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Predicting effects of plantation expansion on streamflow regime for catchments in Australia

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Abstract

The effect of plantations on mean annual streamflow is well understood and there are robust methods available for assessing the impact. Plantations also affect streamflow regime, leading to reductions in low flow and increased number of zero-flow days. Understanding changes in streamflow regime following plantation expansion is important for developing water resources and environmental flow strategy. This study evaluated the impacts of plantation on streamflow regime from 15 catchments in Australia. The selected catchments range in size from 0.6 to 1136 km^2 and represent different climatic conditions and management practices. The catchments have at least 20 yr and in most cases 35 yr of continuous daily streamflow data and well documented plantation records. Catchments with perennial streamflow in the pre-treatment periods showed relatively uniform reductions in most flows after plantation expansions, whereas catchments with ephemeral streamflow showed more dramatic reductions in low flows, leading to an increased number of zero-flow days. The Forest Cover Flow Change (FCFC) model was tested using the data from the selected catchments and comparison of predicted and observed flow duration curves showed that 14 of the 15 catchments have coefficient of efficiency greater than 0.8. The results indicate that the model is capable of predicting plantation impacts on streamflow regime.

1 Introduction

Our understanding of the vegetation impact on mean annual water yield is well advanced and there are robust methods available for assessing these (Bosch and Hewlett, 1982; Zhang et al., 2001, Brown et al., 2005, Zhao et al., 2010; Wei and Zhang, 2010). Recently, a number of studies focused on changes in flow regime following vegetation cover changes and showed different responses in high flows and low flows (Lane et al., 2005; Brown et al., 2006). It has been recognised that there is a need to make predictions of changes in flow regime for water security and ecosystem

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assessments (Brown et al., 2007). An important step in predicting changes in streamflow regime is to select an appropriate statistics that can be used to describe various streamflow regimes found in catchments. The flow duration curve (FDC) approach has been adopted as it provides a statistical method for describing flow distribution and more importantly allows identification of differences between two streamflow time series (Smakhtin, 2001; Brown et al., 2005, 2006). Another useful feature of an FDC is the ability to easily display flow variability and its direct application in water allocation analysis (Brown et al., 2007).

While change to mean annual water yield is important for the purpose of regional and basin-wide planning, the impacts of vegetation change on streamflow regime can be more significant from both water security and environmental flow perspectives. For example, if there is a large area of afforestation in catchments, will this affect water security or environmental flows during extended dry periods? A commonly used approach for predicting the impact of afforestation on streamflow is to rely on detailed physically based models (Baron et al., 1998; Legesse et al., 2003) or conceptual models derived from paired catchment studies (Sivapalan et al., 1996; Scott and Smith, 1997; Hundecha and Bárdossy, 2004). Use of physically based models in large catchments is problematic and impractical because of data requirements. It is desirable to use conceptual models that can be accurately supported by available data.

It is generally understood that plantations affect not only rainfall interception, which directly influences surface runoff, but also deep drainage, which in turn determines the amount of base-flow in a catchment. However, it is difficult to quantify these changes in catchments where no measurements are available since the relative role of plantations in controlling these processes depends upon climate, vegetation, soil, and other catchment characteristics. In this study, a simple conceptual model developed by Brown et al. (2006), the Forest Cover Flow Change model (FCFC), was considered. The FCFC model was designed to adjust a time series of observed or simulated daily flow to account for changes in forest cover and the model was developed based on data from paired catchment studies. The FCFC model was developed for a practical purpose, namely predicting changes in flow duration curves following plantation expansions with minimum data requirement. As a result, the model is simple in its process representation. This raises the issue of transferability of the model to other catchments or regions in predicting plantation impact on streamflow regime.

Plantation forestry is an important land use in Australia and the nationwide plantation area has increased by over 70 % since 1994 and reached a total area of nearly 2 million ha in 2008 (BRS, 2009). Some of the plantations were developed in catchments where gauged streamflow data are available and this provides an opportunity to investigate streamflow response to plantation development (Zhang et al., 2011). Unlike paired experimental catchments that are generally less than 1 km^2 in size, the plantation affected catchments used in this study represent typical catchments where water resources decisions need to be made. Also these catchments can be used to quantify plantation impact on streamflow regime, providing a unique opportunity for testing the FCFC model in large catchments.

The objectives of this paper are to (1) determine changes in flow duration curves from Australian catchments affected by plantation development and (2) test the FCFC model in predicting the effects of plantation expansion on streamflow regime. The catchments used in this study range in size from 0.6 to 1136 km^2, representing typical catchments where land use and water resources decisions need to be made.

2 Methods

2.1 Flow duration curve (FDC)

A FDC represents the relationship between the magnitude and frequency of daily, weekly, monthly (or some other time interval of) streamflow; it provides a measurement of the proportion of time a given streamflow was equalled or exceeded in the period of measurement. A FDC provides a simple, yet comprehensive graphical view of the overall historical variability associated with streamflow and is the complement of the cumulative distribution function of daily streamflow.

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A FDC can be constructed from daily streamflow data by ranking the flow from the maximum to minimum with each flow against the percentage of time this flow is exceeded. It provides a graphical and statistical summary of the streamflow variability and distribution, with the shape being determined by rainfall pattern, catchment size and the physiographic characteristics of the catchment. The shape of the FDC is also influenced by water resources development and land use type (Smakhtin, 1999).

2.2 Forest Cover Flow Change model (FCFC)

The Forest Cover Flow Change model (FCFC) is designed to predict that change to an observed or simulated daily flow duration curve following a change in forest cover (Brown et al., 2006). The FCFC model uses a 6 stage process to adjust the parameters of the model used to describe the shape of the FDC.

The parameterisation of the FDC used within the FCFC model is expressed as:

$$Q = \begin{cases} Q_{50}\left(10^{\frac{s}{c_\mathrm{u}}\left[\exp\left(F^{-1}\left(\frac{x}{\mathrm{CTF}}\right)c_\mathrm{u}\right)-1\right]}\right) & x \le \frac{\mathrm{CTF}}{2} \\ Q_{50}\left(10^{\frac{s}{c_\mathrm{l}}\left[\exp\left(F^{-1}\left(\frac{x}{\mathrm{CTF}}\right)c_\mathrm{l}\right)-1\right]}\right) & \frac{\mathrm{CTF}}{2} < x < \mathrm{CTF} \\ 0 & x \ge \mathrm{CTF} \end{cases} \quad (1)$$

where: Q is the predicted flow, F^{-1} is the inverse of the standard normal cumulative distribution, Q_{50} is the median of the non-zero flow days, CTF is the cease-to-flow percentile, x is a probability value (0–100 %) and s, c_u, c_l are curve fitting parameters. The s, c_u and c_l parameters relate to different sections of the FDC, s being the slope at the origin of the normalised FDC (NFDC) and c_u and c_l being the exponents for the upper and lower sections of the NFDC, respectively.

Figure 1 shows the method used to normalise the FDC of perennial and ephemeral streams. Firstly, the cease-to-flow (CTF) percentile is established (Fig. 1a). The CTF

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percentile is defined as the ratio of the number of non-zero flow days to the total number of days. A non-zero flow day is defined as any day on which flow is greater than or equal to a specified threshold value (adopted here as 0.001 mm d^{-1}). A FDC is then constructed using only the days on which flow is greater than the threshold value as streamflow measurements below this value are considered unreliable (Fig. 1b). The FDC is then normalised by dividing all flow values by the conditional median (Fig. 1c). The conditional median is defined as the median flow of the days on which flow occurs. Finally, the FDC is plotted in log-normal space (Fig. 1d) to produce a normalised FDC (NFDC). This normalisation procedure results in all of the NFDCs intersecting the origin. To adjust the parameters of this model for a change in forest cover, the parameters are linked to a predicted change in mean annual streamflow.

2.3 Model parameters and calibration procedure

The five parameters used to describe the FDC are the CTF percentile, the conditional median and three curve-fitting parameters for the NFDC (referred to as the slope, upper exponent and lower exponent). Observed or predicted flow data is used to determine the CTF percentile and the conditional median while the curve fitting parameters are fitted using a two-stage iterative process with the slope, upper and lower exponents adjusted to minimise the sum of squared error of the difference between the observed and fitted FDCs. The upper exponent is then adjusted to achieve a mass balance between the fitted curve and the observed mean annual flow.

The parameters of the FDC are then adjusted based on a prediction of the change in mean annual streamflow following a change in forest cover. The method used to do this is described in detail in Brown et al. (2006) and follows the process described in Fig. 2.

The quality of the fit of the adjusted FDC to the observed data is judged using the coefficient of efficiency, E, calculated in the log domain (Nash and Sutcliffe, 1970):

$$E = 1 - \frac{\sum_{i=1}^{\text{CTF}} (\log(O) - \log(P))^2}{\sum_{i=1}^{\text{CTF}} \left(\log(O) - \log(\bar{O})\right)^2} \tag{2}$$

Here, O is the observed percentile flow and P is the predicted percentile flow. The closer the coefficient of efficiency is to one the better the fit. The logarithm of the values is used to give more weight to low flow values. E is calculated only between the first percentile and the CTF percentile, thus zero flows are not considered. Once the parameters for each annual FDC are determined, the representative values of s and c_u are estimated as the mean of each of the s and c_u values for all the pre-treatment years.

3 Catchment description and data

3.1 Catchment description

To best represent the climatic conditions and management practices of these regions, 15 catchments have been selected in this study (Fig. 3) and they meet the criteria of having documented plantation areas and continuous streamflow (Q) and climatic data. It is also ensured that the impacts of other landuse change (e.g. farm dams) and water extractions are minimal in the selected catchments.

The catchment areas range from 0.6 km^2 to 1136 km^2 with mean annual rainfall (P) varying from 629 mm to 1011 mm. The potential evaporation (E_0) varies from 726 mm to 1117 mm. The index of dryness (equal to E_0/P) ranges from 0.85 to 1.70, and the runoff coefficient (equal to Q/P) varies from 0.10 to 0.42. The selected catchments represent typical catchments where water resources decisions need to be made.

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3.2 Data

3.2.1 Streamflow data

The catchments selected in this study have at least 20 yr and in most cases 35 yr of continuous daily streamflow data except Burnt Out Creek which has several years of missing data. The streamflow data were obtained from different agencies. Detailed information on the gauging stations and the period of records are listed in Table 1.

3.2.2 Climatic data

Catchment averaged annual rainfall was estimated from gridded SILO daily rainfall (Jefferey et al., 2001). The spatial resolution of the gridded daily rainfall data is 0.05 degrees based on interpolation of over 6000 rainfall stations across Australia. The interpolation uses monthly rainfall data, ordinary kriging with zero nugget, and a variable range. Monthly rainfall for each 5 × 5 km grid cell was converted to daily rainfall using daily rainfall distribution from the station closest to the grid cell (Jefferey et al., 2001). Potential evaporation (E_0) is estimated using measurements of class A pan evaporation with the pan coefficient set to 0.75 following van Dijk (1985).

3.2.3 Plantation and land use data

In order to investigate the effects of plantation expansions on streamflow, plantation data including plantation area and age for each of the selected catchments were provided by the Bureau of Rural Science and State agencies. As an example, cumulative plantation cover (%) over time for Adjungbilly Creek, one of the selected catchments, is shown in Fig. 4. Summary of the plantation data for the selected catchments is listed in Table 1 and details can be found in Zhang et al. (2010). Other information including land use history, farm dams, and water diversions was also obtained for the selected catchments. Over the period of streamflow records, these catchments had minimum

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impact from farm dams and water extractions, and plantation expansion represents the most significant land use change in these catchments.

4 Results

4.1 Effects of plantation expansions on flow duration curves

Figure 5 shows the daily flow duration curves for the pre-treatment and post-treatment periods for the 15 selected catchments. It is clear that all the catchments experienced various degrees of flow regime change. In the pre-treatment period, most catchments had continuous streamflow (e.g. Adjungbilly Creek) while some exhibited ephemeral nature (e.g. Upper Denmark River). The perennial catchments are generally large in size with high rainfall, while the ephemeral catchments are small in size with low rainfall. Distribution of rainfall in relation to potential evaporation can also affect the streamflow regime. Catchments with perennial streamflow showed relatively uniform reduction across their flow distribution, whereas catchments with ephemeral streamflow showed more dramatic reduction in low flows, leading to increased number of zero-flow days (e.g. Burnt Out Creek). Characteristic flows such as high flows (Q_5), median flows (Q_{50}) and low flows (Q_{95}) are defined as the daily flows exceeded 5, 50 and 95 % of the time, respectively. Relative reductions in these flows are listed in Table 2. For most of the catchments, average flow reduction was about 45 % for high and median flows. The reduction in low flow was greater. Burnt Out Creek, Pine Creek, and Red Hill showed much more dramatic changes in these characteristic flows than the other catchments. These changes may be related to catchment size and level of plantation expansions.

4.2 Comparison of estimates of mean annual streamflow reduction

As described in Sect. 2.2, FCFC predicts the mean annual streamflow reduction using the method of Zhang et al. (2001) and it forms the basis of the model. Figure 6

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compares estimates of mean annual streamflow reduction using the method of Zhang et al. (2001) and the time-trend analysis method (Zhang et al., 2011). It can be seen that the methods provided reasonably similar estimates of plantation impact on mean annual streamflow. Average annual rainfall for the whole pre- and post-treatment periods was used in this calculation and this may introduce some error, especially for catchments with relatively large rainfall change over the two periods.

4.3 Comparison between predicted and observed FDCs

Figure 7 shows comparisons between FCFC predicted and observed FDCs for the selected catchments in the post-treatment period. It is clear that all the catchments showed good agreement between the predictions and observations, except for one or two other catchments. Table 3 provides a summary of results for all the catchments. The model under predicted the cease-to-flow (CTF) percentile in a number of catchments, for example, the predicted CTF is 48 % for Yate Flat Creek, while observed value is 67 %. There is a strong correlation between predicted and observed median (see Table 3). The results in Fig. 7 and Table 3 show that the FCFC model works well with 14 of the 15 catchments having coefficient of efficiency greater than 0.8.

5 Discussion

Increasing plantation cover reduces total streamflow as well as changes streamflow regime. After plantation expansions, catchments with perennial streamflow in the pre-treatment periods showed relatively uniform reductions across most flows, whereas catchments with ephemeral streamflow regime showed more dramatic reductions in low flows, leading to increased number of zero-flow days. Although proportional reductions in high flow are small, they represent large volume changes. The low flows showed greater proportional reductions but with smaller volume changes. The perennial catchments have more uniform temporal rainfall distribution and are large in size.

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The combined effect of these factors means the soil water store in these catchments drained slowly, maintaining baseflow throughout the year. The ephemeral catchments are relatively dry catchments with the dryness index (i.e. ratio of average potential evaporation to rainfall) greater than unity. These catchments have winter dominated rainfall and are small in size. During the dry period (e.g. summer), soil water store of the catchments drained quickly, leading to zero flows. The presence of plantation in these catchments enhanced evapotranspiration and lowered soil water levels significantly. As a result, substantial proportional reductions occurred in the low flows with an increased number of zero-flow days.

The FCFC model was developed for a practical purpose, namely predicting changes in flow duration curves following plantation expansions with limited data available. As a result, the model is simple in its process representation and requires minimum input data. Brown et al. (2005) showed that for catchments going from grass to forest (either eucalypt or pine), the method of Zhang et al. (2001) gave a good estimate of the change in mean annual streamflow. However, one of the limitations of Brown et al. (2006) is that the catchments used to test the FCFC model are small headwater catchments. This study further tested the method of Zhang et al. (2001) with data from 15 catchments that have undergone plantation expansions. It should be noted that the catchments used in this study are typical catchments where plantation and water resources decisions need to be made. They range in size from 0.6 to 1136 km^2, and represent different climatic conditions and plantation management practices. The results showed that predicted mean annual streamflow reductions by the method of Zhang et al. (2001) agree well with estimates using an independent method.

The FCFC model uses flow duration curve (FDC) to describe streamflow regime and this is convenient as the area under the FDC equal to the mean annual streamflow, which can be predicted by method of Zhang et al. (2001) (Brown et al., 2005). The FCFC model is sensitive to errors in the estimated change in mean annual streamflow. This is because the key parameters (the median and CTF or 95th percentile flow) are dependent on the estimated mean annual streamflow. For example, if the method of

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Zhang et al. (2001) overestimates the reduction in streamflow as the result of a forest cover change, FCFC is likely to underestimate the CTF point or 95th percentile flow. Conversely, if the method of Zhang et al. (2001) underestimates the change in mean annual streamflow, the 95th percentile flow is likely to be overestimated. However, the FCFC model can be used with estimates of mean annual streamflow change from any models or observations.

The bucket model used to adjust the low flow section of the FDC (the CTF or 95th percentile flow) aims to provide a simple procedure to adjust the percentage of time flow occurs in a catchment. The results shown in Fig. 7 indicate that the bucket model underestimated the CTF or 95th percentile flow in some catchments. It is possible that when applied to large catchments, the bucket model needs some improvement to reflect differences in baseflow response to forest cover change. Brown (2008) showed that the simple bucket model used in the FCFC does a satisfactory job of predicting the change in the CTF percentile. Adjusting the bucket for a change in land use (using the mass balance) relies on the assumption that, apart from the change in plant available water storage, there is no change in other soil properties following a change in vegetation cover. Thus, the amount of soil moisture when the soil is saturated does not change following a change in vegetation cover and the recession constant remains the same. In reality, it is possible that the soil properties will change following a change in vegetation. However, it is thought that the impact of these changes is likely to be insignificant compared to the changes in rooting depth or plant available water storage.

6 Summary

Plantation reduces streamflow volume and changes streamflow regime. Catchments with perennial streamflow in the pre-treatment periods showed relatively uniform reductions in most flows after plantation expansions, whereas catchments with ephemeral streamflow showed more dramatic reductions in low flows, leading to increased number of zero-flow days. Proportional reductions are small in high flows and large in low

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flows. However, the changes in high flow represent larger volume reductions. These changes in high and low flows following plantation development have different implications for water resources management and environmental flows. The Forest Cover Flow Change model (FCFC) was developed to adjust a time series of observed or simulated daily flow to account for significant changes in forest cover. The model assumes that the method of Zhang et al. (2001) is accurate for predicting changes in mean annual streamflow following plantation expansions and it predicts the CTF percentile or 95th percentile by solving a simple bucket model. It is also assumed that, apart from the change in plant available water storage, there is no change in other soil properties following a change in vegetation cover. FCFC is designed for hydrologists, engineers, policy makers, and managers in consultancies and state agencies involved in water resource and plantation management and planning. FCFC is only appropriate for predicting changes in streamflow following changes in forest cover and is not appropriate for other land use changes. The model is not applicable to catchments with significant irrigation or water extraction. FCFC has been validated in small catchments in Australia and South Africa. This study showed that the model is applicable to large catchments as well. This provides users with a means of identifying the change in streamflow regime due to changes in forest cover. FCFC can be used in larger catchment models to look at downstream impact of plantation expansions.

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Table 1. Summary of selected catchments for plantation impact assessment.

Catchment	Gauging Station(ID)	State	Lat	Long	Area (km^2)	Rainfall (mm)	E_0 (mm)	Streamflow (mm)	Plantation cover (%)	Calibration/ testing period
Adjungbilly Ck	Darbalara (410038)	NSW	35.02° S	148.25° E	391	1011	930	212	30.08	1933–1955/1995–2008
Batalling Ck	Batalling (612016)	WA	33.32° S	116.57° E	16.64	629	1089	33	19	1979–1984/2000–2008
Bombala River	Bombala/Falls (222019/222009)	NSW	37.00° S	149.38° E	559	783	779	181	26.8	1960–1978/1990–2000
Burnt Out Ck	(A5030529)	SA	35.13° S	138.70° E	0.6	806	1117	28	67	1978–1982/2003–2007
Crawford River	Lower Crawford (238235)	VIC	37.98° S	141.46° E	606	728	996	73	24.18	1971–1995/2004–2009
Darlot Ck	Homerton Bridge (237205)	VIC	38.15° S	141.77° E	760	688	995	78	13.3	1970–1995/2004–2009
Delegate River	Quidong (222008)	NSW	36.98° S	149.05° E	1135.7	859	726	134	14	1960–1978/1990–2000
Eumeralla River	Eumeralla (237206)	VIC	38.26° S	141.94° E	502	725	987	56	19.84	1974–1995/2001–2008
Goobarragandra Ck	Lacmalac (410057)	NSW	35.19° S	148.20° E	673	1009	952	419	8.32	1947–1955/1990–2008
Jingellic Ck	Jingellic (401013)	NSW	35.53° S	147.41° E	390	838	1018	138	27.50	1966–1980/1996–2005
Pine Ck	Broadford (405290)	VIC	37.29° S	145.05° E	3.2	629	953	37	88	1989–1991/1998–2009*
Red Hill	Red Hill (410998)	NSW	35.12° S	149.35° E	1.95	761	900	109	78	1990–1992/2001–2005*
Traralgon Ck	Koornalla (226410)	VIC	38.32° S	146.53° E	89	959	827	272	58	1958–1965/1993–1999
Upper Denmark River	Kompup (603003)	WA	34.70° S	117.22° E	243	742	1006	37	15.17	1989–1995/2004–2008
Yate Flat Ck	Woonanup (603190)	WA	33.70° S	117.29° E	56.32	742	1006	65	33.57	1989–1995/2004–2008

* The calibration periods for Pine Creek and Red Hill are defined as the first three years since plantation development.

Table 2. Relative changes in high (Q_5), median (Q_{50}), and low flow (Q_{95}) between pre-treatment and post-treatment periods.

Catchment	ΔQ_5 (%)	ΔQ_{50} (%)	ΔQ_{95} (%)
Adjungbilly Ck	−33.7	−31.7	−20.2
Batalling Ck	−23.5	−60.0	–
Bombala River	−61.2	−65.8	−99.2
Burnt Out Ck	−86.6	−100.0	–
Crawford River	−50.2	−53.1	−100.0
Darlot Ck	−51.8	−43.5	−40.7
Delegate River	−48.5	−27.2	−12.4
Eumeralla River	−49.5	−25.0	−38.7
Goobarragandra Ck	−34.6	−48.9	−62.5
Jingellic Ck	−45.1	−32.1	−38.8
Pine Ck	−94.8	−100.0	–
Red Hill	−88.1	−100.0	−100.0
Traralgon Ck	−47.4	−22.5	36.7
Upper Denmark River	−48.6	−89.8	–
Yate Flat Ck	−57.5	−58.0	–

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Table 3. Results of FCFC predictions against observations using measured change in mean annual streamflow.

Catchment	CTF predicted	CTF observed	Median predicted	Median observed	Coefficient of efficiency
Adjungbilly Ck	90	100	0.203	0.158	0.96
Batalling Ck	51	47	0.034	0.053	0.99
Bombala River	55	93	0.218	0.056	0.86
Burnt Out Ck	28	41	0.021	0.010	0.90
Crawford River	73	90	0.037	0.024	0.96
Darlot Ck	91	100	0.087	0.071	0.86
Delegate River	97	100	0.172	0.164	0.96
Eumeralla River	83	100	0.027	0.026	0.91
Goobarragandra Ck	100	100	0.705	0.537	0.94
Jingellic Ck	95	100	0.120	0.091	0.96
Pine Ck	41	43	0.01	0.02	0.99
Red Hill	47	27	0.022	0.022	0.80
Traralgon Ck	63	100	0.306	0.222	0.64
Upper Denmark	48	47	0.040	0.024	0.93
Yate Flat Ck	48	67	0.014	0.013	0.95

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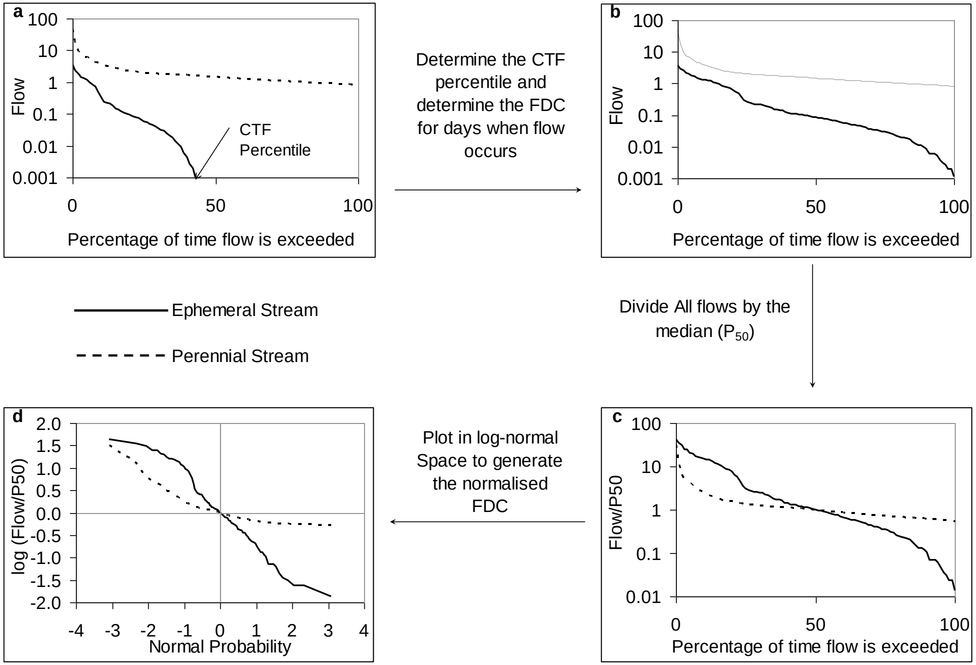

Fig. 1. Normalising the FDC to achieve common parameter space.

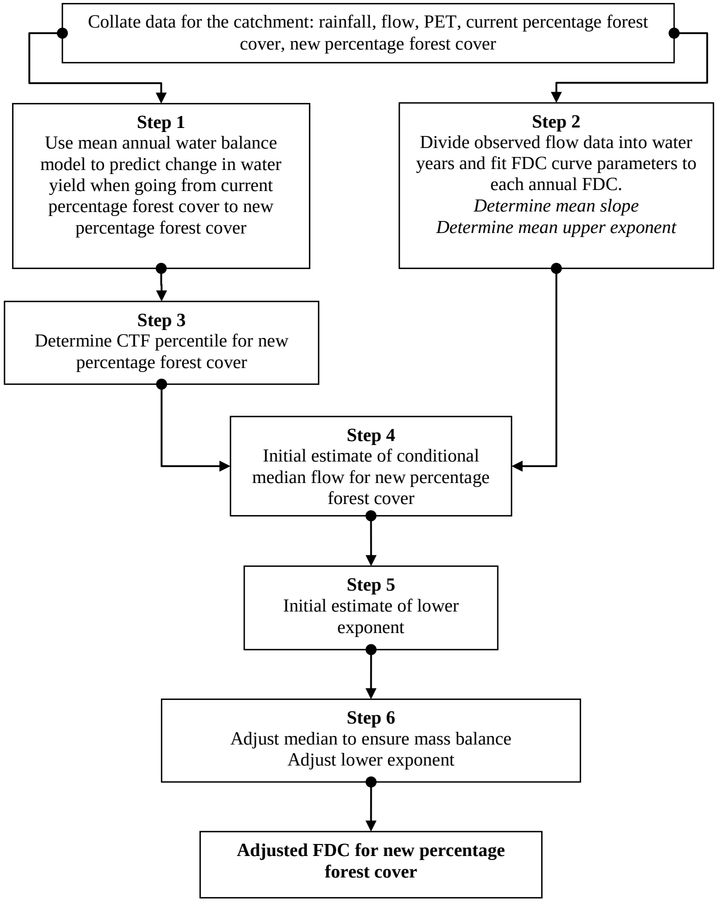

Fig. 2. Flow chart showing the key steps in adjusting the FDC for forest cover change used in the FCFC model.

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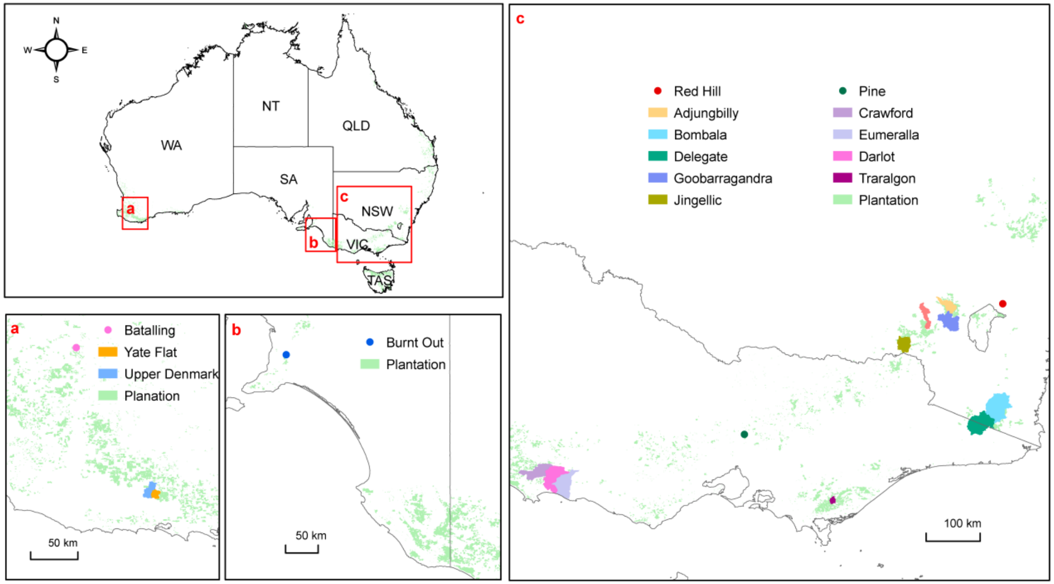

Fig. 3. Location map of the catchments.

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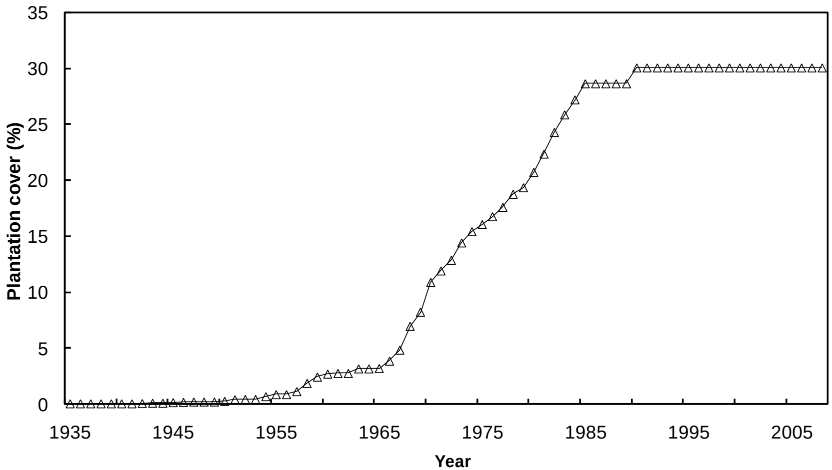

Fig. 4. Cumulative plantation cover (%) over time for the Adjungbilly Creek catchment.

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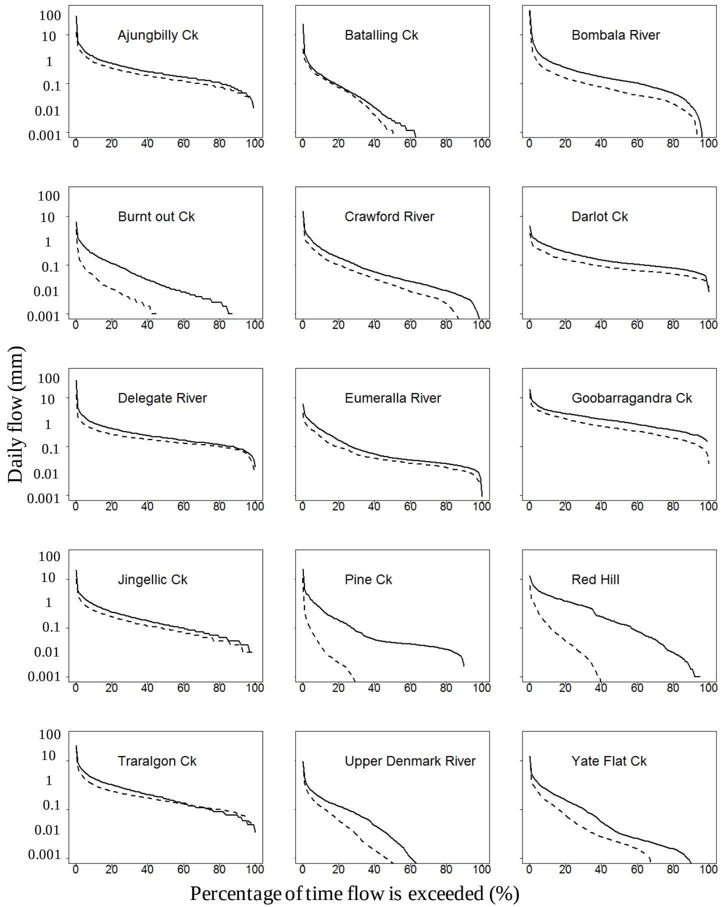

Fig. 5. Changes in daily flow duration curves for the selected catchments. The solid and dotted lines represent daily flow duration curves in the pre-treatment and post-treatment periods, respectively.

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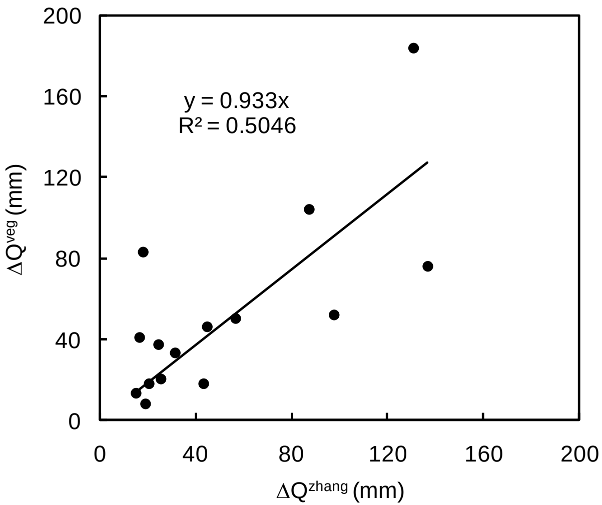

Fig. 6. Comparison between estimates of mean annual streamflow reductions using FCFC (ΔQ^{zhang}) and the time-trend analysis method (ΔQ^{veg}).

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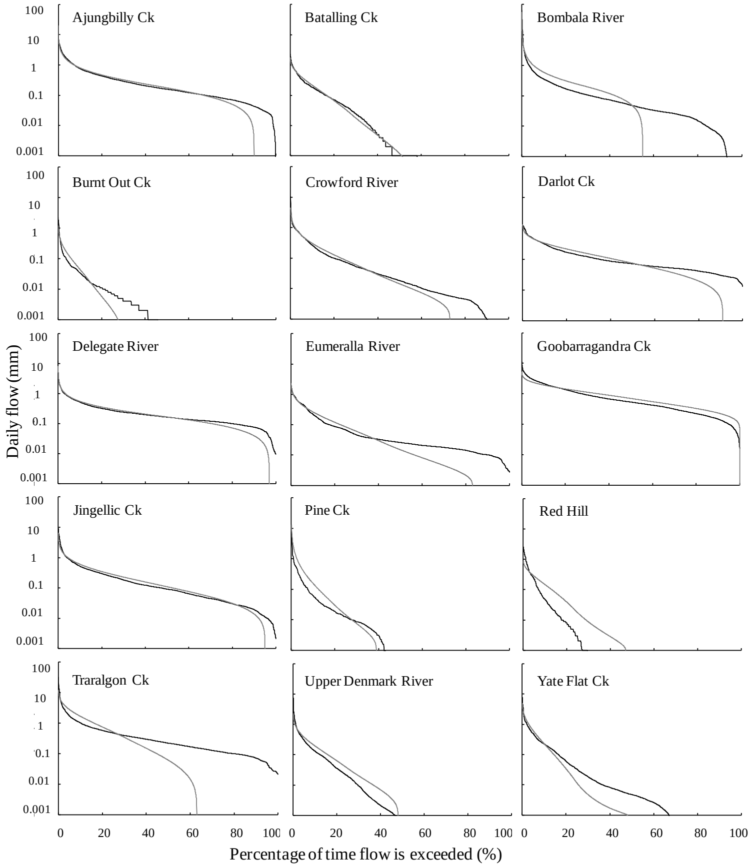

Fig. 7. Comparisons of FCFC predicted and observed flow duration curves for the selected catchments in the post-treatment period. The black lines represent observed flow duration curves, and the grey lines represent predicted flow duration curves.

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