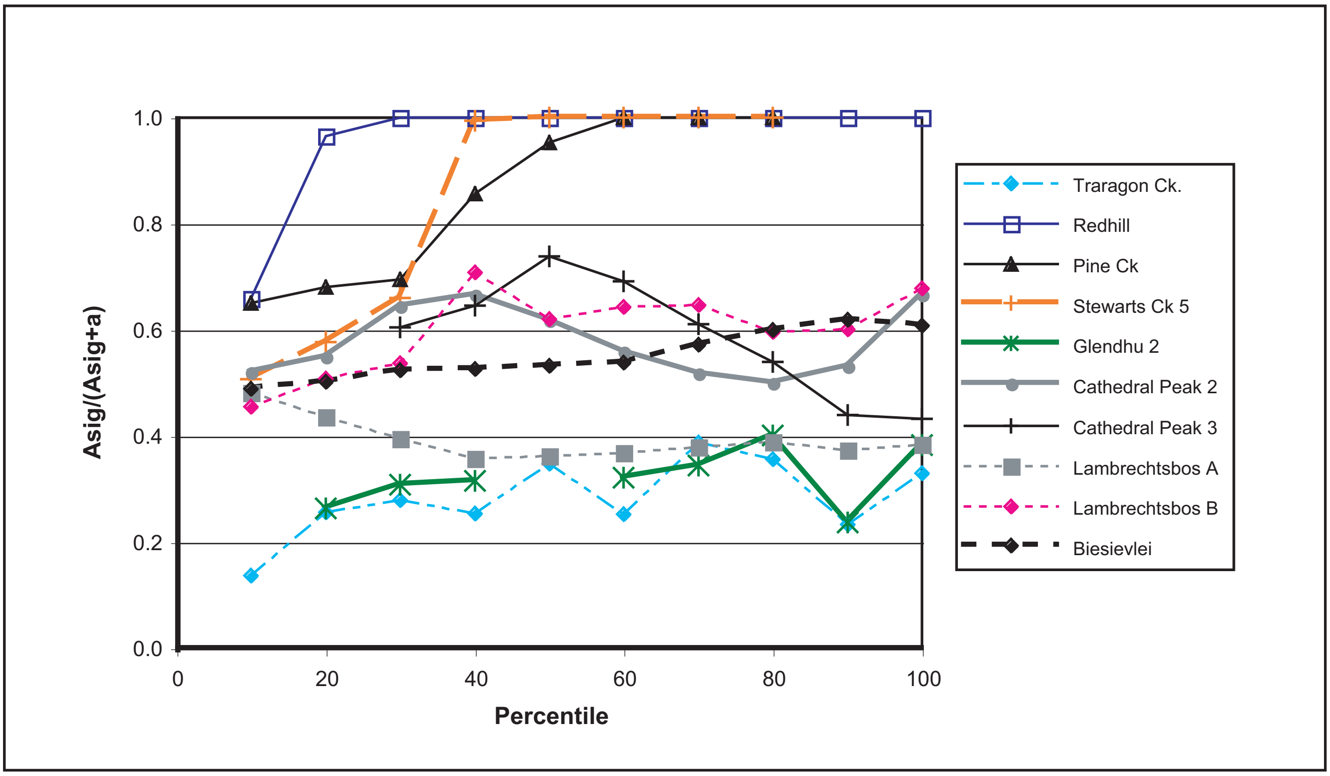

Figure 5. Net Flow Reductions $A_{sig}/(A_{sig}+a)$ for all Catchments.

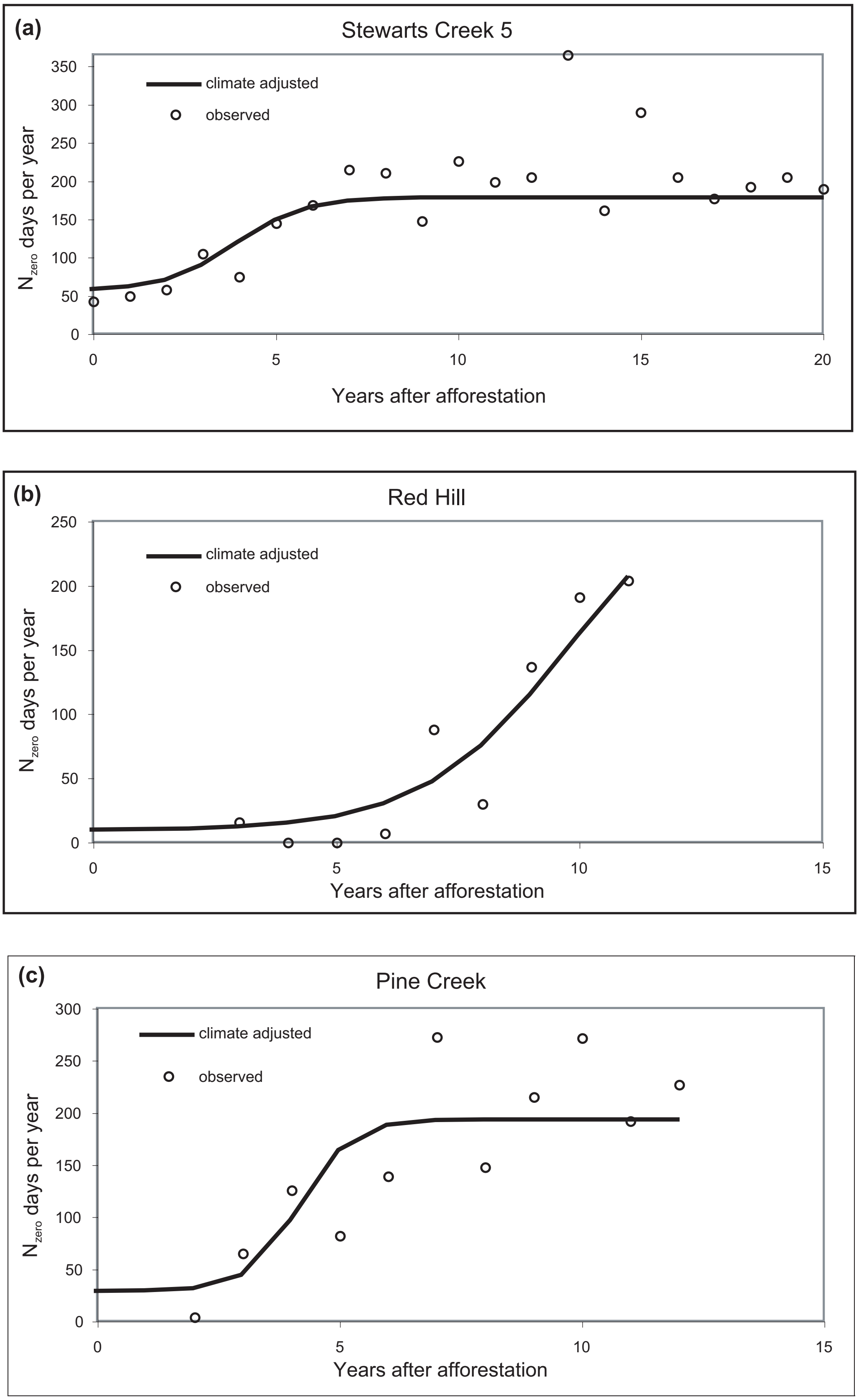

Figure 6. Climate Adjusted Number of Zero Flow Days for (a) Stewarts Creek., (b) Red Hill, and (c) Pine Creek.

Table 6. Published Flow Reductions from Paired Catchment Analyses, after Scott *et al.,* (2000), Hickel (2001), Nandakumar and Mein (1993) and Fahey and Jackson (1997), Compared to Estimated Reductions in this Study.

Catchment	Year	Rainfall[1] (mm)	Total flow reduction %	Low flow reduction %	Estimated from Figure 5	
					Total flow reduction %[2]	Low flow reduction %[3]
Cathedral Peak 2	21	1516 (+80)	50	48	57	54
Cathedral Peak 3	18	1556 (+52)	60	53	62[4]	53
Lambrechtsbos A	13	1111 (-23)	41	34	41	38
Lambrechtsbos B	18	1079 (-9)	69	78	58	63
Biesievlei	20	1388 (+6)	52	62	52	60
Redhill	9	783 (-93)	66	100	75	100
Stewarts Ck. 5	20	1249 (+93)	69		64	
Glendhu	Average reduction		27	<20	32	35

1. Rainfall refers to the rainfall in the year used for comparison of results. The value in brackets refers to the deviation from the mean annual rainfall for the period of record.
2. Total flow reduction calculated by $\sum A_{sig}/\sum(a + A_{sig})$ for all deciles
3. Low flow reduction calculated by $\sum A_{sig}/\sum(a + A_{sig})$ for 70th, 80th, 90th and 100th percentiles.
4. Cathedral Peak 3 the a and Asig values for the 10th and 20th percentiles were excluded as the values of a were lower then the values of the 30th – 100th percentiles.

5. Discussion

The general characterisation of FDCs and adjustment for climate has been very encouraging given the task of fitting our model to ten flow percentiles, for ten different catchments (resulting in 100 model fits) with substantially varying spatial scales, soils and geology, species planted and climatic environments. Although there were poor results for individual deciles, the FDCs at eight of the ten catchments were adequately described by Equation 2. The results of the statistical tests in which the rainfall term was significant for most deciles demonstrated the model structure was appropriate for adjusting the FDCs for climatic (rainfall) variability. The comparisons of our results with published paired catchment analyses are satisfactory, although the different methodologies make direct comparisons of deciles with total flow uncertain. Low flows at Lambrechtsbos B appear to be over-estimated by our model, which is unsurprising as the model fit was poor. The remaining four South African catchments, and also Redhill and Stewarts Creek are in good agreement with the published values, particularly when the deviation of average rainfall is considered. Glendhu 2 reductions are close to the reported 27 percent, but our model produces a heavier impact on the lower flows. Overall, it appears there are no significant discrepancies with the published paired catchment analyses. We suggest our technique represents an alternative to the paired-catchment method for assessing hydrologic response to vegetation treatment where paired data are unavailable.

The model fits show we have quantified the net impact of afforestation for the majority of the flow percentiles in the ten catchments. Results for the 10-50th percentiles were particularly encouraging. It is not surprising that the relationship between rainfall and flow diminishes at lower flows (60-100th percentile) where seasonal storage effects and rainfall distribution become more important drivers for runoff generation. The poorest model fits were gained for Lambrechtsbos A and B. The likely reason for the poorer model fits at Lambrechtsbos A is an annual decrease in stand water use after 12 years (Scott *et al.*, 2000) which does not conform to the sigmoidal form over the full 19 years of record. The failure of the model to fit the lower flows at Lambrechtsbos B is not as explicable. A decrease in stand water use in this catchment is observed as the plantation ages, but does not occur during the first 20 year after treatment (Scott *et al.*, 2000). Other data from South Africa (Scott *et al.*, 2000) indicate there are diminished flow reductions as plantations age, but again, generally after 20 years. Our use of an asymptotic curve assumes a new equilibrium of stand water use is reached. The results of the model fitting generally justify this assumption for the length of plantation growth (up to 20 years) considered here. Australian plantations seldom grow past 20 years, and if so, are most likely to be thinned. Putahena and Cordery (2000) detected a decline in yield from pines at Lidsdale relative to that of the replaced eucalypt forest. Flow then appears to be recovering toward pre-treatment levels after 12 years. This suggests a maximum plantation water use may have been reached and decline in flow reductions has begun. However, there are only three years of published data to support this. The relationship between stand age and water use for plantation species other than *E. regnans* have not been thoroughly investigated, although Cornish and Vertessy (2001) and Roberts *et al.,* (2001) have shown young mixed species eucalypt forests may use more water than mature stands. If the model is constrained to run for 12 years, there is a substantially improved fit for Lambrechtsbos A.

The plots of flow reduction for average rainfall $A_{sig}/(A_{sig} + a)$, and T_{half} values reveal that while there are differences in responses between the analysed catchments as a whole, there are recognisable trends. Perhaps the most general finding was that in seven of the ten catchments the high flows (10th percentile) were less affected than other flows. The catchments demonstrate two types of responses. Response group 1 show a proportionally larger reduction in low flows compared to high flow, while response group 2 shows a more uniform response.

The small Australian catchments converted to pine fit into response group 1 (Stewarts Creek, Pine Creek and Redhill). These catchments have similar shallow soils, potential evapotranspiration and rainfall distribution (relatively uniform) although Stewarts

Creek is significantly wetter. The combination of small catchment area and the increased transpirative demand that exceeds summer and autumn rainfall and stored water results in the large impact on lower flows, compared to high flows.

The remaining catchments fall into response group two. However, within Group 2 the magnitude of the response varies considerably, with greater reduction in flows in the two Cathedral Peak catchments, and Lambrechtsbos B. Given the almost identical environment, species and area planted at Cathedral Peak, a good correspondence between catchments 2 and 3 is expected. Potential evaporation is in phase with rainfall at these sites as they receive 85 percent (1260 mm on average) of their rainfall in summer. The conjunction of peak demand and plant water availability may explain the high reductions relative to the remaining catchments in Group 2. Growth at Glendhu 2 was notably slow (Fahey and Jackson, 1997) and Lambrechtsbos A and Biesievlei are described as being within sub optimal growth zones (Scott and Smith, 1997) characterised by these authors as having relatively slow response times and lesser reduction that at more optimal sites. The Bieslievei data fits this model for both reductions and T_{half} but Lambrechtsbos A conforms only to the former, which may be a consequence of the poorer model performance.

The response groups may be in part explained by the storage characteristics of the catchments. Accurate measures of storage are not available from the literature, but the soil depths and the baseflow index (Table 1) both show the three south eastern Australian catchments with the greatest reduction are likely to have the lowest storage capacity. The greater flow reductions, particularly for low flows, could be expected under these conditions. Given the similar soil depths and BFI of the South African catchments, the differences in flow reduction may be explained by differences in rainfall distribution and growth. Inclusion of a storage term in the model is an obvious option for improving the analysis. However the addition of extra parameters would be at the cost of maintaining model simplicity, particularly as characterising a transient storage is not trivial.

Traralgon Creek would be expected to have both the most subdued flow reductions and longer response time because of the large area of *E. regnans* forest, and uncertain vegetation record Peak stand water use of a natural stand of this species is around 30 years. Additionally in this large, "real world" catchment, there is a continuous cycle of forest management which includes harvesting. A mixture of pasture and "scrub", which could represent significant understorey stands, were replaced by plantation species. Consequently the difference between pre and post treatment ET may be less than at other catchments. Reductions of this magnitude could be more readily expected in larger, multi land-use catchments than the very high impacts estimated at the smaller Australian catchments.

The analysis of zero flow days was successful, demonstrating that the impact on flow intermittence can be evaluated without of the entire FDC. This was helpful as the change in the higher percentiles (low flows) could not always be modelled. The results for the three catchments analysed are a rather stark indication of the potential for highly increased zero flow periods in small catchments, at least in south-eastern Australia. However, it should be noted these curves probably represent a maximum response as they are all derived from small catchments with small storage capacities and large percentages of afforestation. This method could be used to determine change in the frequency of occurrence of any given flow in response to afforestation. Such information can be used to determine the likelihood of maintaining a reservoir storage or an environmental flow that requires on average a flow of x mm d^{-1} or greater. Such analyses may be very useful as inputs to the type of eco-hydrologic models discussed by Hughes and Hannart (2003) that seek to maintain the ecological functioning of streams.

6. Summary and Conclusions

This project sought to (i) develop a method to remove the climate signal from streamflow records so as to identify the impact of vegetation on flow from afforested catchments, and (ii) quantify this impact on the flow duration curve. A simple model was proposed that considered the age of plantation and the annual rainfall to be the principal drivers for evapotranspiration. This model was fitted to the observed deciles of the FDC, and the climate signal was then removed from the streamflow records by adjusting the FDC for average rainfall over the period of record. The model was tested and applied to ten afforested catchments. We also used a similar model to assess the change in the number of zero flow days following afforestation.

We successfully fitted our model to a range of catchments with varying spatial scales, species and environments, and have shown that it provides a means of separating the influence of climate and vegetation on the FDCs. Once the climate signal had been removed from the FDC, the impact of afforestation was assessed and two response types were identified. Response Group 1 showed a proportionally larger reduction in low flows compared to high flows, which may be related to comparatively low soil water storages. Response Group 2 exhibited more uniform reductions across all flow, with similar percentage reductions in both low and high flows. In both response groups high flows (10th percentile) were less affected than other flows in most cases. The characterisation of the number of zero flow days was also successful for the catchments in response group 1 and indicated that a significant increase in the number of zero flows days could be anticipated following afforestation given the correct combination of climatic and catchment characteristics. The zero flow day results and the overall flow reductions compared well with reported values from paired catchment studies. However, it is import to realise that the flow reductions and results of the zero flow day analysis probably represent a maximum impact because of the size of the catchments and the scale of afforestation. This research has led to the development of a method to assess the impact of afforestation on flow regime which does not require paired-catchments to remove climatic variability.

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Appendix 1

Appendix 1. Model parameter values and confidence intervals (*CI*) for complete model, (2)

		Tr Ck.	Redhill	Pine Ck	Stew. Ck	Glen.2	CP 2	CP 3	Lm A	Lm B	Bies.
b	**10**	1.3354	0.9918	0.1686	1.1037	1.4235	2.1171	2.1443	0.8214	0.9515	1.2193
	20	0.6339	0.4175	0.0508	0.6120	0.8540	1.3612	1.5583	0.6653	0.7059	0.7772
	30	0.3889	0.2003	0.0163	0.3839	0.6113	0.8174	0.4977	0.3830	0.5498	0.4086
	40	0.2773	0.1715	0.0100	0.3470	0.5447	0.4170	0.2510	0.1657	0.2819	0.2013
	50	0.1972	0.0970	0.0021	0.2807	0.4816	0.2179	0.1874	0.1216	0.1618	0.1125
	60	0.1591	0.0849	0.0024	0.1883	0.4172	0.1625	0.0844	0.1092	0.1211	0.0668
	70	0.1061	0.0545	0.0000	0.0470	0.3770	0.1114	0.0391	0.0956	0.0933	0.0333
	80	0.0624	0.0343	0.0000	0.0000	0.3557	0.0744	0.0286	0.0924	0.0663	0.0045
	90	0.0382	0.0223			0.3333	0.0476	0.0000	0.0761	0.0421	0.0000
	100	0.0199	0.0138			0.2542	0.0042	0.0000	0.0581	0.0388	0.0000
CI	**10**	0.3644	0.8980	0.2048	0.5280	0.5669	1.0359	1.4650	0.3866	0.2796	0.2510
	20	0.1616	0.3577	0.0435	0.2572	0.3405	0.4121	0.8362	0.3790	0.2564	0.1849
	30	0.1146	0.3947	0.0094	0.2020	0.2208	0.2633	0.3175	0.2567	0.2338	0.1862
	40	0.0782	0.3154	0.0021	0.2125	0.1871	0.2098	0.1445	0.1878	0.1659	0.1899
	50	0.0589	0.0820	0.0010	0.0917	0.1573	0.2186	0.0822	0.1641	0.1261	0.1528
	60	0.0621	0.0679	0.0036	0.0001	0.1334	0.1923	0.0574	0.1484	0.1169	0.0913
	70		0.0326		0.0000	0.1096	0.0718	0.0546	0.1378	0.1054	0.0592
	80	0.0222	0.0300		0.0000	0.0922	0.0331	0.0848	0.1249	0.0965	0.0441
	90	0.0166	0.0267			0.0850	0.0234	0.0000	0.1107	0.0871	
	100	0.0097	0.0000			0.2201	0.0232		0.0954	0.0776	
A_{sig}	**10**	0.2764	7.0618	0.2070	1.8039	3.6611	3.5863	4.5493	1.0670	0.8063	1.6376
	20	0.2688	0.9458	0.0891	0.8830	1.6298	6.2460	4.3640	0.7548	0.6683	1.1999
	30	0.1879	0.5653	0.0307	0.6046	1.9239	5.7557	2.0495	0.5347	0.5604	0.9297
	40	0.1162	0.2943	0.0248	0.6114	1.7616	1.5085	1.3853	0.3939	1.7606	0.7082
	50	0.1140	0.1167	0.0223	1.0743	1.5999	0.9004	1.0795	0.3580	1.6651	0.5548
	60	0.0000	0.0636	0.0207	0.1653	1.6269	0.5402	0.9461	0.3258	1.4192	0.4477
	70	0.0000	0.0383	0.0198	0.4180	1.7917	0.3475	0.4630	0.3057	1.2122	0.4048
	80	0.0477	0.0181	0.0050	0.1228	1.7378	0.2585	0.3101	0.2929	1.0639	0.3549
	90	0.0151	0.0118			1.3257	0.2313	0.2072	0.2571	0.9899	0.3051
	100	0.0143	0.0003			0.1314	0.2371	0.1638	0.2400	0.9305	0.2075
CI	**10**	0.8477	6.0023	0.3712	1.1296	4.2448	3.1965	3.6188	0.9206	0.6655	0.5034
	20	0.3809	0.5632	0.0446	0.4846	2.1119	3.2753	2.9148	0.9031	0.6117	0.3701
	30	0.2815	0.6872	0.0110	0.3753	1.7183	2.0720	1.1379	0.6111	0.5634	0.3875
	40	0.1911	0.5019	0.0025	0.3728	1.4362	0.6352	0.4473	0.4461	1.3554	0.3870
	50	0.1633	0.1147	0.0042	0.4851	1.2507	0.5867	0.2219	0.3894	1.1325	0.3028
	60		0.0465	0.0029	0.0001	1.1758	0.4498	0.1997	0.3534	0.9619	0.1811
	70		0.0472		0.0000	1.1703	0.1676	0.1225	0.3283	0.8666	0.1189
	80	0.0725	0.0310		0.0302	1.1062	0.0784	0.1515	0.2976	0.8094	0.0862
	90	0.0446	0.0264			1.0202	0.0590	0.0931	0.2642	0.7478	0.0943
	100	0.0308	0.0000			0.2311	0.0611	0.0891	0.2279	0.6874	0.0972

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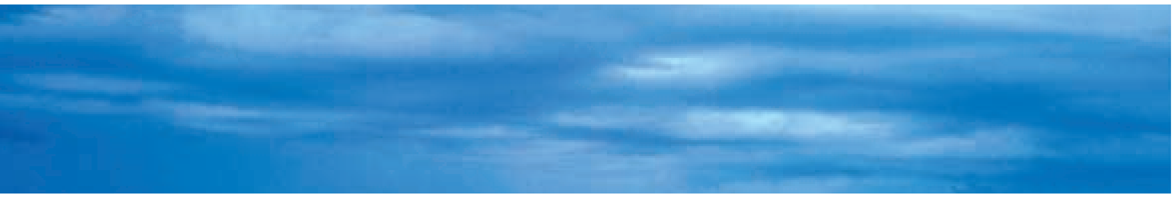

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