Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Hydrology 310 (2005) 28–61
Journal of Hydrology
www.elsevier.com/locate/jhydrol

A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation

Alice E. Brown[a,*], Lu Zhang[b,1], Thomas A. McMahon[c,2], Andrew W. Western[c,3], Robert A. Vertessy[b,4]

[a]*Department of Civil and Environmental Engineering, The University of Melbourne, Cooperative Research Centre for Catchment Hydrology, CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia*
[b]*Cooperative Research Centre for Catchment Hydrology, CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia*
[c]*Department of Civil and Environmental Engineering, Cooperative Research Centre for Catchment Hydrology The University of Melbourne, Vic. 3010, Australia*

Received 6 August 2003; revised 6 December 2004; accepted 17 December 2004

Abstract

Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes resulting from changes in vegetation. This review focuses on the use of paired catchment studies for determining the changes in water yield at various time scales resulting from permanent changes in vegetation. The review considers long term annual changes, adjustment time scales, the seasonal pattern of flows and changes in both annual and seasonal flow duration curves. The paired catchment studies reported in the literature have been divided into four broad categories: afforestation experiments, deforestation experiments, regrowth experiments and forest conversion experiments. Comparisons between paired catchment results and a mean annual water balance model are presented and show good agreement between the two methodologies. The results highlight the potential underestimation of water yield changes if regrowth experiments are used to predict the likely impact of permanent alterations to a catchment's vegetation. An analysis of annual water yield changes from afforestation, deforestation and regrowth experiments demonstrates that the time taken to reach a new equilibrium under permanent land use change varies considerably. Deforestation experiments reach a new equilibrium more quickly than afforestation experiments. The review of papers reporting seasonal changes in water yield highlights the proportionally larger impact on low flows. Flow duration curve comparison provides a potential means of gaining a greater understanding of the impact of vegetation on the distribution of daily flows.

Keywords: Land-use impacts; Flow regime; Forest hydrology; Water yield; Paired catchments; Flow duration curves

* Corresponding author. Tel.: +61 2 6246 5838; fax: +61 2 6246 5845.
E-mail addresses: alice.Brown@csiro.au (A.E. Brown), lu.zhang@csiro.au (L. Zhang), t.mcmahon@civenv.unimelb.edu.au (T.A. McMahon), a.western@civenv.unimelb.edu.au (A.W. Western), rob.vertessy@csiro.au (R.A. Vertessy).
[1] Tel.: +61 2 6246 5802; fax: +61 2 6246 5845.
[2] Tel.: +61 3 8344 7731; fax: +61 3 8344 6215.
[3] Tel.: +61 3 8344 7305; fax: +61 3 8344 6215.
[4] Tel.: +61 2 6246 5790; fax: +61 2 6246 5845.

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2004.12.010

1. Introduction

Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes resulting from changes in vegetation. A number of review articles have summarised the results of these studies. Bosch and Hewlett (1982) reviewed catchment experiments to determine the effect of vegetation change on water yield. Two types of experiments were reviewed, paired catchment studies and time-trend studies that provide circumstantial evidence of the influence of catchment management on water yield. Since 1982, a number of additional paired catchment studies have been reported in the literature. The results of some of these studies have been summarised in the subsequent reviews of Hornbeck et al. (1993), Stednick (1996) and Sahin and Hall (1996). Vertessy (1999, 2000) reviewed the available literature on paired catchment studies with respect to forestry and streamflow. These two reviews provide a comprehensive summary of the present understanding of the impact of vegetation change on water yield, with particular reference to Australian conditions.

This paper focuses on the impact of vegetation changes on water yield at different temporal scales. Firstly, at the mean annual time scale results from previous paired catchment reviews are compared to a mean annual water balance model of Zhang et al. (2001), known as the 'Zhang curves'. The Zhang curves were derived from both paired catchment and time-trend studies and were developed to predict the impacts of permanent vegetation changes on evapotranspiration and water yield at the catchment scale. The adjustment time or time to reach a new equilibrium is then assessed for the different types of paired catchment experiments. This helps in understanding how responses between permanent and transient vegetation changes differ. A summary of papers presenting seasonal changes in water yield is then provided in terms of responses observed in different climatic zones. However, it is important to note that the magnitude of mean annual change, the adjustment time and seasonal response do not tell the whole story in relation to the impact of vegetation change on water yield. For many water resource management issues it is necessary to have an understanding of how vegetation will influence the distribution of daily flows or the flow duration curve (FDC). This paper uses the FDC as a means of displaying how alterations to a catchment's vegetation can affect the distribution of flows. The effects of vegetation changes on the FDC are presented at both mean annual and seasonal temporal scales. This review includes 72 paired catchment studies in addition to those reviewed by Bosch and Hewlett (1982) bringing the total number of paired catchment experiments reviewed to 166. Details of the additional 72 paired catchments can be found in Appendix A.

2. Paired catchment studies

Paired catchment studies involve the use of two catchments with similar characteristics in terms of slope, aspect, soils, area, climate and vegetation located adjacent or in close proximity to each other. Following a calibration period, where both catchments are monitored, one of the catchments is subjected to treatment and the other remains as a control. This allows the climatic variability to be accounted for in the analysis. The changes in water yield can then be attributed to changes in vegetation. The paired catchment studies reported in the literature can be divided into four broad categories:

1. Afforestation experiments—conversions of shorter vegetation (e.g. pasture) to forest. Examples can be found in South Africa (Scott et al., 2000), New Zealand (McLean, 2001), Australia (Hickel, 2001) and the United Kingdom (Kirby et al., 1991; Johnson, 1991).
2. Regrowth experiments—these look at the effects of forest harvesting where regrowth is permitted. Experiments in this category constitute the majority of the paired catchment studies worldwide. They involve the removal of vegetation from a percentage of a catchment followed by regrowth of the same vegetation type (Stednick, 1996).
3. Deforestation experiments—the conversion of densely vegetated land to grass or pasture. The Collie catchments in Western Australia (Ruprecht and Schofield, 1989, 1991a,b; Ruprecht et al., 1991; Schofield, 1991) are an example.
4. Forest conversion experiments—the replacement of one forest type with another. This includes the conversion from softwood to hardwood, deciduous

to evergreen or pine to eucalypt. Stewarts Creek experiment provides an example of the conversion of native vegetation to pine in Victoria, Australia (Mein et al., 1988; Nandakumar, 1993).

The paired catchment experiments reviewed by Bosch and Hewlett (1982), Whitehead and Robinson (1993), Sahin and Hall (1996) and Stednick (1996) focused mainly on regrowth experiments, where harvesting of forests is undertaken followed by the regrowth of the same vegetation type. While the activities involved in regrowth of vegetation may affect the short term water yield, permanent vegetation changes such as afforestation and deforestation are likely to have a much greater long term impact on streamflow and the associated issues, such as salinity and water resource security.

Vertessy (1999) highlighted some of the problems with using regrowth experiments for estimating water yield increases as a result of permanent vegetation change. Where forests are permitted to regenerate, only data obtained in the first few years following treatment are used to build the relationships between percentage changes in cover and change in water yield. This is because data in subsequent years are affected by regrowth and are not representative of the water yield under a new vegetation type. Three problems were highlighted in relation to the use of such data:

1. it takes time for a catchment to adjust its runoff behaviour following vegetation change;
2. soil compaction and disturbance during logging and regeneration burning can temporarily increase overland flow and change the pattern of streamflow; and
3. due to the short data set used to build the linear relationships predicting water yield change, natural variability in the water yield due to climatic variability may have a strong influence on the results.

Various methods have been applied in the analysis of paired catchment data to assess the impacts of vegetation changes on water yield at various time scales. The most common method is to produce a linear regression between the annual discharges from the control and treated catchments during the calibration period (Hornbeck et al., 1993). The regression equation is then used to predict the water yield that would have occurred in the treated catchment if the treatment had not taken place. The difference in the observed and the predicted streamflow is then assumed to be due to vegetation change as this method provides a control over climatic variability (Bari et al., 1996). Although this approach is most commonly used with annual data, it has also been used with monthly data and the quick flow and baseflow components of streamflow (Bari et al., 1996).

South Africa has a very comprehensive set of paired catchment studies that have been used to assess the impacts of afforestation on water yield. A significant amount of literature is available on these catchments and a number of different methods have been used to assess the impacts of afforestation on water yield at an annual scale. The latest South African work is summarised in Scott et al. (2000) and provides details of all the afforestation experiments undertaken in South Africa. To predict the impact of afforestation on annual streamflow and the change in water yield with time due to development of plantations, Scott and Smith (1997) developed an empirical model that predicts the percentage reduction in water yield with time.

Seasonal or monthly analysis of paired catchment data is less common than annual analysis. Typically, linear regression of monthly data during the calibration period (making no adjustments for the serial correlation) is used to establish pre-treatment relationships between the control and the treated catchments. Lane and Mackay (2001) adopted this method to analyse the Tantawangalo Creek catchments in New South Wales as insufficient annual data were available during the pre-treatment period to develop annual relationships. Scott and Lesch (1997) also used monthly data in their analysis of the Mokobulaan experimental catchments in South Africa. To adjust for the changes in soil water storage between months, Scott and Lesch (1997) used both streamflow and rainfall data as independent variables in a monthly multiple regression model. The rainfall term used was an antecedent wetness index incorporating the previous month's wetness index and the rainfall in the present month. Their analysis considered annual flows as well as wet and dry season flows.

Watson et al. (2001) developed an improved method to assess the water yield changes from paired catchment studies and applied these to the Maroonhdah experimental catchments in Victoria, Australia. They argued that the short pre-treatment periods in most paired catchment studies limits the reliability of the annual regression analyses and instead recommended the use of monthly data with an explicit seasonal component. The advantage of using monthly data is that there are 12 times as many data points, than in the analysis of annual data. However, it is important to note that while the use of monthly data represents more information, if the monthly serial correlation is significant, it does not represent 12 times the information in the annual data.

Water yield changes from paired catchment studies have been reported in the literature at mean annual, annual and mean seasonal or mean monthly temporal scales. The following sections on mean annual water yield, response times, mean seasonal water yield, and flow duration curves summarise the use of paired catchments for assessing the impacts of vegetation changes on water yield and flow regime. Specific examples from Australia, South Africa and New Zealand are used to highlight some of the conclusions that can be drawn about permanent vegetation change from paired catchment studies.

3. Mean annual water yield

A number of reviews have been undertaken to draw generalisations from paired catchment studies, particularly in reference to the changes in water yield resulting from changes in forest cover. The first of these reviews was by Hibbert (1967). Thirty nine experimental catchments were reviewed and the following conclusions were drawn:

- reduction in forest cover increases water yield;
- establishment of forest cover on sparsely vegetated land decreases water yield; and
- the response to treatment is highly variable and, for the most part, unpredictable.

In 1982, Bosch and Hewlett undertook a further review of paired catchments. In order to include afforestation experiments in their analysis, they assumed that the maximum decrease in water yield was analogous to the maximum increase in water yield during the first 5 years after treatment for deforestation experiments. This allowed general conclusions to be drawn about the impact of forest cover on water yield. The use of maximum increase in water yield in the first 5 years after treatment may bias the results because the maximum increase is likely to be affected by climate variability and the assumption that adjustment in water yield occurs in less than 5 years from the time of treatment. In reviewing 94 experimental catchments, they concluded:

- reducing forest cover causes as increase in water yield;
- increasing forest cover causes a decrease in water yield;
- coniferous and eucalypt cover types cause ~40 mm change in annual water yield per 10% change in forest cover;
- deciduous hardwoods are associated with ~25 mm change in annual water yield per 10% change in cover;
- brush and grasslands are associated with a ~10 mm change in annual water yield per 10% change in cover;
- reductions in forest of less than 20% apparently cannot be detected by measuring streamflow; and
- streamflow response to deforestation depends on both the mean annual precipitation of the catchment and on the precipitation for the year under treatment.

The reviews of Hibbert (1969) and Bosch and Hewlett (1982) mainly focused on catchments from temperate zones. Bruijnzeel (1988) looked at the impacts of vegetation changes on water yield, particularly dry season flows in the tropics. From this work, it was concluded that:

- surface infiltration and evapotranspiration associated with the representative types of vegetation play a key role in determining what happens to the flow regime after forest conversion;
- if infiltration opportunities after forest removal decrease to the extent that the amount of water leaving an area as quick flow exceeds the gain in

baseflow associated with decreased evapotranspiration, then diminished dry season flows will result;

- if surface infiltration characteristics are maintained the effect of reduced evapotranspiration after clearing will show up as an increase in baseflow; and
- the effect of reforesting will not only reflect the balance between changes in infiltration and evapotranspiration, but will also depend on the available water storage capacity of the soil.

The conclusion that under deforestation either a decrease or an increase in baseflow may occur seems to conflict with many of the results of paired catchment studies in temperate zones, in which increases in baseflow are almost uniformly observed (Hornbeck et al., 1993). This increase in baseflow is also observed in the tropical catchments in Africa. Blackie and Edwards (1979) observed increases in baseflow in cultivated catchments compared to forested catchments. However, in these catchments there were no long term changes in the infiltrations rates. These results highlight that different process responses can cause similar changes in mean annual water yield. The water yield changes can be the result of changes surface runoff, changes in baseflow or changes in both baseflow and surface runoff. The process changes resulting from alterations in vegetation have important seasonal implications. For example, in the Konta area, east Java, forest clearing for dry-land agriculture and urbanisation has resulted in decreased infiltration, which has increased surface runoff and reduced recharge. This has resulted in lower baseflow during the dry season and higher flow during the wet season (Bruijnzeel, 1988). In Mbeya, Tanzania, the difference in streamflow between a forested and cultivated catchment are primarily due to the differences in dry season transpiration, with little or no change in the surface runoff as infiltration rates have remained unchanged (Edwards, 1979). These seasonal responses are discussed further in Section 5.

Reviews by Stednick (1996) and Sahin and Hall (1996) expanded on the work by Bosch and Hewlett (1982). Stednick (1996) reviewed results of studies from the United States and looked only at annual water yield changes as a result of timber harvesting. The focus was on the effect of the percentage of area treated to detect changes in streamflow. Different hydrologic areas were defined based on temperature and precipitation regimes and it was concluded that:

- in general, changes in annual water yield from forest cover reductions of less than 20% of the catchment could not be detected by streamflow measurement; and
- rationalisation of data suggested this valued might change depending on the temperature and precipitation of the area. For example, a measurable increase in streamflow is observed for treatments of 15% of the catchment area in the Rocky Mountains compared with the Central Plains over 50% of the catchment area needs to be treated before changes in water yield can be detected.

The conclusion that at least 20% of a catchment needs to be treated before detectable changes in water yield occur agrees with the conclusions of Bosch and Hewlett. However, while the changes in water yield for treatment areas of less than 20% are not be statistically detectable, at the larger catchment scale it is often important to be able to predict the changes in water yield when less then 20% of the catchment is treated. This difference between being able to make predictions and being able to detect the changes is important to consider when using results for predictions.

Sahin and Hall (1996) used a similar approach to Bosch and Hewlett (1982) in their analysis of 145 experimental catchments in dividing the vegetation types into broad categories (hardwood, conifer, conifer-hardwood, eucalypts, rainforest, scrub and grassland). However, instead of using the maximum increase in water yield in the first 5 years after treatment, they used the average water yield changes in the first 5 years after treatment. Using fuzzy linear regression analysis, they concluded that for a 10% reduction in:

- conifer-type forest, water yield increased by 20–25 mm;
- eucalypt forest, water yield increased by 6 mm;
- scrub, water yield increased by 5 mm; and
- deciduous hardwoods increased water yield by 17–19 mm.

As expected these estimates are lower than those of Bosch and Hewlett (1982) where the maximum change in water yield in the first 5 years after treatment were used. The use of maximum increase will lead to higher estimate of the reduction in water yield as opposed to the same analysis performed with average increases. The use of maximum increase is also likely to be driven by climate variability as the maximum increase will generally correspond to the year of greatest rainfall. However, if average values are used the results are potentially impacted by regrowth vegetation after clearing and the adjustment time scales associated with vegetation changes.

Fig. 1 shows the results of the Bosch and Hewlett (1982), Stednick (1996) and Sahin and Hall (1996) plus the additional catchments included in this review. The predicted water yield changes from Bosch and Hewlett (1982) and Sahin and Hall (1996) are also depicted as dotted and solid lines, respectively. The data have been divided into four broad vegetation types, conifers, eucalypts, hardwoods (these catchments are primarily from the Northern Hemisphere and include deciduous vegetation types) and scrub (remaining catchments, usually shorter vegetation types). Some of the within group variability shown in Fig. 1 can be explained by the difference in mean annual rainfall (MAR) of the catchments. Fig. 2 shows the results for each of the experiments (scaled to 100% of area treated) against the MAR. From a similar plot, Bosch and Hewlett (1982) concluded that water yield changes are greatest in high rainfall areas. The results for the different vegetation types for all studies in this review support this conclusion.

While paired catchments provide a means of comparing the response of water yield to different treatments and vegetation types, methodologies are

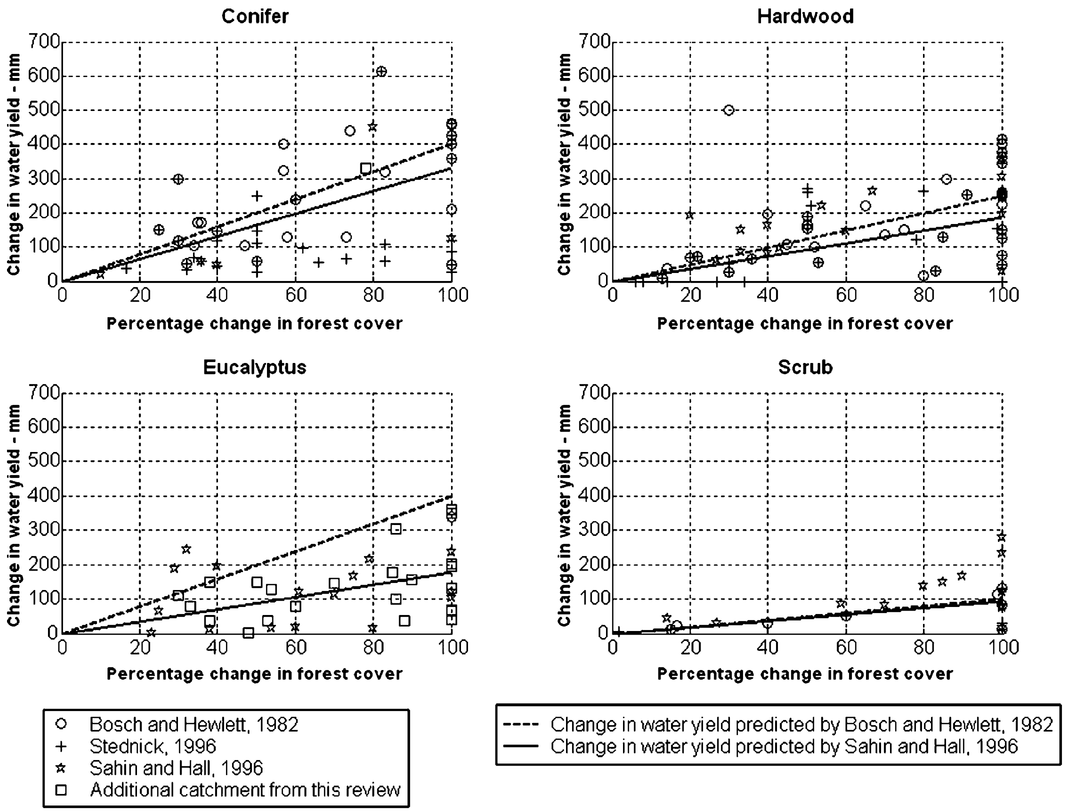

Fig. 1. Water yield changes as a result of changes in vegetation cover from Bosch and Hewlett (1982), Sahin and Hall (1996) and Stednick (1996). Results from Bosch and Hewlett and Stednick represent the maximum increase in the first 5 years after treatment for deforestation, regrowth and forest conversion experiments or maximum change in water yield for afforestation experiments. The results from Salin and Hall are the average increases in water yield in the first 5 years after treatment.

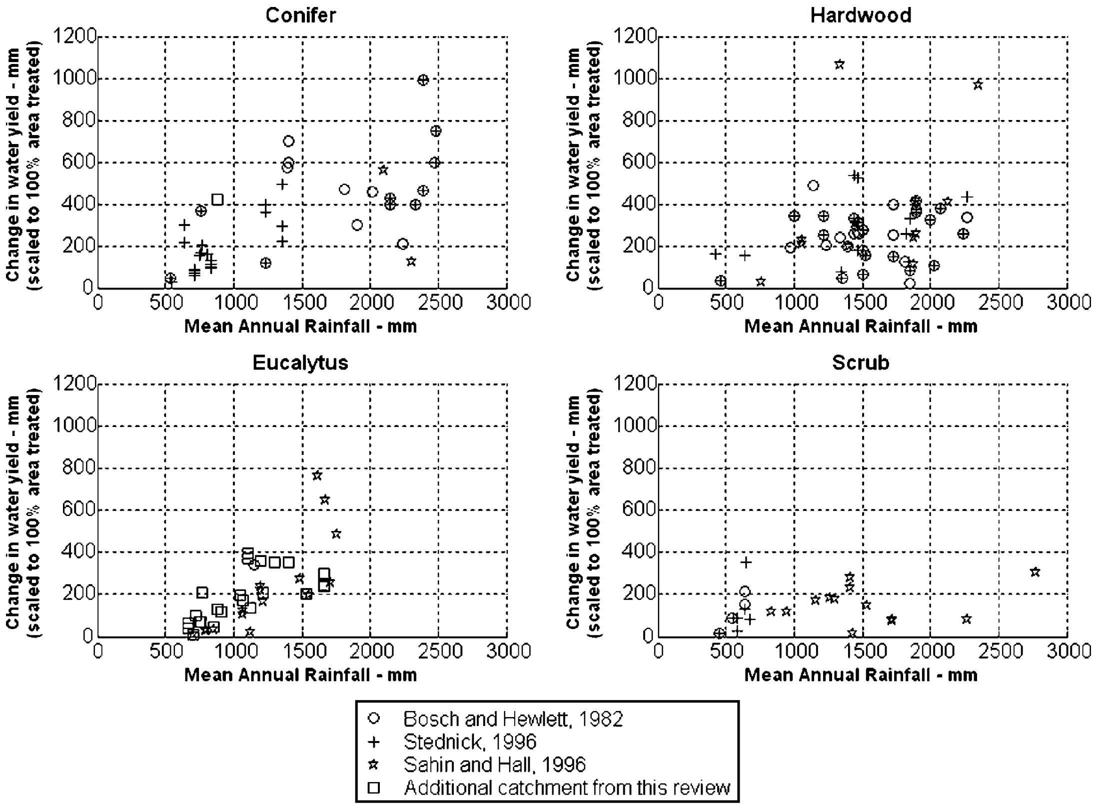

Fig. 2. Distribution of water yield changes (scaled to 100% change in cover) a function of mean annual rainfall for the studies shown in Fig. 1.

required that allow prediction of the effects of permanent changes in vegetation. These predictions have to be based on both available data and a good understanding of the processes impacted by the vegetation change.

The main process responsible for changes in water yield as a result of alterations in vegetation at the mean annual scale is evapotranspiration (Zhang et al., 2001; Holmes and Sinclair, 1986; Turner, 1991). Holmes and Sinclair (1986) used the relationship between mean annual evapotranspiration and mean annual rainfall to predict the increase in water yield when converting from forest to grass in a catchment. Their results were based on a series of catchments in Victoria, Australia. When assessing the mean annual changes in water yield, the storage change term in the water balance is small compared with the other terms, hence the change in runoff can be predicted from the change in evapotranspiration. Zhang et al. (1999, 2001) expanded on the work by Holmes and Sinclair (1986) by analysing results from 250 studies worldwide. Using a pair of curves to illustrate the difference in evapotranspiration under different vegetation types along a rainfall gradient, Zhang et al. (2001) developed a simple two parameter model to estimate the mean annual evapotranspiration at the catchment scale for two broad vegetation types, forest and grass. Fig. 3 shows the Zhang curves and the data points used to derive these generalisations. The difference between the grass and forest curve represents the change in mean annual water yield for a 100% change in vegetation for a given mean annual rainfall. It should be noted that both paired catchments and time-trend studies were used in the derivation of the Zhang curves.

Fig. 4 provides a comparison of the expected water yield changes predicted by the Zhang curves and results from paired catchment studies. While paired catchment studies were used in the derivation of

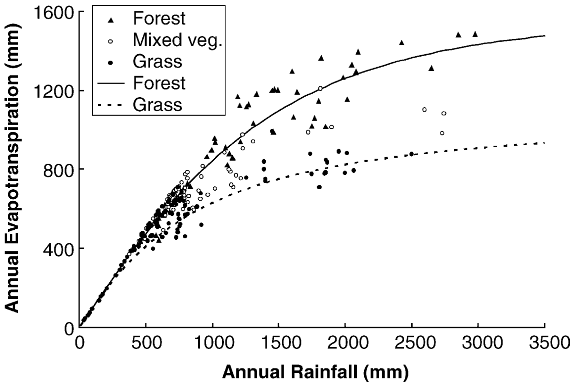

Fig. 3. Relationship between land cover, mean annual rainfall and mean annual evapotranspiration (Zhang et al., 2001).

the Zhang curves, Zhang et al. used only mean annual values from periods when the catchments were considered to be in equilibrium. Zhang only included both the pre- and post-treatment data for one of the paired catchments (Coweeta 17) analysed here. Therefore, it was not considered necessary to remove common catchments for this comparison. There is general agreement between the model and the paired catchment results, particularly for the conifer and eucalypt catchments. The large amount of scatter in the hardwood (deciduous and mixed) catchments (Figs. 2 and 4) is primarily due to catchments from the Coweeta experimental watersheds. These catchments show a marked difference in response to vegetation change depending on the catchment's aspect. Catchments with a polar (northern) aspect have nearly three

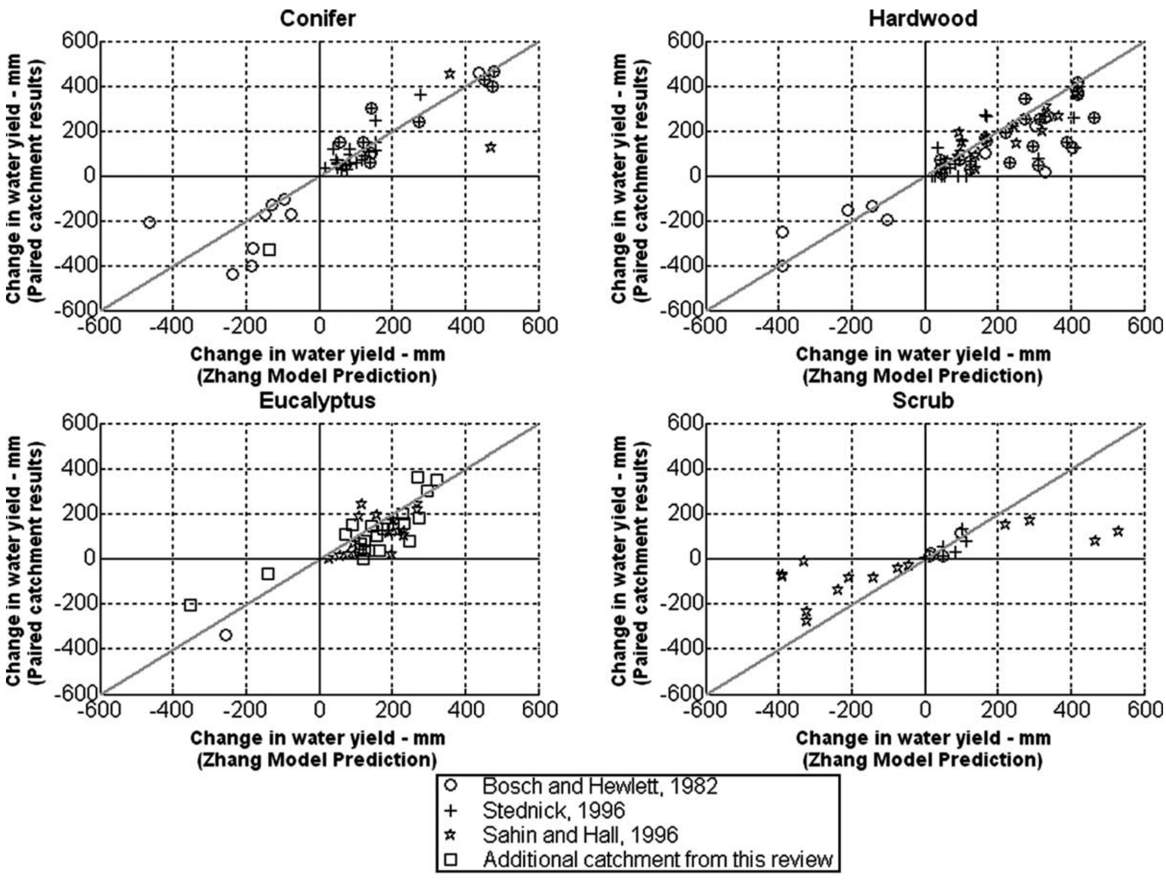

Fig. 4. Prediction of change in water yield based on the Zhang model compared with results from paired catchment studies for different vegetation types.

times the water yield increase of catchments with an equatorial (southern) aspect (Swank et al., 1987). While the north facing catchments from Coweeta show good agreement with Zhang curves, the Zhang curves over-estimate the water yield change from the south facing catchments. The scrub catchments are representative of vegetation that falls into neither the grass nor the forest category but are an intermediate vegetation structure. As would be expected in these catchments the change in water yield is less than the predicted change when going from a grass to forested catchment.

In general the Zhang curves produce larger estimates of the mean annual water yield change than is reported for paired catchment studies. This is to be anticipated as paired catchment studies generally relate to timber harvest or regrowth experiments (i.e. the catchments with an increase in yield in Fig. 4). The results of regrowth experiments are generally reported as the maximum or average change in the first 5 years after treatment rather than the long term water yield change as predicted by the Zhang curves. The difference in the agreement between the paired catchment studies and the Zhang curves for different experimental types can also been seen in Fig. 4. Afforestation with hardwoods and eucalypts show good agreement with the Zhang curves while the regrowth and deforestation experiments with the same vegetation types show smaller changes than those predicted by the Zhang curves. For conifers the Zhang curves under predicts the increase in evapotranspiration due to afforestation, while deforestation and regrowth experiments showed good agreement. It should be noted that this comparison implicitly assumes that the response time of the paired catchments is short enough so that the observed changes in yield are representative of long term permanent changes in vegetation. As will be discussed further below, this is typically not the case for regrowth experiments.

In reviewing paired catchment studies both Stednick (1996) and Sahin and Hall (1996) state that difficulties occur when summarising the result of catchment experiments due to the lack of certain key statistics from the reported results (Sahin and Hall, 1996) or insufficient detail of the site characteristics (Stednick, 1996). This may account for the lack of generalisation about the impacts of vegetation age on water yield and seasonal flows in previous review papers. While the information contained in previous reviews may be useful for determining the short term changes in water yield following vegetation change, it does not allow for the likely long term impact of permanent vegetation change or the inter- and intra-annual changes to be investigated. The mean annual relationships encapsulated in the Zhang curves provide a method to assess the impact of permanent vegetation changes on mean annual flows. However, they do not provide a method for assessing inter- or intra-annual variability or the time it takes a catchment to adjust to changes in vegetation type and reach a new equilibrium condition.

4. Annual water yield response time

A change of land-use in a catchment may lead to changes in its water balance components. The response time of streamflow is generally determined by climate (mostly rainfall), vegetation characteristics, catchment properties, and vegetation management practices. Response in streamflow will be slower following afforestation compared to deforestation as it takes time for trees to reach equilibrium water use. For example, streamflow usually will respond rapidly over a period of days or weeks following clearing or bushfire in a small headwater catchment. Typically, a catchment will take a number of years to adjust to vegetation changes, particularly where the vegetation itself develops over time. The response time can be defined as the time taken for the annual catchment yield to reach a new equilibrium state following a disturbance. Understanding of the response times is useful for water allocation policy and regional planning.

Using paired catchment data Hornbeck et al. (1993) looked at the long term effects of forest treatment on water yield in the USA under a range of climatic conditions. They found a variety of responses in water yield including:

- initial increases occur promptly after forest clearing;
- increases could be prolonged by controlling the regrowth (analogous with permanent vegetation change)—when regeneration of forest cover was

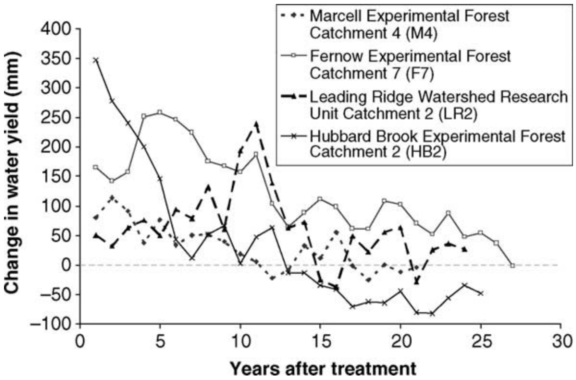

Fig. 5. Change in annual water yield for four paired catchment studies in the USA. M4—100% Basal area cut. F7, Upper half clear-cut (year 0), herbicides on upper half (2–7), lower half cut (year 4), herbicide on entire catchment (5–7). LR2—Lower 24% clear-cut (year 0), mid slope 27% clear-cut (years 4–5), herbicide on lower and mid slope (year 7) 40% Upper slope clear-cut (year 8–9), herbicide all catchment (year 10). HB2—100% clear felled (year 0), herbicide on entire catchment (years 2–4). After Hornbeck et al. (1993).

permitted the increase in streamflow diminished rapidly in about 3–10 years; and
- a small increase or decrease in water yield may persist for at least a decade.

Fig. 5 shows the impact of vegetation changes for four catchments in the USA. The differing responses are consistent with our conceptual understanding based on the treatment undertaken; for example, in the Hubbard Brook experimental forest (HB2), 100% of the catchment was clear-cut and regrowth was then permitted. In this case an initial increase in water yield is observed (due to reduced interception and transpiration), as regrowth occurs the water yield increase is reduced. The observed reduction in water yield after about 15 years is due to the increased evapotranspiration of the regrowth compared to the old growth forest. The Marcell Experimental forest catchment (M4) shows a similar trend to Hubbard brook, with an initial increase followed by a decline to pre-treatment levels. For the Fernow experimental forest (F7) the increase in water yield is more persistent than in Hubbard Brook. In the F7 catchment clearing was undertaken in two stages, the upper half of the catchment occurred in year 0 and the clearing of the lower half the catchment in year 4. Herbicides were applied to the catchment to prevent regrowth until year 7. After this point, the effect of the regrowth can again be seen with water yield returning to pre-treatment levels by year 27. The Leading Ridge Watershed research unit catchment (LR2) also shows the effect of a staggered treatment, with an increase in flows until the entire catchment was cleared in year 9 and herbicides applied in year 10. As regrowth occurs after the competition of the treatment the water yield returns to pre-treatment levels.

The regrowth experiments of the types shown in Fig. 5 are useful for estimating the initial increase in water yield and the time taken for a catchment to return to its pre-disturbance state. However, they provide very limited information on the long term impact of permanent vegetation changes that may occur under deforestation or afforestation, where the water yield will not return to pre-treatment conditions.

There are limited examples of paired catchment studies examining the impact of permanent vegetation changes on water yield. A number of paired catchment studies in south Western Australia have focused on the deforestation of native forest to be replaced by agriculture (Ruprecht and Schofield, 1989). Fig. 6 shows the results of four different paired catchments in the Collie Basin in Western Australia. These catchments experience a Mediterranean climate with a mean annual precipitation ranging from 600 to 1400 mm. Predominant pre-treatment vegetation in these catchments consists of jarrah (*Eucalyptus marginata*)

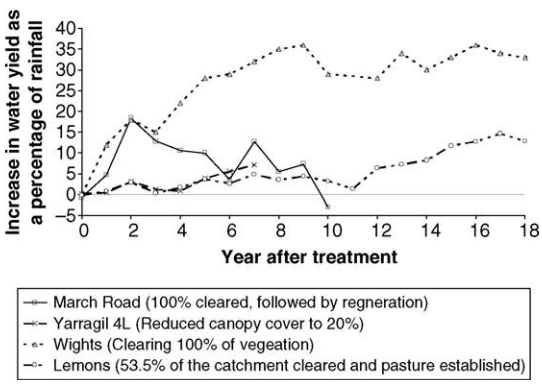

Fig. 6. Water yield increase for paired catchments, south Western Australia. Wights catchment (Ruprecht and Schofield, 1989), Yarragil (Stoneman, 1993), March Road (Bari et al., 1996), Lemons (Ruprecht and Schofield, 1991a).

and karri (*Eucalyptus diversicolor*). March Road, Yarragil 4L, Wights and Lemons catchments have mean annual rainfalls of 1050, 1120, 1200, 750 mm, respectively.

Looking at the results for the deforestation in the Wights catchment, it can be seen that an initial increase in water yield is observed in the first year after treatment (due to decreased interception and evapotranspiration). This is followed by a steady increase in water yield, as groundwater levels rise, until a new equilibrium is reached (Ruprecht and Schofield, 1989; Silberstein et al., 2003). The other deforestation catchments in Fig. 6 (Lemons and Yarragil) have only been partially cleared and do not show an initial increase in water yield following treatment. Instead these catchments show a steady increase in water yield over time. From the length of results reported in the literature it is not possible to establish when they reached a new equilibrium condition. The results of clearing followed by regrowth in the March Road catchment show a similar trend to the regrowth in Hubbard Brook Catchment 2 USA (Fig. 5) with an initial increase in water yield in the 2 years following treatment (due to reduced interception) followed by a return to pre-treatment levels in year 10.

The above results highlight the limitations of regrowth studies in predicting the long term effects of permanent vegetation changes. It is clear that in many cases the initial increase after clearing is not always representative of the long term increase as it may take several years for a catchment to reach a new equilibrium state. This is particularly important in the hardwood forest of North East USA and some eucalypt forest, where regrowth is primarily from the same root systems, making the changes in water yield short lived. However, regrowth experiments have the potential to be used to investigate the likely changes in evapotranspiration and streamflow with relation to forest age. This has been the focus of a number of paired catchment studies in south eastern Australia, where after clearing and subsequent regeneration, a decrease in water yield occurs. This decrease is due to the vigorous nature of the regrowth, which has a greater transpiration rate compared with old growth forests (Cornish and Vertessy, 2001; Vertessy et al., 2001; Roberts et al., 2001). Using paired catchment studies involving regrowth, it may be possible to predict the impact of afforestation or tree plantations on inter-annual water yield.

The Mountain ash forests in southern Australia provide an excellent example of this reduction in water yield following the regeneration of vegetation after bushfire. Mountain ash forests are confined to the wetter parts of Victoria and Tasmania and grow at altitudes of between 200 and 1000 m, where mean annual rainfall exceeds 1200 mm. Fire is an infrequent but vital component of the life cycle of these forests with the seedlings only growing on exposed soil with direct sunlight (Vertessy et al., 2001). Following fire, hundreds of seeds germinate per hectare, the intense competition between the plants for light results in rapid tree growth and natural thinning of weaker trees. There is a significant body of empirical evidence to show that the amount of water yield from these catchments is closely linked with stand age (Langford, 1976; Kuczera, 1987; Watson et al., 1999). The 'Kuczera curve' that describes the relationship between stand age and annual water yield is characterised by the following features (Vertessy et al., 2001):

- the mean annual water yield from large catchments covered with old growth mountain ash forest (>200 year) is approximately 1195 mm for regions where mean annual rainfall is ~ 1800 mm;
- after burning and full regeneration of mountain ash forest the water yield reduces to 580 mm at an age of ~ 27 years; and
- after 27 years of age the mean annual water yield increases and returns to pre-disturbance levels, taking as long as 150 years to fully recover.

The work by Cornish and Vertessy (2000) and Roberts et al. (2001) indicates that this may be a more general behaviour for eucalypt forests in Australia and does not only apply to mountain ash forests.

South Africa has the longest and most detailed record of paired catchment afforestation experiments, addressing permanent vegetation change from grassland to forest. Using data from South African afforestation experiments, Scott and Smith (1997) developed a series of generalised curves to predict the impact of afforestation on annual total flows and lows flows as a function of plantation age, species planted, and site suitability as shown in Fig. 7. The curves in

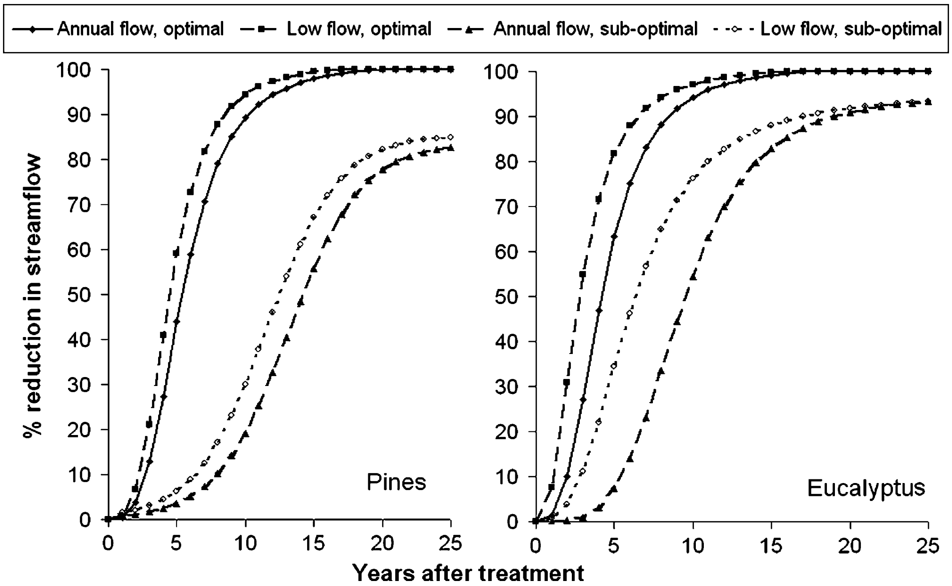

Fig. 7. Generalised curves from estimating the percentage reduction in total and low flow after 100% afforestation with pine and eucalypt afforestation (Scott and Smith, 1997).

Fig. 7 are similar to those observed in Fig. 6 (particularly for Wights catchment) indicating a similar type of response for both afforestation and deforestation experiments, with a period of transience being observed before a new equilibrium is reached. Fig. 8 shows the comparison of annual results from deforestation, afforestation and regrowth experiments in areas of similar rainfall. The afforestation and deforestation experiments show that while a similar change in water yield is observed in the long term the time taken to reach this equilibrium is dependent on the treatment, with a new equilibrium being established more rapidly under deforestation than under afforestation.

Many of the paired catchment studies reported in the literature do not report long term changes and thus the generalisations about the time taken to reach a new equilibrium are limited. The models of Kuczera (1987) and Scott and Smith (1997) provide examples of predictive tools that can be used to look at the adjustment timescale associated with changes in vegetation. However, these models are limited in there applicability, with the Kuczera curve being specific to Mountain Ash forest and the Scott and Smith curves being specific to South Africa. While the Scott and Smith curves may be applicable to other parts of the world, the results indicate that in South Africa eucalypts use more water than pines. These results conflict with results from Australia, where pines are thought to use more water than eucalypts (Vertessy and Bessard, 1999).

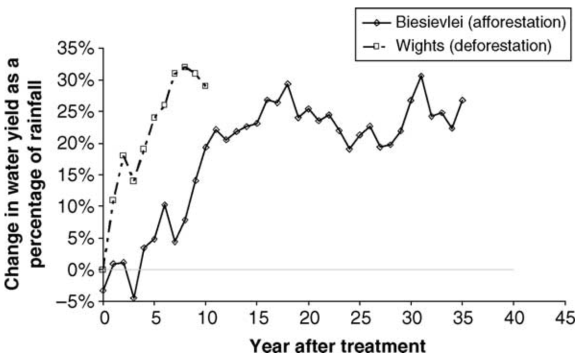

Fig. 8. Changes in water yield as a percentage of rainfall for a deforestation experiment (Wights catchment) and an afforestation experiment (Biesievlei catchment). Wights catchment is located in Western Australia with mean annual rainfall of 1200 mm after Ruprecht and Schofield, 1989. Biesievlei catchment is located in South Africa with mean annual rainfall of 1298 mm, after Scott et al. (2000).

5. Seasonal water yield

Our understanding of the vegetation impact on mean annual water yield is well advanced and there are robust methods available for predicting the impact of vegetation change on the mean annual water balance (Zhang et al., 2001). Methods have also been established that allow the prediction of water yield changes in response to vegetation change at the annual time scale (Kuczera, 1987; Scott and Smith, 1997). The effects of vegetation on seasonal, monthly and daily flows are less well understood. However, the impact of vegetation change on seasonal water yield can be as or more important than the impact on annual water yield. The analysis of paired catchment data in the USA in the 1970s and early 1980s commonly used regression by least squares on both annual and monthly data (Hibbert, 1969; Hornbeck et al., 1987; Rich and Gottfried, 1976; Johnson and Kovner, 1956). This allowed the impact of annual water yield as well as seasonality to be assessed. However, no generalisations have been made on the responses in seasonal water yield to changes in vegetation. This may be due to the mainly qualitative and graphical nature of many of the seasonal flow results reported in the literature.

To gain a good understanding of the processes affecting water yield it is important to note that the annual streamflow and evapotranspiration do not tell the complete story because of seasonal interactions of factors affecting the water balance, such as soil moisture content (Johnson and Kovner, 1956). While on a mean annual basis the changes in soil moisture can be assumed to be negligible, this is not the case on a seasonal basis. This section aims to provide a qualitative summary of the impact of vegetation change on seasonal water yield. This has been achieved by reviewing papers reporting seasonal water yield changes and grouping the results into four broad categories based on climate. No attempt has been made to divide the results based on treatment or vegetation type. The climatic groupings adopted are tropical/summer dominant rainfall catchments, snow affected catchments, catchments with winter dominant rainfall, and catchments with uniform rainfall.

Table 1 provides a summary of the observed seasonal changes in water yield. When summarising seasonal responses a differentiation has been made between the absolute and proportional responses. Absolute responses refer to the total volume change,

Table 1
Seasonal response in water yield

Climate	Absolute response	Proportional response	References
Tropical/summer dominant rainfall	Larger changes in summer months, when rainfall is greater then monthly average	Two types of responses observed: (1) Similar changes in all months (2) larger changes in winter months, when rainfall is below monthly average	Blackie (1979), Blackie and Edwards (1979), Bruijnzeel (1988, 1990), Gafur et al. (2003), Sharda et al. (1988), Scott and Lesch, (1997) and Van Lill et al. (1980)
Snow affected catchment	Largest changes in months of snow melt	Larger change in summer growing season	Baker (1984), Troendle et al. (2001), Alexander et al. (1985), Troendle (1983), Schneider and Ayer (1961), Hornbeck et al. (1970) and Hornbeck (1975)
Winter dominant rainfall	Largest changes in winter months when rainfall in above monthly average	Largest change in summer months when rainfall is below monthly average	Bari et al. (1996), Bren and Papworth (1991), Burch et al. (1987), Caissie et al. (2002), Gallart et al. (2002), Keppeler and Ziemer (1990), Kirby et al. (1991), Lewis et al. (2000), Mein et al. (1988), Miller et al. (1988), Rogerson (1971), Rothacher (1970), Ruprecht et al. (1991) and Watson et al. (2001)
Uniform rainfall	Uniform change across all seasons	With deciduous vegetation there is a larger change during the spring months. Evergreen vegetation shows uniform change across all seasons	Hibbert (1969), Johnson and Kovner (1956), Lane and Mackay (2001), McLean (2001) and Swank et al. (2001)

while proportional responses refer to the change with respect to the flow under the original vegetation type. The differences between absolute and proportional reductions have important management implications. While most of the water yield or volume change occurs during wetter months, the proportional responses vary considerably depending on the climate and treatment type.

In winter dominant rainfall catchments similar responses are seen in all studies, with a much larger proportional reduction the summer flows compared with the winter flows. This is mainly driven by the change in interception and evapotranspiration. In catchments with winter dominant rainfall the maximum potential evapotranspiration occurs during the period of lowest rainfall, i.e. the rainfall and potential evapotranspiration are out of phase. This results in highest demand for water by vegetation, when water availability is low. Under forests, there is a greater ability of the vegetation to extract water from soil moisture stores resulting in lower baseflow compared to grass catchments.

In summer dominant rainfall catchments the results can vary from uniform changes across all seasons (Sharda et al., 1998) to large changes in dry season flow (Edwards, 1979; Scott et al., 2000). These different responses can be seen from the results from the Glenmorgan research farm, India and Cathedral Peak, South Africa (Fig. 9). Both of these catchments have summer dominant rainfall and have been afforested, however, the proportional changes in water yield are significantly different. The difference in responses observed in summer dominant rainfall catchments, undergoing similar changes in vegetation highlights the difficulties associated with making generalisations about the seasonal impacts on water yield. At the seasonal time scale other catchment characteristics such as soil depth and type play a much larger role in the response than on the mean annual basis.

This difference in absolute and proportional response can be seen in results from the Glenmorgan research farm in India where Sharda et al. (1998) used a monthly average dataset to look at the seasonal nature of water yield changes. It was observed that the major reduction in mean annual flow caused by the blue gum (*Eucalyptus globulas*) plantation occurred during the months from July to October, when 60% of the mean annual rainfall occurred. These results indicate that the major reductions in flow volume occur during the monsoon (July–October). However, it should also be noted that although the reduction in flow during the dry period was small on a volume basis compared with the wet season, the percentage reduction in flow is significant during all months of the year. The early and late monsoon periods show different responses in water yield change, which may be related to soil moisture dynamics introducing delays in response time.

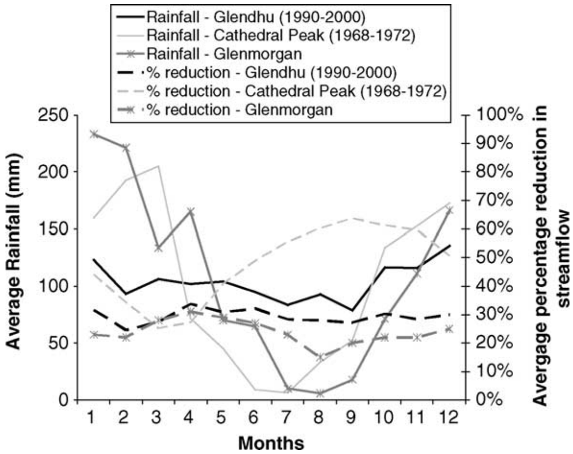

Fig. 9. Average monthly reductions in streamflow from the Glendhu catchment (afforestation with pines 1980) and Cathedral Peak II, South Africa (afforestation 1950–1955), Glenmorgan research Farm, India. Values 1–12 on the *X*-axis represent the months January to December for Southern Hemisphere catchments and July to June in the Northern Hemisphere catchment.

A similar analysis was carried out on the Glendhu catchment in New Zealand, these results are also presented in Fig. 9. These three examples illustrate different seasonal responses to afforestation in different climatic regions. The New Zealand example depicts a reasonably constant rainfall through out the year coupled with a constant reduction in streamflow. The Indian and South African examples have highly seasonal rainfall; resulting in seasonal variation in the reductions in water yield.

As stated by Vertessy (1999), the information on the seasonal variations in water yield is limited and rather confusing. The way in which the data on seasonal yield are presented in the literature is generally descriptive or graphical, making it hard to generalise between the results of different studies. While on an annual basis the results of paired catchment studies seem to be easily generalised according to vegetation type, this is not the case for seasonal data.

6. Flow duration curves

While the magnitude of changes at the mean annual, annual and seasonal time steps are important, many water resources management issues require an understanding of the impact of vegetation on flow regime. A catchment's flow regime is described by the magnitude, frequency, duration, timing and rate of change of streamflow at a given point. The impact of changing vegetation type on flow regime can be depicted by a catchment's flow duration curve (FDC).

The FDC for a catchment provides a graphical (and statistical) summary of the streamflow variability at a given location, with the shape being determined by rainfall pattern, catchment size and the physiographic characteristics of the catchment. The shape of the flow duration curve is also influenced by water resources development (water abstractions, upstream reservoirs, etc.) and land-use type (Smakhtin, 1999).

FDCs can be constructed using multiple temporal scales of streamflow data: annual, monthly or daily flows, depicted either using all the flows for the period of record or flows from a particular year. Seasonal FDCs can also be constructed by using only flows for a particular season over the period of record or on an annual basis. For example, a daily annual FDC is constructed from daily flows for a single year, while a daily period of record FDC is constructed from daily flows for the period of record. Ideally, comparisons between FDCs for different vegetation types would be made between daily period of record FDCs. These FDCs are more representative of catchment flows than daily annual FDCs. However, due to the limitations in length of data available for paired catchment studies it is often necessary to use daily annual FDCs for comparisons. One of the limitations of using daily annual FDCs for a comparison of high and low flows under different vegetation types is that the relative distribution of high and low flows varies depending on whether a particular year is wet or dry. Therefore, when making the comparison between daily annual FDCs it is important to compare years with similar precipitation to minimise the variations due to climate (Burt and Swank, 1992).

In discussing the impacts of vegetation change on flow regime, low and high flow need to be defined. The most widely used definition of low flow is any flow that is exceeded for 70–99% of the time (Smakhtin, 2001), hence this definition has been adopted. High or peak flows are taken here as the flows that are exceeded for 1–5% of the time.

The flow duration curves discussed below are daily annual FDC, and have been plotted for catchments in different climatic zones with differing vegetation changes. While data exists to plot such curves for a large number of catchments, only three examples that have previously been reported in the literature are discussed. These examples are the Red Hill catchment in south eastern Australia, where a pine plantation was established on pasture, Wights catchment in south Western Australia where pasture replaced native vegetation and the Glendhu catchment in New Zealand, where a pine plantation was established on tussock grassland.

Fig. 10 depicts the change in flow regime for the Red Hill catchment in south eastern Australia. The catchment is located about 50 km west of Canberra, in the Murrumbidgee basin and is part of the paired catchment study looking at the impact of pine plantations on water yield. Red Hill has a catchment area of 195 ha and ranges in altitude from 590 to 835 m. The climate of the area is highly variable with a winter dominant rainfall. The mean annual rainfall is 876 mm (Hickel, 2001). FDCs for 1 and 8 year old pines (based on a water year from May to April) have been used to quantify the relative changes in the high and lows flows as a result of vegetation change. The 1- and 8-year old pines were chosen as these years have similar rainfalls, 887 and 879 mm, respectively. The FDC indicated that there is approximately a 50% reduction in high flows while there is 100% reduction in low flows, with all flows in the designated low flow range ceasing once the pine plantation is well established.

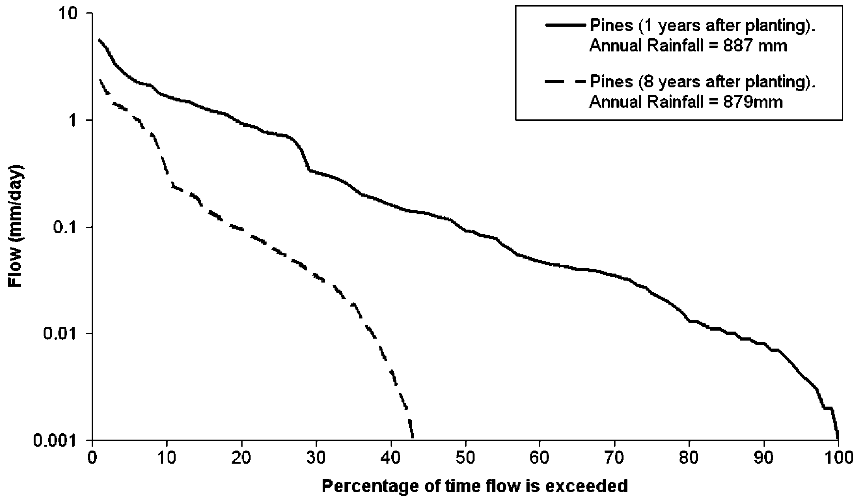

Fig. 10. Flow duration curves for the Red Hill catchment, near Tumut, New South Wales, Australia. One year old pines and 8 year old pines (after Vertessy, 2000).

Fig. 11 depicts the response to conversion of native forest to pasture in the Wights catchment in south Western Australia. As discussed in Section 4 the Wights catchment is part of a series on paired catchment studies in south Western Australia. In these catchments, the interplay between the local groundwater flow system and vegetation plays an important role in the hydrological response. The replacement of native forests by pastures in these catchments has lead to a rapid increase in groundwater discharge area (Schofield, 1996), resulting in large increases in low flows. As with Fig. 10, it can be seen that all sections of the flow regime are affected by the change in vegetation. Comparing the FDC for native vegetation (1974–1976) with a period of similar climatic conditions of

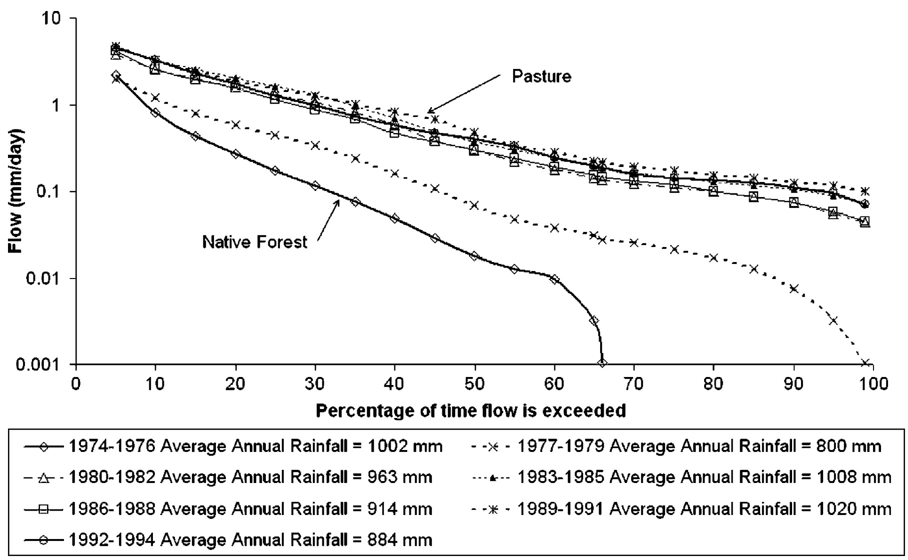

Fig. 11. Flow duration curves for the Wights catchment in south Western Australia. (Based on a water year from April to March).

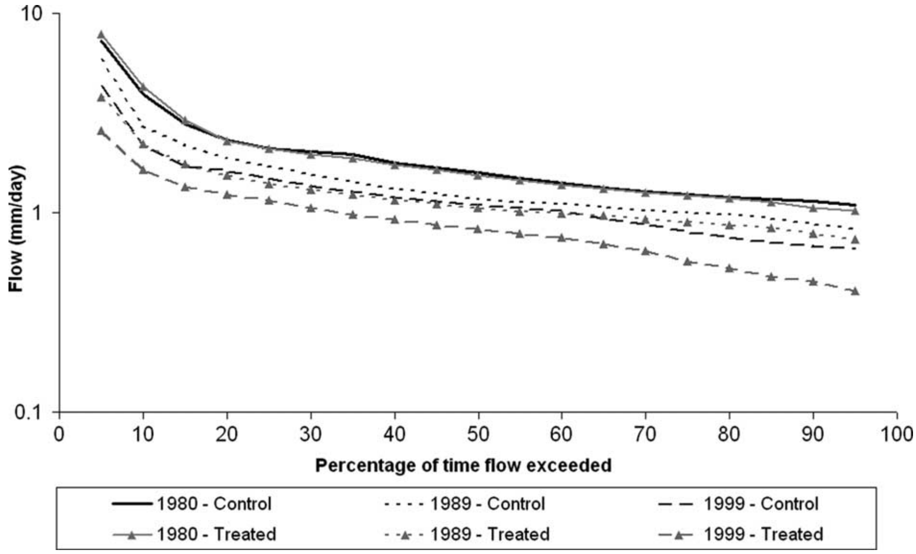

Fig. 12. Flow duration curve from the Glendhu experimental catchments New Zealand. 1980—during the calibration period (both catchments tussock). 1989—6 years after pine plantation established. 1999—16 years after pine plantation established. (McLean, 2001).

pasture (1983–1985) we observe a 50% reduction in high flows when going from pasture to forest and a 100% reduction in low flows.

Fig. 12 depicts the FDC response to the establishment of pine plantations in the Glendhu experimental catchments in New Zealand (169°45′E, 45°50′S). The control and treated catchments have mean annual rainfalls of 1310 and 1290 mm, respectively. The treatment involved the planting of 67% of the catchment with *Pinus radiata* (McLean, 2001). The results from Glendhu show a different response in the FDC compared to Figs. 10 and 11. Unlike the Red Hill and Wrights catchments the control and treated FDC are similar during the calibration period. Therefore, the changes in high and low flows have been assessed through comparing the control to the treated catchment at various stages after treatment. The reductions in low and high flows are similar for all sections of the FDC with an approximate 30% reduction in both low and high flows as a result of the vegetation change. This response is typical of many catchments in higher rainfall areas, including the Mountain Ash catchments in Victoria (Watson et al., 1999) and the Biesievlei catchment in South Africa.

Figs. 10–12 depict two possible responses in flow regime as a result of vegetation change. The response seen in the Red Hill and Wights catchments are typical of areas where the annual actual evapotranspiration of forests approaches annual precipitation, while the response seen in Glendhu is typical of areas where annual precipitation is greater than the annual potential evapotranspiration. In the Mountain Ash catchments in southern Australia, Watson et al. (1999) noted that in wetter catchments all flows respond to climatic and vegetation changes in unison with the changes in the mean flow, however, in the drier parts of their study area changes in low flows are accentuated.

As with the assessment of mean annual and annual flow, the annual FDC does not show how the flow regimes of different seasons are impacted. Analysing seasonal FDCs can overcome this limitation. However, few papers report seasonal FDCs. Hornbeck et al. (1997) looked at both annual and seasonal flows for the first year after clear felling in the Hubbard Brook experimental forest. Separating annual water yield change into changes during the growing (full leaf area) and dormant seasons (minimum leaf area) allowed investigation of the FDC response during periods of

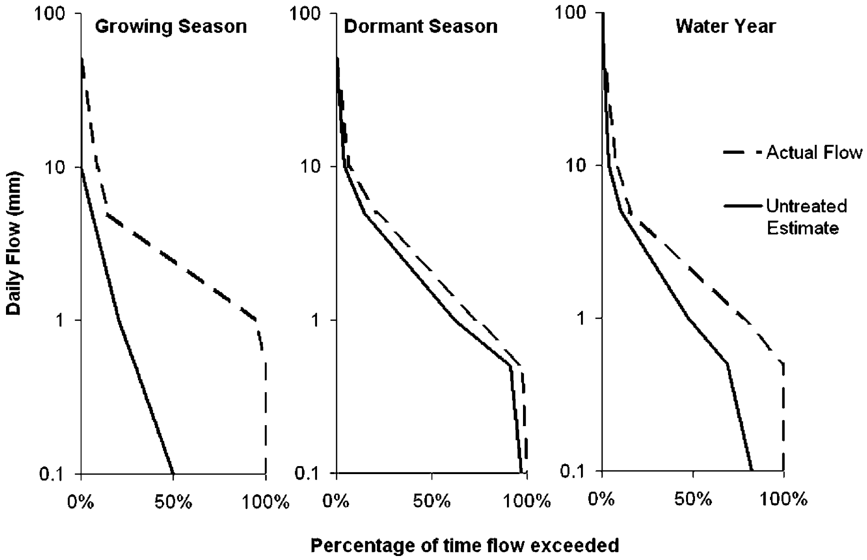

Fig. 13. Flow duration curves for the first year after the clear-felling treatment—Hubbard Brook experimental forest (after Hornbeck et al., 1997).

maximum evapotranspiration and periods of minimum evapotranspiration. Hornbeck et al. (1997) observed that most of the increase in annual yield occurred during the growing season as shown in Fig. 13. They concluded that water yield increases were a result of decreased transpiration and primarily occurred as augmentation to low flows during the growing season (Fig. 13). While this seasonal break-up is obvious for deciduous catchments, the definition of seasons is less obvious for evergreen vegetation or catchments with uniform climate.

Using a similar approach to the analysis of Hornbeck et al. (1997) and McLean (2001) produced FDCs during winter (July–September) and summer (December–February) seasons where vegetation was converted from tussock to pine plantations in New Zealand. McLean (2001) concluded that:

- differences were more variable in summer flows than in the winter. This was due to the high variability in the rainfall over the summer months; and
- the seasonal effects of vegetation modifications are not easily identified using flow duration curves.

The difference in the results between Hornbeck et al. (1997), who found notable seasonal differences, and McLean (2001), who could not detect seasonal changes, can be attributed to the deciduous nature of the vegetation in the USA compared with the evergreen vegetation of the pine plantations in New Zealand. The distinct dormant season in the USA where there are no leaves on the trees results in lower interception and transpiration rates making the evapotranspiration rates of forested areas very similar to those of short crops. As with the mean seasonal responses discussed in Section 5, the response of the seasonal FDC to vegetation change will also differ depending on the rainfall pattern. The comparison between the annual FDCs for Red Hill (Fig. 10) gives us some indication of the likely impact of pine plantation on the seasonal FDCs in this catchment. It would be anticipated that a larger proportional reduction in low flows in the Red Hill catchment indicates a larger change in the summer FDC, compared to the winter FDC as the majority of low flows occur during the summer months.

Jones and Grant (2001) noted that the nature of the analysis undertaken could influence the results.

This was illustrated by the original analysis of peak flow responses to clear cutting and roads in small and large basins, western Cascades (Jones and Grant, 1996) and the subsequent reanalysis of the same data by Thomas and Megahan (1998), where the use of differing methods on the same data set yielded different results. The interpretation of the results from the two analyses has resulted in Jones and Grant (2001) concluding both analyses showed that forest harvest has increased peak discharges in small events by as much as 50% and by as much as 100% in large events. Thomas and Megahan (2001) agreed that peak flow increases (of up to 100%) in small events may occur, but argued that that no evidence existed to suggest that this was the case for all event sizes including large floods.

7. Discussion

During the review of literature three major limitations were highlighted in relation to the previous analyse of paired catchment data. These are:

- generalisations about annual increases in water yield (Bosch and Hewlett, 1982; Stednick, 1996; Sahin and Hall, 1996) are based on short term results of regrowth experiments (maximum change in the first 5 years after treatment, or first year increases). The results of permanent vegetation change experiments indicate that, depending on the changes in soil storage and the transpiration–vegetation age characteristics of the new vegetation type, it takes longer than 5 years for a new hydrologic equilibrium to be established;
- changes in vegetation type will affect not only mean annual flow, but also the variability of annual flow. Peel et al. (2001) noted that differences in the variability of annual runoff were due to two factors, the variability of annual precipitation and the distribution of evergreen and deciduous vegetation; and
- in order to make quantitative generalisation about the impacts of vegetation changes on seasonal water yield, a method needs to be established that can be applied to a large number of catchments, so that when comparing results between sites, the generalisations are not complicated by conflicting results from different analytical methods.

Paired catchment studies provide a useful method for determining the relationships between percentage vegetation change and water yield in relatively small catchments. The results summarised in this paper indicate that for any impact of vegetation change to be detected, at least 20% of the catchment needs to be treated (Bosch and Hewlett, 1982). This result is derived from the research on small experimental catchments with typical record lengths of less than 10 years following treatment and longer records may mean that smaller changes can be detected. However, methods are needed for scaling these results to larger catchments where the area subject to vegetation change is likely to be patchy and relatively small compared to the overall catchment size. A few studies have attempted to make estimates of mean annual water yield change in larger catchments.

Mundy et al. (2001) developed a model to simulate the temporal changes in streamflow associated with afforestation of existing grassland and the subsequent management of the forest for timber harvesting for the Adjungbilly catchment (389 km^2) in New South Wales using results from paired catchment studies of Red Hill (for pine plantations) and Karuah (for eucalypt forest). The results indicated that while the trend in streamflow changes are statistically insignificant in this larger catchment, the model did satisfactorily simulate the magnitude and nature of the changes in mean annual yield from the catchment given the historical changes in vegetation type, indicating that paired catchment results can be extrapolated to larger catchments. Scott et al. (1998) used the generalised curves of Scott and Smith (1997) for annual reduction in water yield, to determine the likely change in water yield on total runoff and low flows at regional scale as a result of afforestation in South Africa. This is the best example of prediction of water yield changes at a regional scale at the annual time scale.

The two examples above show how generalisations from small catchment experiments are being extrapolated to a regional scale and how treatments that cover less than 20% of the catchment might impact on water yield. It is worth noting that a potentially significant scale effect relates to the change in geomorphology as one move from upland catchments to lowland catchments. In current applications to larger scales it is assumed that these different areas of the landscape react similarly to change in vegetation.

One of the advantages of paired catchment studies is that they remove climate variability through the comparison of two catchments subject to the same climatic conditions under different land uses. The separation of climatic variability effects from the water yield changes as a result of vegetation alterations is a key problem for time trend studies. In cases where paired catchments are available, the separation of land use impacts from climatic factors can be achieved through the comparison of the two catchments. This can be done not only for annual and mean annual totals, but also for flow regime as depicted by the daily annual flow duration curves in Figs. 10–12. There is also the potential to use paired catchments to determine the seasonal impacts of vegetation change.

8. Summary

The previous reviews of paired catchment studies have focused mainly on regrowth experiments. In such studies, changes in water yield are only observed in the first couple of years following treatment before returning to pre-treatment levels. This paper has focused on the application of paired catchment results to the prediction of different aspects of hydrologic response to permanent vegetation change. Firstly, the changes in mean annual yield documented in previous paired catchment reviews were compared with the mean annual water balance model of Zhang et al. (2001). This analysis indicated good agreement between the paired catchment and the mean annual water balance approach. A comparison of the long term annual results of regrowth, deforestation and afforestation experiments indicated that following permanent changes in vegetation it takes more than 5 years for a catchment to reach a new equilibrium, with deforestation experiments reaching a new equilibrium earlier than afforestation experiments. The transient nature of the water yield changes makes the use of regrowth experiments for predicting the impacts of permanent vegetation changes on water yield questionable. Table 2 provides a summary of the uses and limitation of paired catchments for predicting permanent changes in vegetation at different temporal scales.

This review highlights the lack of information available in the literature for making quantitative generalisations about the impacts of vegetation changes on seasonal yield and flow regime. While the effect of vegetation change on a mean annual basis is well understood the research on seasonal water yield reported in the literature is limited and primarily of a descriptive or graphical nature making quantitative generalisations difficult. While many papers on individual paired catchment studies report seasonal results it was not considered possible to make quantitative predictions, due to the qualitative or graphical nature of many of the results presented. The papers reporting seasonal results were grouped by climate and some broad generalisation made. In all catchments the largest volume changes occur during the wet periods with small volume changes during the dry periods. The main difference between catchments came in the proportional reductions. Nearly all winter dominant and snow affected catchments showed larger proportional changes in dry summer months compared to the wet winter months. In tropical catchments two types of responses where observed, with either a uniform proportional change in water yield in all seasons or a greater proportional change in dry season flow. Catchments with uniform rainfall tended to show more uniform reductions in water yield across all seasons.

As a means of gaining an understanding of the impact of vegetation change on flow regime, the FDC was used as a means of displaying the complete range of daily flows over a given time period. While insufficient data were available for making generalisations about the FDC response to vegetation change, the three examples used highlight this as a useful method of assessing the likely impact of vegetation on daily flows that requires further exploration.

Table 2
Summary of results from paired catchment studies, highlighting the limitation and uses of the transient vegetation studies (regrowth and forest conversion experiments) and permanent vegetation studies (afforestation and deforestation experiments) for making generalisation at different timescales and list references for predictive tools currently available

Time scale	Summary of results	Generalisations/predictive models
Bosch and Hewlett's (1982)	Bosch and Hewlett (1982) estimations may underestimate the impacts of permanent vegetation changes due to use of maximum increase in the first 5 years after treatment Zhang curves provide a good predictive tool for estimating the change in water yield between grass and forested catchment. However, no differentiation is made between tree species Results of comparison between paired catchment results and Zhang curves indicate that under afforestation, conifers tend to use more water than hardwoods or eucalypts	Bosch and Hewlett (1982), Vertessy and Bessard (1999) and Zhang et al. (2001)
Annual	Water yield changes over time until a new equilibrium is reached following permanent alteration to vegetation in a catchment It may take several decades for a catchment to reach equilibrium under new vegetation type or to return to pre-treatment levels following fire or forest harvesting Regrowth and forest conversion experiments do not show the same extent of water yield change as deforestation and afforestation experiments	Kuczera (1987) and Scott and Smith (1997)
Seasonal	Generalisations about seasonal water yield are difficult to make based on the reported literature due to different definitions of seasons and the graphical and descriptive nature of the results Based on climate groups, different seasonal responses are observed. Tropical or summer dominant rainfall catchments show larger absolute changes in the wet season, while proportional changes are either similar during all seasons or greater during the winter months. Winter dominant rainfall catchments show largest absolute responses in the winter season, while larger proportional reductions are observed during the summer months	Scott and Smith (1997)
Flow duration curves	Provide a useful means of displaying the complete range of daily flows Allow the impacts on low and high flows to be assessed at different temporal scales (annual or seasonal) Seasonal flow duration curves can be used to assess the seasonal impacts on daily flows	–

Acknowledgements

The authors acknowledge the Cooperative Research Centre for Catchment Hydrology and the MDBC project 'Integrated assessment of the effects of land use changes on water yield and salt loads' (D2013) for providing funding for this review. The senior author was supported by a University of Melbourne Research Scholarship and the CRC for Catchment Hydrology. State Forest—NSW, Western Australian Rivers Commission, CSIR South Africa and Manaaki Landcare Research kindly provided us with paired catchment data from Red Hill, Wights, South Africa and New Zealand, respectively. We thank Sandra Roberts, Peter Richardson, Francis Chiew and an anonymous reviewer for their helpful comments on this paper.

Appendix A

Table A1

Table A1

Treated catchment										Control catchment									
Catchment	Area (ha)	Slope (%)	Mean elevation (m)	Aspect	Climate	Pre-treat-ment vege-tation	Post-treat-ment vege-tation	Mean annual rainfall (mm)	Mean annual stream-flow (mm)	Catch-ment control	Area (ha)	Slope (%)	Mean elevation (m)	Control aspect	Mean annual rainfall (mm)	Mean annual stream flow (mm)	Treatment	Cali-bration period	Source of info
Karuah, NSW, Australia																			
Barratta	36.4		450–940		Moist warm temperate climate	Tall wet sclerophyll forest	Regrowth	1577	588	Crabap-ple/Sassa-fras	14.7/ 25.3		450– 940 m		1637/ 1429	456/ 307	Logging without regeneration burn	1976–1983	Cornish (1993) and Cornish and Vertessy (2001)
Bollygum	15.1							1499	500								Logging without regeneration burn	1976–1983	
Coachwood	37.5							1444	373								Plantation estab-lished after tractor clearing	1976–1983	
Corkwood	41.1							1639	503								Logging plus regeneration burn	1976–1983	
Jackwood	12.5							1368	313								Logging plus regeneration burn	1976–1983	
Kokata	97.4							1562	518								Plantation estab-lished after tractor clearing	1976–1983	
Lidsdale, NSW, Australia																			
L-6	9.4	12		SW	Sub-tropical	Eucalypt forest	*Pinus radiata*	755		L-5							Feb 1978 100% cleared and wind-rowed, and then burnt in April 1978. During winter 1978 catchment was planted with *P. radiata*	1967–1978	Putuhena and Cordery (2000)
Tantawangalo Creek, NSW, Australia																			
Willbob	85.6		800–950		Regional rainfall is reasonably uniform throughout the year	Open Sclero-phyll forest	Regrowth	1100		Ceb	21.7				1100		30% of area logged	1986–1989	Lane and Mackay (2001)
Wicksend	68.2																38% of area logged	1986–1989	
Tumut, NSW, Australia																			
Redhill	195	9			Temperate with highly variable and winter dominant rainfall	Pasture	Pines	876		Kylies run	135	12			876		50 ha afforested in 1988 and the remaining area (145 ha) affor-ested in 1989	None	Hickel (2001)

(*continued on next page*)

Table A1 (*continued*)

Treated catchment										Control catchment									
Catchment	Area (ha)	Slope (%)	Mean elevation (m)	Aspect	Climate	Pre-treatment vegetation	Post-treatment vegetation	Mean annual rainfall (mm)	Mean annual streamflow (mm)	Catchment control	Area (ha)	Slope (%)	Mean elevation (m)	Control aspect	Mean annual rainfall (mm)	Mean annual stream flow (mm)	Treatment	Calibration period	Source of info
Yambula State Forest, NSW, Australia																			
Geebung Creek	80.2		157–331	E	Temperate rainy climate, moist in all seasons with warm summers	Dry Sclerophyll forest	Regrowth	900		Pomaderris Creek	75.9				900		Integrated harvest (Jan–April 1987)	1979–1986	MacKay and Cornish (1982), Moore et al. (1986), Crapper et al. (1989), Roberts (2001) and Roberts et al. (2001)
Peppermint creek	127.5		230–476														Post-logging burn (June–July, 1987)	1977–1979	
Grevillea Creek	92.5																Wild fire—Jan 1979	1977–1979	
																	Integrated harvest (Dec 1986–June 1987)	1977–1978	
Stringybark creek	140		230–476														Wildfire—Dec 1972 Wildfire—Jan 1979 Integrated harvesting-May 1978–Jane 1979) Wildfire—Jan 1979		
Germans Creek	225.1		230-476														Wildfire—Jan 1979	1977–1979	
																	Salvage logging: June–Dec 1979		
Wyvuri experimental catchments, Babinda, Queensland, Australia																			
North creek	18.3	34		W	Tropical	Mesophyll vine forest		4239	2873	South creek	25.7						1971–1973 67% area logged, cleared raked and ploughed; bare 2 years	1969–1971	Cassells et al. (1982), Gilmore et al. (1982), Bonell et al. (1983) and Cassells et al. (1985)
Brigalow Research Station, Queensland, Australia																			
C2	11.7				Subhumid on the coast and extending to semi-arid towards the west	Native Brigalow forest	Crops	686	39	C1	16.8				699	20	Cropping 1985	1965–1983	Lawrence and Sinclair (1986) and Lawrence and Thorburn (1989)

C3	12.7					Pasture	695	32	C1	16.8			699	20	Pasture 1983	1965–1983	
Cropper creek, Victoria, Australia																	
Clem creek	46.4		E	Mediterranean-cool wet winters and hot dry summers	Dry sclerophyll eucalypt forest	*Pinus radiata*	1400		Ella creek/ Betsy creek	113.0/ 44.3		E	1400		December 1979 vegetation removed leaving 30 M buffer strip around stream. Area planted with radiata pine	1975–1979	Bren and Papworth (1991)
North Maroohdah experimental area, Victoria, Australia																	
Black spur 1	17	7.1	SW	Mediterranean-cool wet winters and hot dry summers	1939 *E. Regnans*	Regrowth	1662		Black spur 4	9.8	17.2		1662		50% basal area removed by clear felling small patches	71/72–75/76 (4 years)	O'Shaughnessy et al. (1989), Jayasuriya and O'Shaughnessy (1988), Nandakumar (1993) and Watson et al. (1999, 2001)
Black spur 2	9.6	14.6	SE			Regrowth	1662		Black spur 4	9.8	17.2		1662		40% basal area removed by uniform thinning	1/7/1970–20/12/1976	
Black spur 3	7.7		SE			Regrowth	1662		Black spur 4	9.8	17.2		1662		50% uniform thinning (14-3-1977–2-5-1977)	1-7-1970–14-3-1977	
Ettercon 1	11.67					Regrowth			Ettercon 3	15.01					Jan-1982 to Mar 1982 39% strip thinning	28/7/1971–Jan 1982	Watson et al. (1999, 2001)
															Understorey removed-1979	5/8/1971–1979	
Ettercon 2	8.83					Regrowth			Ettercon 3	15.01					Infested with Psyllids-1998	15-7-1971–	
Ettercon 4	9.03					Regrowth			Ettercon 3	15.01					35% strip thinned Jan 1982–Mar-1982	Jan-1982	
Monda 1	6.31					Regrowth			Monda 4	6.31					79% clearfelled and regenerated with 2000 seedlings /ha	11-6-1970–5-12-1978	Jayasuriya and O'Shaughnessy (1988) and Watson et al. (1999, 2001)
Monda 2	3.98					Regrowth			Monda 4	6.31					5/12/77–26/4/78 clearfelled	11/6/1970–5/12/1977	Watson et al. (1999, 2001)
Monda 3	7.25					Regrowth			Monda 4	6.31					20/3/78 burnt	11/8/1970–5/12/1977	
															17:5-78 seedlings	13/7/1971–4/12/1984	
															75% clearfelled and regenerated with 5000 seedlings/ha 5/12/1977–26/4/1978 clearfelled 6/3/1978 burnt		

(*continued on next page*)

Table A1 (*continued*)

Treated catchment										Control catchment									
Catchment	Area (ha)	Slope (%)	Mean elevation (m)	Aspect	Climate	Pre-treatment vegetation	Post-treatment vegetation	Mean annual rainfall (mm)	Mean annual streamflow (mm)	Catchment control	Area (ha)	Slope (%)	Mean elevation (m)	Control aspect	Mean annual rainfall (mm)	Mean annual stream flow (mm)	Treatment	Calibration period	Source of info
																	17/5/1978 planted		
																	5/12/1977–26/4/1978 80% clearfelled and regenerated with 500 seedlings/ha 21/4/1978 burnt 9/5/1978 planted		
Myrtle 2	30.8					1759 *E. regnans*	Regrowth			Myrtle 1	25.21						74% clearfelled 4/12/1984–9/3/1985 Burnt 20/3/1985 Seeded. Winter 1985		
Coranderrk experimental area, Victoria, Australia																			
Blue Jacket	64.8	36.6		SW	Mediterranean-cool wet winters and hot dry summers	1850 *E. regnans* and *E. oblique*	Regrowth			Slip	62.3	40.3		S			Selective cut Nov 1972–Mar 1973	11/8/1958–8/11/1972	Watson et al. (1999), Nandakumar (1993) and Nandakumar and Mein (1997)
Piccaninny	52.8	37.8		S	Mediterranean-cool wet winters and hot dry summers	1850 *E. regnans* and *E. obliqua*	Regrowth			Slip	62.3	40.3		S			Clearfelling of 85% of vegetation in Nov 1971–Apr 1972	7/3/1956–16/11/1971	Watson et al. (1999), Nandakumar (1993) and Nandakumar and Mein (1997)
Stewarts Creek, Victoria, Australia																			
CA2	4.0	8.3		NE	Mediterranean-cool wet winters and hot dry summers	Mixed Species Eucalypt forest. Mixed Species Eucalypt forest	Bare ground (1969–1975) Pasture 1976	1120 (1960–1980)		CA1	4.3	9.0		NE	1400 (1960–1967)		Cleared 1969, Bare ground: April 1969–1975 Pasture 1976	1960–1969	Mein et al. (1988) and Nandakumar (1993)

CA5	17.6	7.6		NW			Bare ground: June 1969–April 1970. Pines: April 1970	1120 (1960–1980)		CA4	25.3	6.0		NW	1120 (1960–1980)		Cleared May 1969, Bare ground: April 1969–1970. Growing Pine forest: April 1970	1960–1969	
Parwan Experimental area, Victoria, Australia																			
Parwan 1	1.6			N	Mediterranean type climate	Native Pasture	Woodland	538		Parwan 3	1.6			N	538		Native Pasture (1954–1959) regeneration of woodland (1959–1968) grazing (1968–74)	1954–1959	Nandakumar (1993)
Parwan 2	1.6			N		Native Pasture	Improved pasture	538		Parwan 3	1.6			N	538		Native Pasture (1954–1959) Improved Pasture (1959–1968) Grazing (1968–74)	1954–1959	Nandakumar (1993)
Parwan 4	1.6			S		Native Pasture	Woodland	538		Parwan 5	1.6			S	538		Native Pasture (1954–1959) Regeneration of woodland (1959–1968) Grazing (1968–74)	1954–1959	Nandakumar (1993)
Parwan 5	1.6			S		Native Pasture	Improved pasture	538		Parwan 5	1.6			S	538		Native Pasture (1954–1959) Improved Pasture (1959–1968) Grazing (1968–74)	1954–1959	Nandakumar (1993)
Reefton Experimental area, Victoria, Australia																			
Reefton 1	70.4	6	559	N	Mediterranean type climate	Native Eucalypt forest	Regrowth	1233	180	Reefton 3-6	95.1	5	596	NW	1265	209	Native forest until 1984, 20% of the forest cleared in April 1984	1971–1980	Nandakumar (1993)
Reefton 2	76.1	12	588	W	Mediterranean type climate	Native Eucalypt forest	Regrowth	1250	258		107.2	9	594	SW	1249	234			
											156.2	5	640	SW	1308	228	Native Forest until April 1984. Understorey burnt in April 1984	1971–1980	Nandakumar (1993)
											521.2	2	651	S	1440	318			
Collie River Basin, Western Australia																			
Dons					Mediterranean climate	Eucalypt Forest	Agriculture	720		Ernie	270				720		Clearing of native forest by strip clearing, soil clearing and parkland clearing	1974–1976	Ruprecht and Schofield (1991b)
Lemons	344	8				Eucalypt forest	Agriculture	750									53.5% of catchment cleared between November 1976 and March 1977	1974–1976	Ruprecht and Schofield (1991a)
Wrights	94					Eucalypt forest	Agriculture	1200		Salmon							100% cleared in Summer 1976–1977	1974–1976	Ruprecht and Schofield (1989)

(*continued on next page*)

Table A1 (*continued*)

Treated catchment										Control catchment									
Catchment	Area (ha)	Slope (%)	Mean elevation (m)	Aspect	Climate	Pre-treatment vegetation	Post-treatment vegetation	Mean annual rainfall (mm)	Mean annual streamflow (mm)	Catchment control	Area (ha)	Slope (%)	Mean elevation (m)	Control aspect	Mean annual rainfall (mm)	Mean annual stream flow (mm)	Treatment	Calibration period	Source of info
Balingup Brook Tributary	93.3					Jarrah (*Eucalyptus marginata*)	Agriculture	880		Thomson Brook/ Ludlow River	10,20-0/1010				950/950		Afforestations	1978–1980 (first 3 years since reforestation)	Borg et al. (1988)
March road	261		170–230 m			Native forest dominated by *E. marginata* and *E. calophylla* and *E. diversicolor*	*E. diversicolor*	1050		April Road South	248				1050		Cleared January 1982–March 1983	1976–1982	Bari et al. (1996)
April Road North						Eucalypt forest	Regrowth	1070		Lewin North							Nursery raised karri seedlings were hand-planted in the same year of logging		Ruprecht and Schofield (1989)
Lewin South						Eucalypt forest	Regrowth	1220									Clear felling leaving 100 m buffers		
Wellbucket						Eucalypt forest	Regrowth										Selection cut and regeneration Selection cut and regeneration. Basal area reduced from 16 to 11 m^3/ha. Crown cover reduced from 55 to 22%	1982–1985 1977–1981	
Yarragil 4L	126	2.0		S		Eucalypt forest	Regrowth	1120	4.3	Yarragil 4X	270	3.1		SE			80% of canopy cover removed		Stoneman (1993)
Yerraminnup S						Eucalypt forest	Regrowth	850		Yarraminnup North							Logging leaving 50 m buffer and regeneration	1982–1985	Ruprecht and Schofield (1989)
Hansen	80					Eucalypt forest				Lewis	80						1985–86 intensive uniform thinning treatment was applied across the catchment excluding the swamp and a 50 m buffer strip	1978–1984	Ruprecht et al. (1991)

India																			
Doon Valley	1.45	5.1		SE		Derived scrub with sal seedlings	*E. grandis* and *E. camaldulensis*	1167									Conversion from natural grassland to Bluegum plantation (rotation 10 years). Blue gum harvested in 1982 followed by a second rotation of coppiced bluegum	1968–1972	Oyebande (1988)
Glenmorgan B	32				Montage temperate humid climate	Grassland	Bluegum Rotation 1 then Bluegum rotation 2	1380		Glenmorgan A	32				1380				Sharda et al. (1988) and Sharda et al. (1998)
Big Bush, New Zealand																			
DC1	8.57		550	NW	Evenly distributed rainfall throughout the year, mean annual temperature of 10.5 °C	Mixed evergreen native forest remnants and plantations of exotic species	*Pinus radiata*	1530		DC2	4.74		550	NW			83% of area skidder-logged between April and December 1980. *P. radiata* planted May 1981	1975–1980	Fahey and Jackson (1997)
DC4	20.19		550	NW													94% clearfelled and harvested by hauler between May 1980 and June 1981, planted with *P. radiata* in September 1981	1975–1980	
Glendhu State Forest, New Zealand																			
GH2	310		460–670	N	Rainfall occurs as many small events of long duration and low intensity. Dry spells are common in summer	Snow-Tussock	*P. radiata*	1350		GH1	218		460–670	N	1350		67% planted with *P. radiata* in 1982 at 1230 stems/ha	1979–1982	McLean (2001) and Fahey and Jackson (1997)
Maimai, Westland, New Zealand																			
M13	4.25	37	340	SW	Superhumid, microthermal, with adequate rainfall in all seasons	Evergreen mixed beech–podocarp–hardwood forest	Regrowth	2650	1550	M15	2.64	34	335	SW	2650	1550	95% clearfelled, vegetation left in riparian zone	1977	Rowe et al. (1994)
M14	4.62	36	340	SW			Regrowth	2650	1550	M15	2.64	34	335	SW	2650	1550	100% clearfelled	1977	Rowe and Pearce (1994)

(*continued on next page*)

Table A1 (*continued*)

Treated catchment										Control catchment									
Catchment	Area (ha)	Slope (%)	Mean elevation (m)	Aspect	Climate	Pre-treatment vegetation	Post-treatment vegetation	Mean annual rainfall (mm)	Mean annual streamflow (mm)	Catchment control	Area (ha)	Slope (%)	Mean elevation (m)	Control aspect	Mean annual rainfall (mm)	Mean annual stream flow (mm)	Treatment	Calibration period	Source of info
M5	2.31	36	290	SW			Regrowth	2650	1550	M6	1.63	36	285	SW	2650	1550	100% clearfelled	1977	
M8	3.84	36	305	SW			Regrowth	2650	1550	M6	1.63	36	285	SW	2650	1550	90% clearfelled, vegetation left in riparian zone	1977	
Uitsoek State Forest, South Africa																			
Mokobulaan B	34.6	0.22	1318–1486	E	Sub-tropical with 80% of the average annual rainfall of 1167 mm falling within the summer months of October to March	Sub-climax grassland, North Eastern Mountain Sourveld, maintained by regular burning and grazing	Pines	1197	196	Mokobulaan C	36.9	0.26	1341–1494	E	1199	118	100% afforested with *Pinus patula*, January 1971 1971–1370 stems/ha 1979–650 stems/ha	1956–1971	Van Lill et al. (1980), Dye (1996), Scott and Lesch (1997), Scott and Smith (1997) and Scott et al. (2000)
Westfalia, South Africa																			
Westfalia D	39.6	0.33	1050–1320	SE	Sub-tropical with Summer rainfall season	Transitional between evergreen high forest and deciduous woodland	*Eucalyptus grandis*	1253	590	Westfalia B	32.6	0.42	1140–1420	SE	1253	492	Riparian zone (10%) of area cut in 1981. 83% afforested with *E. grandis* in 1983	1975–1981	Scott and Smith (1997) and Scott et al. (2000)
Taiwan																			
LHC-4	5.86	40		SE	Warm and humid, the average monthly temperature never falling below 15 degrees	Warm-temperate montane rainforest	Regrowth	2100	1100	LHC-5	8.39			SW			1978–1979 100% clear cut	1970–1977	Hsia and Koh (1983)
Beaver Creek, Arizona, USA																			
WS 12	184		2150	SW		Uneven aged stands of ponderosa pine		617	150	WS 13	369		2195	SW	609	93	100% removal of overstory		Baker (1986)
WS 14	546		2194	S				650	117	WS 13	369		2195	SW	609	93	57% strip cutting with thinning		Baker (1986)
WS 16	102		2164	SE				703	135	WS 15	66		2103	S	685	99	68% strip-cut with thinning		Baker (1986)
WS 17	121		2115	SW				726	206	Watershed 18	98		2054	S	728	180	77% removal of overstory		Baker (1986)
WS 8	730		2225	W				679	174	WS 13	369		2195	SW	609	93	33% removal of overstory		Baker (1986)
WS 9	454		2194	W				645	155	WS 8	730		2225	W	658	160	31% strip cut with thinning		Baker (1986)

Fraser experimental forest, USA											
Deadhorse creek–North Fork	41		Cool and humid with long, cold winters and short, cool summers	Lodgepole pine on all lower and mid-south slopes, and alpine tundra above the timber line	Regrowth	Lexen Creek	124	3002–3536	Timber removed on 36% of land area (1977)	1970–1977	Alexander et al. (1985) and Troendle and King (1987)
Deadhorse Creek–Upper Basin	78				Regrowth	Lexen Creek	124	3002–3536	30% harvested in irregular shaped clear-cuts, varying in size from 1 to 6 ha (summers of 1983–1984)	1975–1982	Alexander et al. (1985) and Troendle and King (1987)
Caspar Creek, California, USA											
South Fork	424	37–320	Mediterranean, dry summers			North Fork	483	37–230	Road construction 1967 Logging 1971–1973	1963–1967	Keppeler and Ziemer (1990) and Wright et al. (1990)
Plynlimon, United Kingdom											
Severn	1055					Wye	870				Kirby et al. (1991)
Balquhidder experiment, United Kingdom											
Kirkton	685	540				Monoachyle	770	470			Johnson (1991)

References

Alexander, R.R., Troendle, C.A., Kaufmann, M.R., Shepperd, W.D., Crouch, G.L., Watkins, R.K., Love, L.D., 1985. The Fraser Experimental Forest, Colorado: Research Program and Published Research 1937–1985, General Technical Report RMRS-GTR-118. U.S. Department of Agriculture, Forest Service, Rocky Mountain Range and Experiment Station, Fort Collins, CO. 35 p.

Baker, M.B., 1984. Changes in streamflow in an herbicide-treated pinyon-juniper watershed in Arizona. Water Resources Research 20 (11), 1639–1642.

Baker, M.B., 1986. Effects of Ponderosa pine treatments on water yield in Arizona. Water Resources Research 22 (1), 67–73.

Bari, M.A., Smith, N., Ruprecht, J.K., Boyd, B.W., 1996. Changes in streamflow components following logging and regeneration in the southern forest of Western Australia. Hydrological Processes 10 (3), 447–461.

Blackie, J.R., 1979. Summary of results of the Kericho experiments Hydrological changes as a result of conversion of forest to tea plantation, Kenya. East African Agricultural and Forestry Journal 43, 139–140.

Blackie, J.R., Edwards, K.A., 1979. General conclusions from the land use experiments in east Africa. East African Agricultural and Forestry Journal 43, 273–277.

Bonell, M., Gilmore, D.A., Cassells, D.S., 1983. Runoff generation in tropical northeast Queensland, Australia, and the implications for land use management. Hydrology of humid tropical regions with particular reference to the hydrological effect to agriculture and forestry practice, Proceedings of Hamburg Symposium, August 1983. IAHS Publication No. 140 1983 pp. 287–297.

Borg, H., Bell, R.W., Loh, I.C., 1988. Streamflow and stream salinity in a small water supply catchment in southwest Western Australia after reforestation. Journal of Hydrology 103 (3–4), 323–333.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55 (1/4), 3–23.

Bren, L.J., Papworth, M., 1991. Early water yield effects of a conversion of slopes of a eucalypt forest catchment to radiata pine plantation. Water Resources Research 27, 2421–2428.

Bruijnzeel, L.A., 1988. (De)forestation and dry season flow in the tropics: a closer look. Journal of Tropical Forest Science 1 (3), 229–243.

Bruijnzeel, L.A., 1990. Hydrology of moist tropical forests and effects of conversion: a state of knowledge review. UNESCO, International Hydrological Programme, Paris.

Burch, G.J., Bath, R.K., Moore, I.D., O'Loughlin, E.M., 1987. Comparative hydrological behaviour of forested and cleared catchments in southeastern Australia. Journal of Hydrology 90 (1/2), 19–42.

Burt, T.P., Swank, W.T., 1992. Flow frequency responses to hardwood-to-grass conversion and subsequent succession. Hydrological Processes 6 (2), 179–188.

Caissie, D., Jolicoeur, S., Bouchard, M., Poncet, E., 2002. Comparison of streamflow between pre and post timber harvesting in Catamaran Brook (Canada). Journal of Hydrology 258 (1–4), 232–248.

Cassells, D.S., Gilmour, D.A., Bonell, M., 1982. Drainage processes in a north Queensland rainforest catchment—their influence on catchment response to land use change. Rural Drainage in northern Australia, Darling Downs Institute of Advanced Education Toowoomba, Queensland 27–29 September 1982, 257–282.

Cassells, D.S., Gilmour, D.A., Bonell, M., 1985. Catchment response and watershed management in the tropical rainforests in north eastern Australia. Forest Ecology and Management 10, 155–175.

Cornish, P.M., 1993. The effects of logging and forest regeneration on water yields in a moist eucalypt forest in New South Wales, Australia. Journal of Hydrology 150, 301–322.

Cornish, P.M., Vertessy, R.A., 2001. Forest age-induced changes in evapotranspiration and water yield in eucalypt forest. Journal of Hydrology 242, 43–63.

Crapper, P.F., O'Loughlin, E.M., Mackay, S.M., 1989. The hydrological affect of intensive logging operation on a small forested catchment near Eden, NSW, Hydrology and Water Resources Symposium 1989. University of Canterbury, Christchurch. The Institution of Engineers, Australia pp. 444–448.

Dye, P.J., 1996. Climate, forest and streamflow relationships in South African afforested catchments. Commonwealth Forestry Review 75 (1), 31–38.

Edwards, K.A., 1979. The water balance of the Mbeya experimental catchments. East African Agricultural and Forestry Journal 43, 231–247.

Fahey, B., Jackson, R., 1997. Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. Agricultural and Forest Meteorology 84 (1–2), 69–82.

Gafur, A., Jensen, J.R., Borggaard, O.K., Petersen, L., 2003. Runoff and losses of soil and nutrients from small watersheds under shiffting cultivation (Jhum) in the Chittagong Hill Tracts of Bangladesh. Journal of Hydrology 279 (1–4), 293–309.

Gallart, F., Llorens, P., Latron, J., Reguees, D., 2002. Hydrological processes and their seasonal controls in a small Mediterranean mountain catchment in the Pyrenees. Hydrology and Earth System Sciences 6 (3), 527–537.

Gilmore, D.A., Cassells, D.A., Bonell, M., 1982. Hydrological research in the tropical rainforests of North Queensland: some implications for land use management, The First National Symposium on Forest Hydrology. Institute of Engineering, Australia. National Conference Pulb, Institute of Engineering 1982 pp. 145–152.

Hibbert, A.R., 1967. Forest Treatment effects on water yield, Reprint from Proceedings of International Symposium on Forest Hydrology, Penn State University 1965 527–543. Pergamon Press, New York. 1967.

Hibbert, A.R., 1969. Water yield changes after converting a forested catchment to grass. Water Resources Research 5 (3), 634–640.

Hickel, K., 2001. The effect of pine afforestation on flow regime in small upland catchments. Masters Thesis, University of Stuttgart.

Holmes, J.W., Sinclair, J.A., 1986. Water Yield from some afforested catchments in Victoria. Hydrology and Water Resources Symposium, Griffith University, Brisbane, 25–27 November 1986. Australia, The Institution of Engineers pp. 214–218.

Hornbeck, J.W., 1975. Moderating the impact of contemporary forest cutting on hydrologic and nutrient cycles, IAHS-AISH Publication No. 117 1975 pp. 423–433.

Hornbeck, J.W., Pierce, R.S., Federer, C.A., 1970. Streamflow changes after forest clearing in New England. Water Resources Research 6 (4), 1124–1132.

Hornbeck, J.W., Martin, C.W., Pierce, R.S., Bormann, F.H., Likens, G.E., Eaton, J.S., 1987. The northern hardwood forest ecosystem: ten years of recovery from clearcutting, Research Paper NE-596. U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Broomall, PA. 30 p.

Hornbeck, J.W., Adams, M.B., Corbett, E.S., Verry, E.S., Lynch, J.A., 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology 150 (2/4), 323–344.

Hornbeck, J.W., Martin, C.W., Eagar, C., 1997. Summary of water yield experiments at Hubbard Brook experimental forest, New Hampshire. Canadian Journal of Forest Research 27, 2043–2052.

Hsia, Y.J., Koh, C.C., 1983. Water yield resulting from clear cutting a small hardwood basin in central Taiwan. Hydrology of humid tropical regions with particular reference to the hydrological effects of agriculture and forestry Practice, Proceedings of the Hamburg Symposium, August 1983. IAHS Publication No. 140 1983 pp. 215–220.

Jayasuriya, M.D.A., O'Shaughnessy, P.J., 1988. The use of mathematical models in evaluating forest treatments effects on streamflow, Hydrology and Water Resources Symposium, 18th, 1–3 Feb 1988. Australian National University, The Institution of Engineers, Australia pp. 135–139.

Johnson, R.C., 1981. Effects of upland afforestation on water resources, The Balquhidder Experiment 1981–1991. Institute of Hydrology, Report No. 116 1981.

Johnson, E.A., Kovner, J.L., 1956. Effect on streamflow of cutting a forest cnderstory. Forest Science 2, 82–91.

Jones, J.A., Grant, G.E., 1996. Peak flow responses to clear-cutting and roads in small and large basins, Western Cascades, Oregon. Water Resources Research 32, 959–974.

Jones, J.A., Grant, G.E., 2001. Comment on "Peak flow response to clear-cutting and road in small and large basins, western Cascades, Oregon: a second opinion" by R.B. Thomas, W.F. Megahan. Water Resources Research 37, 175–178.

Keppeler, E.T., Ziemer, R.R., 1990. Logging effect on streamflow: water yield and summer low flows at Caspar Creek in Northwestern California. Water Resources Research 26 (7), 1669–1679.

Kirby, C., Newson, M.D., Gilman, K., 1991. Plynlimon research: the first two decades. Institute of Hydrology, Report No. 109.

Kuczera, G., 1987. Prediction of water yield reductions following a bushfire in ash-mixed species eucalypt forest. Journal of Hydrology 94 (3/4), 215–236.

Lane, P.N.J., Mackay, S.M., 2001. Streamflow response of mixed-species eucalypt forest to patch cutting and thinning treatments. Forest Ecology and Management 143, 131–142.

Langford, K.J., 1976. Change in yield of water following a bushfire in a forest of *Eucalyptus regnans*. Journal of Hydrology 29 (1/2), 87–114.

Lawrence, P.A., Sinclair, D.P., 1986. Analysis of rainfall variability on the Brigalow experimental catchments, Hydrology and Water Resources Symposium, Griffith University, Brisbane 25–27 November. Institution of Engineers, Australia pp. 334–339.

Lawrence, P.A., Thorburn, P.J., 1989. Changes in hydrology, soil fertility and productivity of Brigalow catchments following clearing. Queensland Department of Primary Industries. Project Report. RQR89002.

Lewis, D., Singer, M.J., Dahlgren, R.A., Tate, K.W., 2000. Hydrology in a California oak woodland watershed: a 17-year study. Journal of Hydrology 240, 106–117.

MacKay, S.M., Cornish, P.M., 1982. Effects of wildfire and logging on the hydrology of small catchments near Eden, NSW, The First National Symposium on Forest Hydrology. The Institution of Engineers, Australia. National Conference Publication No. 82/6 1982 pp. 111–117.

McLean, S., 2001. Baseflow response to Vegetation change, Glendhu State Forest, Otago, New Zealand. Masters Thesis.

Mein, R.G., Bieniaszewska-Hunter, H., Papworth, M., 1988. Land use changes and the hydrologic water balance—Stewarts Creek experimental area, Hydrology and Water Resources Symposium, 18th, 1–3 Feb 1988. Australian National University. National conference publication (Institution of Engineers, Australia); 88/1 1988 pp. 129–134.

Miller, E.L., Beasley, R.S., Lawson, E.R., 1988. Forest harvest and site preparation effects on stormflow and peakflow of ephemeral streams in the Ouachita mountains. Journal of Environmental Quality 17 (2), 212–218.

Moore, I.D., Mackay, S.M., Wallbrink, P.J., Burch, G.J., O'Loughlin, E.M., 1986. Hydrologic characteristics and modelling of a small forested catchment in southeastern New South Wales. Pre-logging condition. Journal of Hydrology 83 (3/4), 307–335.

Mundy, S.C., Nathan, R.J., Daamen, C.C., Cornish, P.M., 2001. Development and application of a model to assess the impact of practical plantation forestry on water yields, MODSIM, Volume 1: Natural Systems (Part One). The Australian National University Canberra, Australia 10–13 December 2001 pp. 449–454.

Nandakumar, N., 1993. Analysis of paired catchment data to predict the hydrological effects of land-use changes. PhD Thesis, Monash University, Melbourne, Australia.

Nandakumar, N., Mein, R.G., 1997. Uncertainty in rainfall-runoff model simulations and the implications for predicting the hydrologic effects of land use change. Journal of Hydrology 192 (1–4), 211–232.

O'Shaughnessy, P.J., Jayasuriya, M.D.A., Aney, S.G., 1989. A review of the catchment management policies of three major water supply authorities with special reference to recent Melbourne Board of Works forest hydrology research results, Forest planning for people: Conference of the Institute of Foresters of Australia, 13th, 18–22 Sept 1989, Leura NSW, Proceedings. Institute of Foresters of Australia, Sydney pp. 107–121.

Oyebande, L., 1988. Effects of tropical forest on water yield, in: Reynolds, E.R.C., Thompson, F.B. (Eds.), Forest, Climate and Hydrology, Regional Impacts. The United Nations University, .

Peel, M.C., McMahon, T.A., Finlayson, B.L., Watson, F.G., 2001. Identification and explanation of continental differences in the variability of annual runoff. Journal of Hydrology 250 (1–4), 224–240.

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

Rich, L.R., Gottfried, G.J., 1976. Water yields resulting from treatments on the Workman Creek experimental watersheds in Central Arizona. Water Resources Research 12 (5), 1053–1060.

Roberts, S., 2001. Water yield and transpiration in mixed species dry sclerophyll eucalypt forests in south eastern Australia. PhD Thesis, The University of Melbourne.

Roberts, S., Vertessy, R., Grayson, R., 2001. Transpiration from *Eucalyptus seeberi* (L. Johnson) forests of different age. Forest Ecology and Management 143, 153–161.

Rogerson, T.L., 1971. Hydrological characteristics of small head-water catchments in the Ouachita mountains. U.S. Forest Service Research Note SO-117.

Rothacher, J., 1970. Increases in water yield following clear-cut logging in the Pacific Northwest. Water Resources Research 6 (2), 653–658.

Rowe, L.K., Pearce, A.J., 1994. Hydrology and related changes after harvesting native forest catchments and establishing *Pinus radiata* plantations. Part 2. The native forest water balance and changes in streamflow after harvesting. Hydrological Processes 8 (4), 281–297.

Rowe, L.K., Pearce, A.J., O'Loughlin, C.L., 1994. Hydrology and related changes after harvesting native forest catchments and establishing *Pinus radiata* plantations. Part 1. Introduction to study. Hydrological Processes 8 (3), 263–279.

Ruprecht, J.K., Schofield, N.J., 1989. Analysis of streamflow generation following deforestation in southwest Western Australia. Journal of Hydrology 105 (1–2), 1–17.

Ruprecht, J.K., Schofield, N.J., 1991a. Effects of partial deforestation on hydrology and salinity in high salt storage landscapes. I: extensive block clearing. Journal of Hydrology 129 (1/4), 19–38.

Ruprecht, J.K., Schofield, N.J., 1991b. Effects of partial deforestation on hydrology and salinity in high salt storage landscapes, II: strip, soils and parkland Clearing. Journal of Hydrology 129 (1/4), 39–55.

Ruprecht, J.K., Schofield, N.J., Crombie, D.S., Vertessy, R.A., Stoneman, G.L., 1991. Early hydrological response to intense forest thinning in southwestern Australia. Journal of Hydrology 127 (1/4), 261–277.

Sahin, V., Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology 178 (1/4), 293–309.

Schneider, W.J., Ayer, G.R., 1961. Effect of reforestation on streamflow in Central New York, U.S. Geological survey water—supply paper 1602 1961. 61 p.

Schofield, N.J., 1991. Hydrological response to vegetation changes and its consequences in Western Australia, Challenges for sustainable development: International Hydrology and Water Resources Symposium, 2–4 Oct 1991, Perth. National Conference Publication (Institution of Engineers, Australia); 91/19 1991 pp. 386–391.

Schofield, N.J., 1996. Forest management impacts on water values. Recent Research Developments in Hydrology 1, 1–20.

Scott, D.F., Lesch, W., 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. Journal of Hydrology 199 (3–4), 360–377.

Scott, D.F., Smith, R.E., 1997. Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. Water S.A. 23 (2), 135–140.

Scott, D.F., Le Maitre, D.C., Fairbanks, D.H.K., 1998. Forestry and streamflow reductions in South Africa: a reference system for assessing extent and distribution. Water S.A. 24 (3), 187–200.

Scott, D.F., Prinsloo, F.W., Moses, G., Mehlomakulu, M., Simmers, A.D.A., 2000. A re-analysis of the South African afforestation experimental data, Water Research Commission, WRC Report No. 810/1/00, South Africa 2000.

Sharda, V.N., Samraj, P., Chinnamani, S., Lakshmanan, V., 1988. Hydrological behaviour of the Nilgiri sub-watersheds as affected by Bluegum Plantations: Part II. Monthly water balances at different rainfall and runoff probabilities. Journal of Hydrology 103 (3–4), 347–355.

Sharda, V.N., Samraj, P., Samra, J.S., Lakshmanan, V., 1998. Hydrological behaviour of first generation coppiced bluegum plantations in the Nilgirl sub-watersheds. Journal of Hydrology 211 (1–4), 50–60.

Silberstein, R., Adhitya, A., Dabrowski C., 2003. Changes in flood flows, saturated area and salinity associated with forest clearing for agriculture. CRC for Catchment Hydrology, Technical Report 03/01. Monash University, Victoria, Australia.

Smakhtin, V.U., 1999. A concept of pragmatic hydrological time series modelling and its application in South African context, Ninth South African National Hydrology Symposium: 29–30 November 1999 1999 pp. 1–11.

Smakhtin, V.U., 2001. Low flow hydrology: a review. Journal of Hydrology 240 (3–4), 147–186.

Stednick, J.D., 1996. Monitoring the effects of timber harvest on annual water yield. Journal of Hydrology 176 (1/4), 79–95.

Stoneman, G.L., 1993. Hydrological response to thinning a small jarrah (*Eucalyptus marginata*) forest catchment. Journal of Hydrology 150 (2/4), 393–407.

Swank, W.T., Swift, L.W., Douglass, J.E., 1987. Streamflow changes associated with forest cutting, species conversions, and natural disturbances, in: Swank, W.T., Crossley, D.A. (Eds.), Forest Hydrology and Ecology at Coweeta. Springer, New York, pp. 291–312.

Swank, W.T., Vose, J.M., Elliott, K.J., 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. Forest Ecology and Management 143 (1–3), 163–178.

Thomas, R.B., Megahan, W.F., 1998. Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: a second opinion. Water Resources Research 34, 3393–3403.

Thomas, R.B., Megahan, W.F., 2001. Reply to comment on Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon: a second opinion. Water Resources Research 37, 181–183.

Troendle, C.A., 1983. Potential for water yield augmentation from forest management in the Rocky Mountain Region. Water Resources Bulletin 19 (3), 359–373.

Troendle, C.A., King, R.M., 1987. The effect of partial and clearcutting on streamflow at Deadhorse creek, Colorado. Journal of Hydrology 90 (1/2), 145–157.

Troendle, C.A., Wilcox, M.S., Bevenger, G.S., Porth, L.S., 2001. The Coon Creek water yield augmentation project: implementation of timber harvesting technology to increase streamflow. Forest Ecology and Management 143 (1–3), 179–187.

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

Van Lill, W.S., Kruger, F.J., Van Wyk, D.B., 1980. The effect of afforestation with *Eucalyptus grandis* hill ex maiden and *Pinus patula Schlecht. Et Cham.* on streamflow from experimental catchments at Mokobulaan, Transvaal. Journal of Hydrology 48 (1/2), 107–118.

Vertessy, R.A., 1999. The impacts of forestry on streamflows: a review, in: Croke, J., Lane, P. (Eds.), Forest Management for the Protection of Water Quality and Quantity Proceedings of the Second Erosion in Forests Meeting, Warburton, 4–6 May 1999, Cooperative Research Centre for Catchment Hydrology, Report 99/6, pp. 93–109.

Vertessy, R.A., 2000. Impacts of plantation forestry on catchment runoff, in: Sadanandan Nabia, E.K., Brown, A.G. (Eds.), Plantations, Farm Forestry and Water Proceedings of a National Workshop, 20–21 July, Melbourne, pp. 9–19.

Vertessy, R.A., Bessard, Y., 1999. Anticipation the negative hydrological effects of plantation expansion: results from GIS-based analysis on the Murrumbidgee Basin, in: Croke, J., Lane, P. (Eds.), Forest Management for the Protection of Water Quality and Quantity Proceedings of the Second Erosion in Forests Meeting, Warburton, 4–6 May 1999, Cooperative Research Centre for Catchment Hydrology, Report 99/6, pp. 69–74.

Vertessy, R.A., Watson, F.G.R., O'Sullivan, S.K., 2001. Factors determining relations between stand age and catchment water balance in mountain ash forests. Forest Ecology and Management 143 (1–3), 13–26.

Watson, F.G.R., Vertessy, R.A., McMahon, T.A., Watson, I.S., 1999. The hydrologic impacts of forestry on the Maroohdah catchments. CRC for Catchment Hydrology, Technical Report 99/1. Monash University, Victoria, Australia.

Watson, F., Vertessy, R., McMahon, T., Rhodes, B., Watson, I., 2001. Improved methods to assess water yield changes from paired-catchment studies: application to the Maroondah catchments. Forest Ecology and Management 143 (1–3), 189–204.

Whitehead, P.G., Robinson, M., 1993. Experimental basin studies—an international and historical perspective of forest impacts. Journal of Hydrology 145 (3/4), 217–230.

Wright, K.A., Sendek, K.H., Rice, R.M., Thomas, R.B., 1990. Logging effects on streamflow: storm runoff at Caspar Creek in Northwestern California. Water Resources Research 26 (7), 1657–1667.

Zhang, L., Dawes, W.R., Walker, G.R., 1999. Predicting the effect of vegetation changes on catchment average water balance. CRC for Catchment Hydrology, Technical Report 99/12. Monash University, Victoria, Australia.

Zhang, L., Dawes, W.R., Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research 37 (3), 701–708.