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Impact of forest cover changes on annual streamflow and flow duration curves

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SUMMARY

The effect of forest cover changes on mean streamflow is well understood and worldwide data have shown that increasing forest cover decreases the total volume of flow at the catchment scale. However, due to the different methods used to assess the impact of forest cover at the annual and sub-annual time-scale general conclusions can be difficult to draw. In this paper, consistent methods of analysing paired catchment data are used to assess the impact of forest cover change in afforestation and deforestation experiments on annual streamflow and flow duration curves (FDCs). The results indicate that in catchments undergoing a permanent change in forest cover it takes between 8 and 25 years for a catchment to reach a new equilibrium. Analysis of FDCs showed that three types of responses could be observed. These are: catchments with changes in the number of zero flow days (response group 1), catchments with proportionally larger changes in low flows compared to high flow (response group 2), and catchment with a uniform changes in all flows (response group 3).

1. Introduction

In predicting the impact of forest cover changes on streamflow it has been shown that predictions of changes to mean annual streamflow are well supported by a range of studies (Zhang et al., 2001; Brown et al., 2005; Zhao et al., 2010; Wei and Zhang, 2010) but the predictions of changes to annual, monthly and daily streamflow become progressively more difficult (Vertessy, 1999). This is because on a mean annual basis, climatic variability and storage impacts are effectively removed by averaging streamflow over a long period. This makes it easy to compare the average streamflow between catchments under different amounts of forest cover. The review of Brown et al. (2005) discussed the fact that differences in mean annual streamflow between catchments under different amounts of forest cover do not tell the entire story about the impact of forest cover changes on streamflow.

To assess the impact of forest cover changes on streamflow at the annual and sub-annual time step it is important that catchment data are analysed using a consistent method (Watson et al., 1999). This allows results to be compared and conclusions to be drawn across the range of catchment studies. Many studies have looked at the impact of forest cover changes on streamflow at the annual time step (Kuczera, 1987; Watson et al., 1999; Scott and Smith, 1997; Hornbeck et al., 1993; Zhang et al., 2011; Chappell and Tych, 2012). However, each of these individual studies used a different method to estimate the change in annual streamflow, making it difficult to draw general conclusions. While the results of these studies all tell us that similar responses are observed for the different types of forest cover change, a consistent method of analysis is needed to ensure comparability of the results. The impact of forest cover changes at annual timescales gives us an understanding of the magnitude of the change and the time it takes for the change in streamflow to occur. However, in many instances it is also important to understand how vegetation changes impact on shorter time scales. One of the difficulties in assessing the impact of changed forest cover on streamflow at shorter time scales is the need to summarise the data in a manner that is easy to understand and captures the characteristics of the streamflow time series. The flow duration curve (FDC) provides a good means of summarising a streamflow record that comprises a number of data points, such as daily or monthly streamflow. FDCs are widely used for summarising a streamflow time series in hydrology (Vogel and Fennessey, 1995). However, very few studies assess the impact of forest cover changes on FDCs and none try to compare the results across different catchments. Studies that have looked at the impact of forest cover changes on the FDC include: Burt and Swank (1992), Hickel (2001), McLean (2001), Silberstein et al. (2004), Lane et al. (2005) and Zhang et al., 2012. As with the comparison of

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annual flows, the methods used to assess the changes in the FDC differ for each of these individual studies, making it difficult to compare the results across the range of catchments.

In this paper, consistent methods of analysing paired catchment data are used to assess the impact of permanent changes in forest cover change on annual streamflow and FDCs. The annual response and FDC analysis are undertaken to improve our understanding of the types of responses that can be expected following changes in forest cover. This paper firstly describes the method used to assess annual streamflow response and FDCs. The results of the analysis are then summarised and discussed.

2. Data

Data from 16 paired catchment studies are used in this paper. These comprise of twelve afforestation experiments (converting from pasture to forest cover) and four deforestation experiments (clearing and allowing pasture to re-establish or keeping the catchment vegetation free). Fig. 1 shows the locations of the 16 catchments, and Table 1 provides details of the experiments used here.

3. Methodology

3.1. Estimating the change in annual streamflow

The methodology outlined in Watson et al. (2001) for analysing paired catchment data using monthly data has formed the basis for the methodology used to assess the magnitude of annual streamflow changes in this paper. Monthly data were used as short pretreatment periods (2–3 years) in most paired catchment studies limit the reliability of the annual regression analyses. However, in this paper, the explicit (or deterministic) seasonal component used by Watson et al. is dropped as the inclusion of a seasonal component implies there is a difference between the control and the treated catchment that varies seasonally in a systematic manner. It was considered that, for the paired catchment studies used in this paper, there was no difference in the seasonality of the control and the treated catchment and thus the seasonal component does not add any extra value to the analysis.

Watson et al. (2001) showed that the use of a linear regression between monthly flows rarely gives homoscedastic residuals as the variance of the residuals increases as flow increases, thus transformation of the data is required to obtain homoscedastic residuals so that the significance of the change in streamflow can be determined statistically. Watson et al. (2001) adjusted for these heteroscedastic residuals by using a log/log regression of the monthly flow data. This log/log regression is appropriate in catchments where the data set contain no months of zero streamflow. The data sets used in this paper contains a number of ephemeral streams with months of zero flow data. Thus, a log/log transformation could not be used. To gain homoscedastic residuals a transformation using the fifth root has been adopted (Eq. (1)).

$$y^{\frac{1}{5}} = \alpha + \beta x^{\frac{1}{5}} + \varepsilon \quad (1)$$

Here x is the monthly flow in the control catchment, y is the monthly flow in the treated catchment and α and β are the coefficients of the regression relationship and ε is a serially correlated, zero mean, normally distributed error term. Plots of the residuals from the fifth root regression show that the residual to be homoscedastic. Eq. (1) is fitted during the control period and then used to predict flows during the treatment period. During the treatment period ε can be calculated by reorganising Eq. (1). It can be interpreted as representing the overall impact of treatment at month t.

To calculate 95% confidence intervals and determine the statistical significance of the observed change in streamflow, it is necessary to remove any auto-correlation in ε between months. This has been achieved by removing the lag-one auto regressive (AR1) component from the time series of ε leaving the 'disturbance'. Thus, the disturbance a_t is given by Eq. (2).

$$a_t = \varepsilon_t - \phi\varepsilon_{t-1} \quad (2)$$

Here, ϕ is the auto-regression parameter, estimated as the lag-one auto-correlation coefficient. The disturbance, a_t, is not a measure of the total hydrological change at month t. Rather it is the change

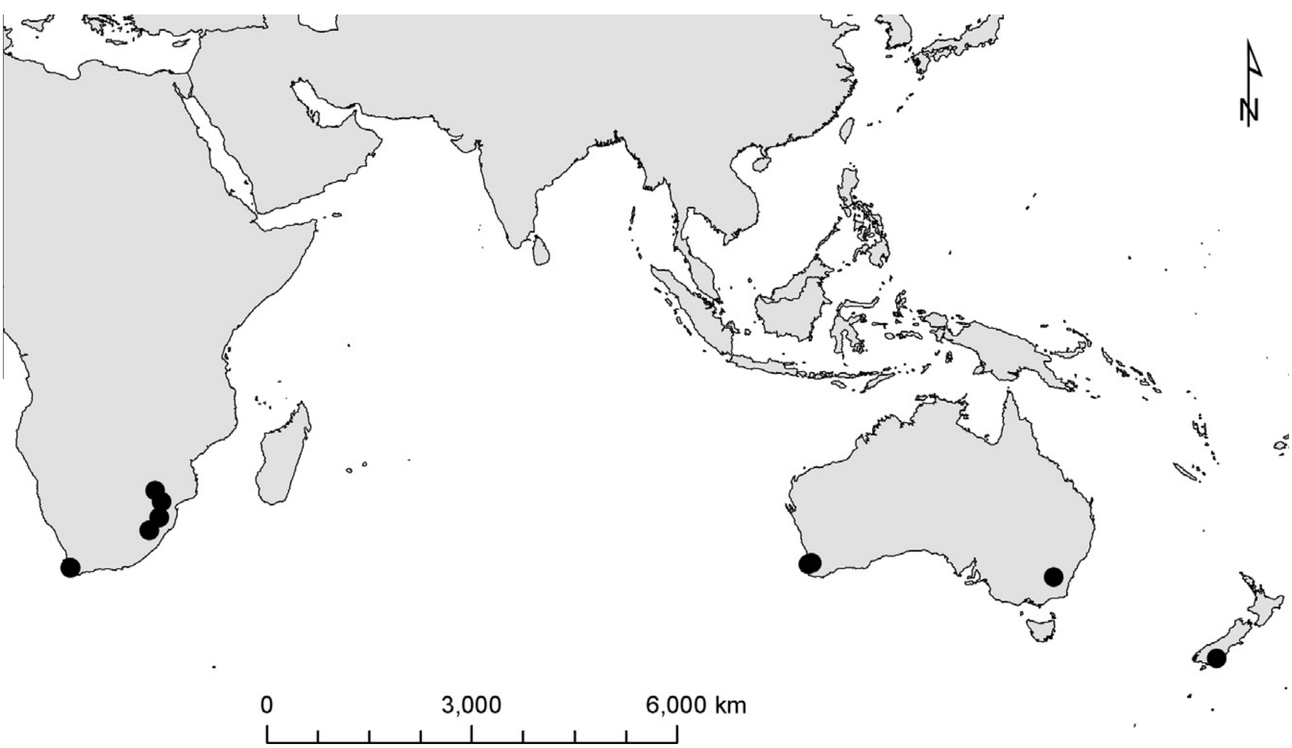

Fig. 1. Location of catchments showing 4 in Australia, 1 in New Zealand and 11 in South Africa.