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Effects of vegetation cover change on streamflow at a range of spatial scales

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Abstract: Vegetation plays an important role in controlling catchment water balance and information on the impact of vegetation cover change on streamflow can help water resources managers to develop sustainable management plans. Our understanding of the vegetation impact on streamflow is primarily based on studies from paired catchments, which are typically less than 1 km^2 in size. Can results from these catchments be applied to larger catchments where water management decisions need to be made?

This study attempts to address this issue by analyzing streamflow response to vegetation cover change for catchments ranging from 10^0 to over 10^4 km^2 in size with forest cover change from 11 to 100%. Monthly values of streamflow, rainfall, and potential evapotranspiration are available for these catchments, and also available is vegetation change history. The dynamic water balance model of Zhang et al. (2008) was used to estimate changes in streamflow in response to vegetation cover change. For afforestation experiments, the model was calibrated against streamflow for both pre-streamflow change period determined by a change-point in streamflow and pre-treatment period determined by vegetation change. For clearing experiments, alternative process of model calibration was carried out where the model was calibrated against streamflow from post-streamflow change period determined by change-point in streamflow. In both cases, the calibrated model was used to predict streamflow if no vegetation change had occurred. The difference between the predicted streamflow and the measured streamflow is attributed to the effect of vegetation change.

Results showed that the water balance model was well calibrated for both the calibration periods defined by vegetation change history and change point in annual streamflow. Estimated changes in streamflow varies linearly with percentage forest cover affected (Figure 1). A consistent relationship between streamflow change and forest cover change was observed over a spatial scale of 10^0 to over 10^4 km^2. This study also demonstrated the benefits of using pre-streamflow change records to define a calibration period and alternative process of model calibration in cleared catchments.

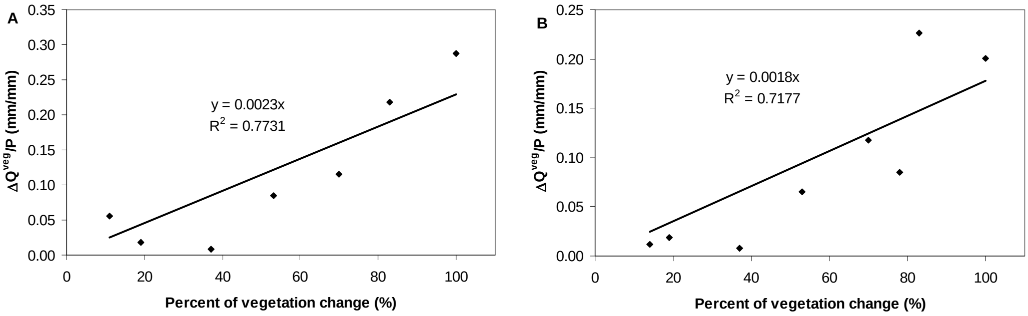

Figure 1. Relationships between normalized streamflow change ($\Delta Q^{veg} / P$) and percentage vegetation cover change. ΔQ^{veg} is streamflow change due to vegetation cover change and P is mean annual rainfall. (A) Calibration period is defined by vegetation change history, and (B) Calibration period is determined by change point in annual streamflow

Keywords: *Vegetation change, streamflow, spatial scale, water balance model*

1. INTRODUCTION

The vegetation cover changes, such as afforestation, deforestation, or forest conversion, affect runoff response of a catchment through changing the hydrological cycle of the area by altering the balance between rainfall and evaporation (Costa et al., 2003). The effect on streamflow is highly location-specific and scale-dependent (Chomitz and Kumari, 1998). McCulloch and Robinson (1993) also proposed the scale dependence of the interrelationship between forests and hydrology. Will similar results of streamflow changes emerge from larger catchments compared with small catchments following alterations of vegetation?

Small experiments (usually < 1 km^2) have demonstrated that streamflow increased following deforestation and that afforestation decreased streamflow (Bosch and Hewlett, 1982; Bruijnzeel, 1990; Sahin and Hall, 1996). Larger catchments (usually > 100 km^2) have much spatial variability tending to be a mosaic of different land uses and practices, with heterogeneous geology, topography and soils, which will moderate the integrated hydrological response (Wilk et al., 2001). The larger scale catchment studies have not found a consistent pattern of hydrological response to changes in vegetation cover. It is therefore not certain if the results from small experiments hold for larger catchments.

Madduma-Bandara and Kuruppuarachchi (1997) reported an increase in mean annual flow following land use change from forests to crop for the 1108 km^2 Mahaweli basin in Sri Lanka. Costa et al. (2003) showed results from large scale catchments (the upper Tocantins basin, 175 360 km^2) agreeing with what expected from small deforestation experiments. Siriwardena et al. (2006) showed that changes in streamflow from the Comet River catchment in Australia (16,440 km^2), agree with the deforestation effects on streamflow from small catchments. However, some studies showed results of vegetation effects on streamflow from large catchments that are not consistent with the results from small scale catchments. Gentry and Lopez-Parodi (1980) studied the Amazon River at Iquitos and suggested that the streamflow increase was mainly caused by deforestation in the upstream Andes. However, Richey et al. (1989) concluded that the primary reason for the change in streamflow from this catchment is climate variability. Qian (1983) was unable to detect notable effect on streamflow after deforestation from catchments ranging in size from 7 to 727 km^2 on the island of Hainan, China. Wilk et al. (2001) studied the 12,100 km^2 Nam Pong catchment in northeast Thailand, and could not detect trends in streamflow despite a 53% forest reduction in the last three decades.

The mail purpose of this study was to investigate the effects of vegetation cover changes on streamflow over a range of spatial scales.

2. CATCHMENTS AND DATA DESCRIPTION

In this study, a range of spatial scale catchments with the area from 10^0 to 10^4 km^2 are selected from Australia and South Africa (Figure 2). The initial criteria for selection of these catchments are a known vegetation history and streamflow records of good quality. Table 1 shows a brief description of these catchments. Most of the small catchments are paired catchments, but all the larger catchments are single catchments.

Deforestation, afforestation and reforestation occurred in these catchments with vegetation cover change from 11% to 100%. The catchments studied include wet and dry catchments with the annual rainfall ranging from 603 to 1513 mm with different seasonal distributions. Potential evapotranspiration (PET) in these catchments range from 1112 to 1942 mm, and streamflow from 28 to 697 mm, which resulting in the index of dryness varying from 0.77 to 2.94 and runoff coefficient ranging from 0.04 to 0.42.

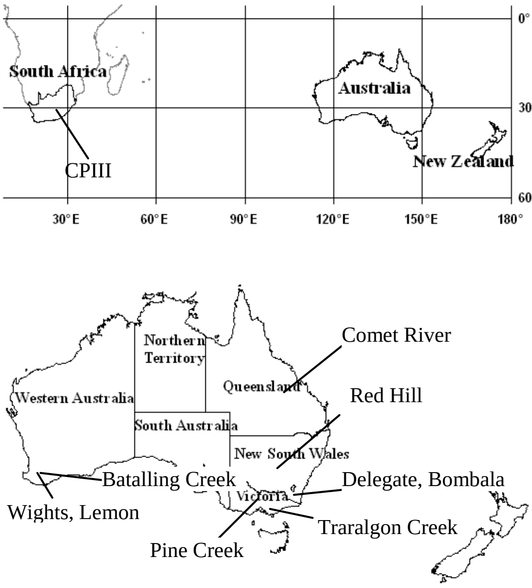

Figure 2. Location and map of the study area

Daily streamflow and rainfall data are available for these catchments. Mean monthly potential evapotranspiration (PET) was calculated using the Priestley-Taylor equation for each of the catchments (Priestley and Taylor, 1972).

Table **1**. Summary of experimental catchments

Catchment	Area (km^2)	Rainfall (mm)	Streamflow (mm)	PET (mm)	Description of treatment	Data record
Wights	0.94	961	406	1471	1976/1977, 100% clearing	1974-1997
CPIII	1.42	1519	611	1298	1958, 83% afforestation	1952/53-1980/81
Red Hill	1.95	837	109	1340	1988/1989, 78% afforestation	1990-2005
Pine Creek	3.2	623	47	1590	1986/87, 100% afforestation	1988-2003
Lemon	3.44	703	56	1436	1976/1977, 53% clearing	1974-1997
Betalling Creek	16.64	603	34	1433	1985, 19% reforestation	1976-1999
Traralgon Creek	87	1469	297	1137	Late of 1950s, 70% afforestation	1955-1998
Delegate	1135.7	859	134	1112	14% afforestation	1951-2003
Bombala	1363.5	783	199	1202	11% afforestation	1951-2003
Comet River	16400	660	28	1942	Mid-1960s, 51% clearing	1919/20-1999/00

3. METHODS

The approach adopted in this study is to calibrate a water balance model for a calibration period with a stable vegetation conditions and then to apply the calibrated model to a prediction period with changed vegetation conditions to simulate streamflow that would occur if there were no vegetation change. For the afforestation experiments, the model was calibrated against streamflow for both pre-streamflow change period determined by a change-point in streamflow and pre-treatment period determined by vegetation change as described by Zhao et al. (2009). For the clearing experiments, alternative process of model calibration was carried out where the model was calibrated against streamflow from post-streamflow change period determined by change-point in streamflow. This process overcomes the problem of short pre-clearing data for model calibration in some catchments. In both cases, the calibrated model was used to predict streamflow if no vegetation change had occurred. Table 2 lists the calibration periods and prediction periods used in this study. The difference between the predicted streamflow and the measured streamflow is attributed to the effect of vegetation change.

The dynamic water balance model of Zhang et al. (2008) was used in this study. The model has four parameters and simulates streamflow from monthly rainfall and areal potential evapotranspiration data. The model has been applied to 265 catchments in Australia with the area between 50 to 2000 km^2, and the results indicates that the model has the potential to be used to investigate vegetation effects on streamflow (Zhang et al., 2008). The schematic diagram of the dynamic water balance model is shown in Figure 3.The model was calibrated against recorded streamflow at monthly time scale. A generalized pattern search method was applied for parameter optimization.

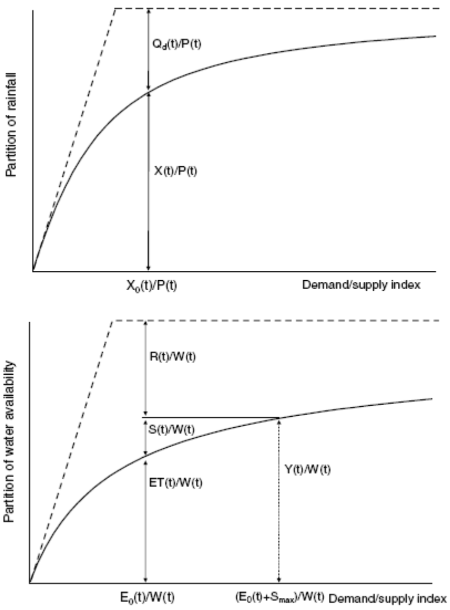

Figure 3. The schematic diagram of the dynamic water balance model (Zhang et al., 2008)

Table 2. Calibration and prediction periods determined by vegetation change (A) and change-point in annual streamflow (B).

	Catchment	Calibration period	Prediction period
A	Wights	1981-1994	1974-1977
	CPIII	1954/55-1958/59	1967-1980
	Lemon	1988-1994	1975-1977
	Batalling Creek	1978-1984	1990-1999
	Traralgon Creek	1957-1965	1979-1999
	Bombala	1962-1979	1990-2000
	Comet River	1970/71-1999/00	1919/20-1948/49
	Catchment	Calibration period	Prediction period
B	Wights	1981-1994	1974-1980
	CPIII	1954/55-1966/67	1967-1980
	Red_Hill	1992-1996	1997-2005
	Pine Creek	1991-1993	1994-2003
	Lemon	1988-1994	1975-1987
	Traralgon Creek	1957-1978	1979-1999
	Delegate@Quidong	1962-1978	1990-2000

4. RESULTS

The dynamic water balance model works reasonably well for most of the catchments. The coefficient of efficiency ranges from 0.50 to 0.90. Varying degrees of scatter and comparison between the simulated and observed streamflow over the calibration period for Wights catchment is shown in Figure 4. The coefficient of efficiency is 0.90. It is clear that the model can be well calibrated against the recorded streamflow.

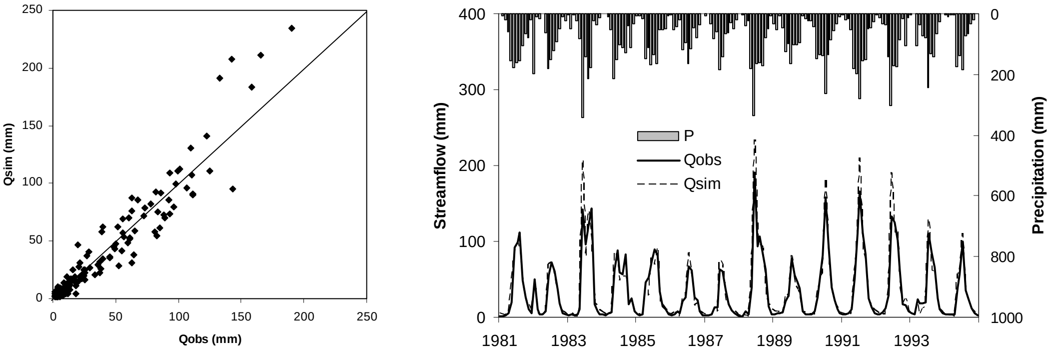

Figure 4. Comparison of observed and simulated monthly streamflow in the calibration period for Wights

For all the catchments in this study, the predicted annual streamflow was higher than the observed in the prediction period, i.e. the streamflow showed reduction following vegetation changes in the prediction period, as shown in Figure 5. Considering the alternative process for model calibration in the clearing catchments, increased streamflow was shown following clearing. Therefore, the effects of afforestation and clearing on streamflow in a range of catchments with area from 10^0 to over 10^4 km^2 support the conclusion obtained from small experimental catchments that forest clearing increase streamflow and afforestation results in decrease in streamflow.

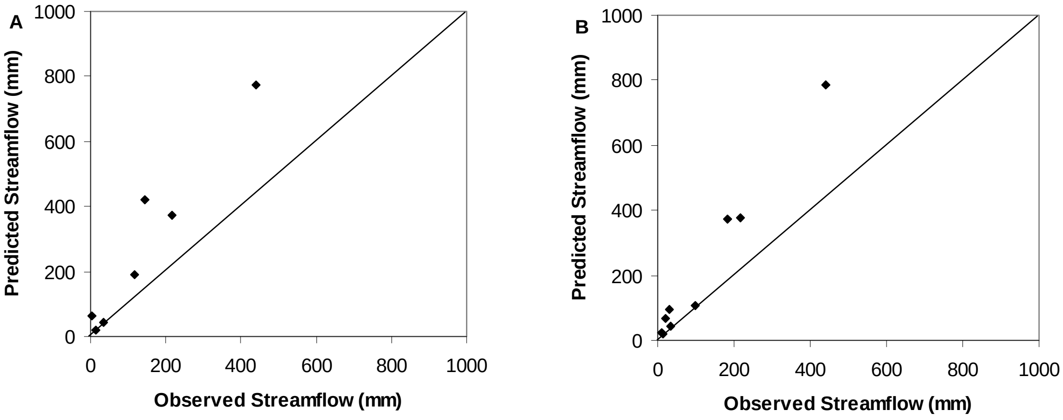

Figure 5. Comparison of observed and predicted mean annual streamflow in the prediction period for all the catchments

The vegetation effects calculated for small catchments (i.e. Wights, CPIII, Lemon, and Red Hill) using the dynamic water balance model are compared with results obtained using the paired catchment method and other single catchment methods in Zhao et al. (2009) (see Table 3). Different methods give consistent results of vegetation effects for the four small catchments. The average vegetation effects on streamflow for the four small catchments are 91%, 87%, 85% and 49%, respectively. These results can be well explained by the vegetation change history and climate variability.

Figure 6 quantitatively presents the vegetation effects on streamflow in different catchments, i.e. the mean annual streamflow changes due to vegetation change (ΔQ^{veg}). The vegetation effects on streamflow are also expressed as the mean annual streamflow changes standardized by the mean rainfall ($\Delta Q^{veg} / P$), and the annual average observed streamflow in the calibration period ($\Delta Q^{veg} / Q^{obs}_{cali}$) to provide general assessment of vegetation effect. The results indicate that the relationship between the proportion of a catchment that is afforested or cleared and the resultant effects on streamflow is linear no matter whether the calibration period was determined by vegetation change or streamflow change. The vegetation effects on streamflow estimated for larger scale catchments are consistent with what would be expected for small catchments.

Table 3. Effects of vegetation changes on mean annual streamflow across catchments using different estimation methods (%)

Catchments	A				B				Average
	Method 1	Method 2	Method 3	Method 4	Method 1	Method 2	Method 3	Method 4	
Wights	100	98	89	90	81	94	91	86	91
CPIII	80	57	84	73	100	100	100	102	87
Lemon	75	98	78	84	72	100	92	81	85
Red Hill	-	-	-	-	42	27	71	57	49

Note: 1) Method 1 is the dynamic water balance model used in this study.
2) Method 2, 3, and 4 are the paired catchment method, time-trend analysis method, and sensitivity-based method, respectively.
3) The results for Method 2-4 are from Zhao et al. (2009).

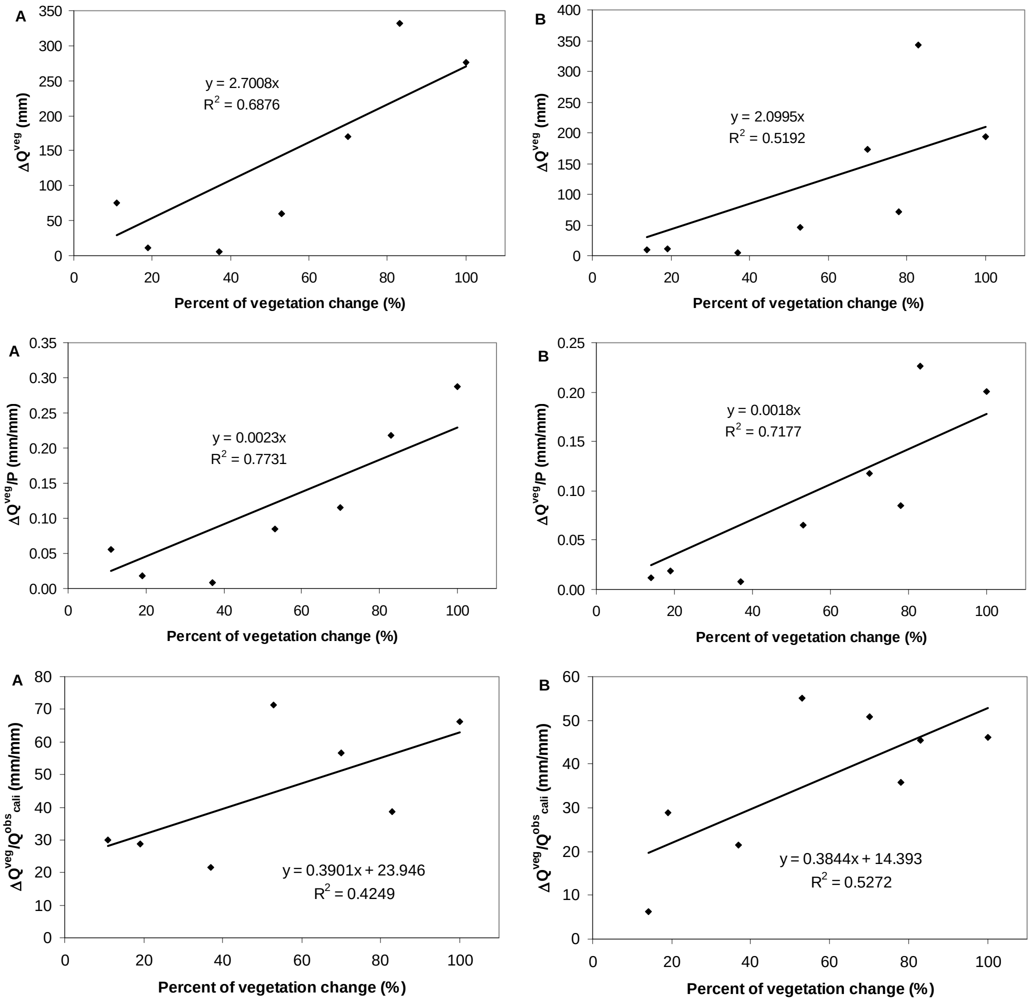

Figure 6. Mean annual streamflow changes due to vegetation change (ΔQ^{veg}), normalized streamflow change by mean rainfall ($\Delta Q^{veg} / P$), and normalized streamflow change by annual average observed streamflow in the calibration period ($\Delta Q^{veg} / Q_{cali}^{obs}$), plotted against percentage vegetation cover change.

5. DISCUSSION AND CONCLUSIONS

Studies in small scale catchments (< 1 km^2) showed increased streamflow following clearing of forest cover and decreased streamflow after establishment of forest cover. One of the advantages of these catchment studies is that the most experimental conditions can be tightly controlled (Bosch and Hewlett, 1982). Bosch and Hewlett (1982) suggested that a linear relationship may exist between the maximum increases in streamflow during the first five years and the percentage reduction in the vegetation cover for the clearing experiments, and equivalently between the maximum decreases in streamflow following afforestation and the increase percentage of vegetation cover for the afforestation catchments. This study showed that streamflow change following vegetation change occurs not only in small catchments but also in larger catchments. The magnitude of streamflow change following vegetation change observed for small catchments are also found in larger catchments. From this point of view, the results from small catchments provide useful information on the potential effect of vegetation cover change on streamflow in larger catchments where management decisions are more relevant.

Effects of vegetation change on streamflow may be difficult to discern especially in large catchments because of non-uniform landuse, different stages of regeneration, and spatial variations in rainfall (Bruijnzeel, 2003; Costa et al., 2003; Siriwardena et al., 2006). Those studies show no detectable vegetation effects on streamflow from large cleared catchments may be due to the fact that regeneration occurred in the catchments that may have offset the effects of clearing on streamflow (Bruijnzeel, 1990; Wilk et al., 2001). However, for the Comet River (16,400 km^2), the clearing was mainly carried out in the valley areas closer to the river and downstream stretches of the tributaries, resulting in increased cropping and grazing activities in cleared area (Siriwardena et al., 2006). Thus the regeneration after clearing has largely been controlled and the vegetation effect on streamflow is consistent with the results from small catchments. Delegate and Bombala catchments have been affected significantly by high water use plantations in upland areas, and estimated vegetation effects on streamflow are consistent with those obtained from small catchments.

The results show in Figure 6 indicate that the dynamic water balance model yield consistent estimates vegetation effect on streamflow when calibrated using pre-treatment period and pre-streamflow change period. This confirmed the choice of calibration period based on the change point in annual streamflow analyzed in Zhao et al. (2009). Applicability of the alternative process of model calibration using streamflow records in the post-streamflow change periods as the calibration condition gives consistent estimates of vegetation effects from the cleared catchments (Wights, Lemon and Comet River) with the results from Zhao et al. (2009) and Siriwardena et al. (2006). The use of alternative process to define the calibration period is shown to be appropriate. The practical advantage of using this alternative process is that it provides an objective way for calibrating model for catchments with short pre-treatment records.

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