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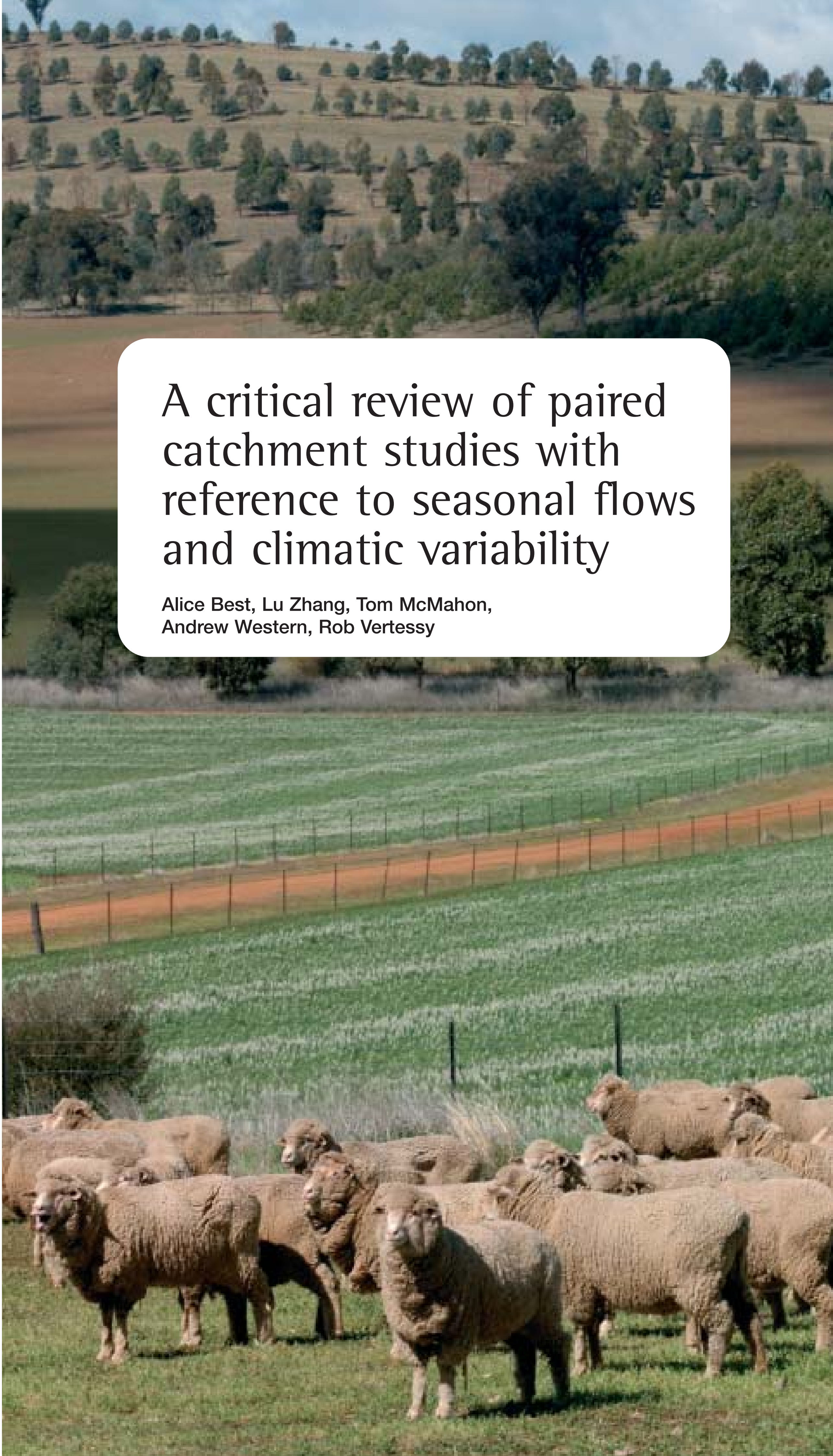

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Executive summary

Since European settlement in Australia, large-scale clearing of native vegetation for agriculture has caused alterations in the hydrologic regime of many Australian catchments. The Forest Plantations 2020 Vision states that by 2020 the area of tree plantations within Australia will treble. If implemented, this will impact on water yield at both local and regional scales. Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes resulting from changes in vegetation and they provide a possible means of predicting the likely impacts of broad-scale vegetation changes on water yield.

This review focuses on the use of paired catchment studies as a means for determining long-term changes in water yield as a result large scale changes in vegetation. Paired catchment studies can be divided into four broad categories: afforestation experiments, deforestation experiments, regrowth experiments and forest conversion experiments. The methods used to assess the magnitude of annual and seasonal changes in water yield have been reviewed and implications for applying paired catchments results to large catchments, where the land use is likely to consist of a mosaic of vegetation at different stages of development, have been identified. Current knowledge gaps in relation to the impacts of broad scale vegetation changes on flow regime and seasonal flows are highlighted and possible methods of addressing these gaps are suggested.

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1. Introduction

Since European settlement in Australia, large-scale clearing of native vegetation for agriculture has caused alterations in the hydrologic regime of many Australian catchments. In southern Australia salinity is recognised as one of the most serious environmental degradation issues, affecting both soil and water quality. The massive clearing of native vegetation and its replacement by shallow-rooted annual crops and pastures has caused salinity, through the reductions in evapotranspiration and increases in groundwater recharge. The decrease in evapotranspiration is also likely to lead to an increase in streamflow, which not only increases water supply, but also helps to dilute salt inflows (Zhang et al. 1999). Plantations for Australia: The 2020 Vision (DPIE 1997) states that by 2020 the area of tree plantations within Australia will treble. If implemented, this will impact on water yield at both local and regional scales. The response of catchments to such a land use change is likely to vary in both space and time and in order to develop sustainable land management options, it is necessary to predict the effects of such afforestation on water yield and it seasonal variability.

Paired catchment studies have been widely used as a means of determining the magnitude of water yield changes as a result of 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. They updated an earlier review by Hibbert (1967) in which 39 experimental catchments, predominantly in the USA, were analysed and the following generalisation made:

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

Bosch and Hewlett (1982) added an additional 55 catchments to those reviewed by Hibbert (1967). 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. While Bosch and Hewlett (1982) supported the first two conclusions made by Hibbert, their results indicated that to a certain degree the influence of afforestation and deforestation could be predicted. 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 Hornmeck et al. (1993), Stednick (1996) and Sahin and Hall (1996). Vertessy (1999, 2000) reviewed the literature available on paired catchment studies with respect to forestry and streamflow. These two reviews provide a comprehensive summary of the present understanding of land use change impacts on water yield, with particular reference to Australian conditions. While the impact of afforestation and deforestation on mean annual water yield is well understood, there is little reported in the literature on seasonal water yield and what has been reported is mainly of a descriptive nature.

While results from the many paired catchment studies demonstrates that they can be used to assess the impact of land use change on water yield at the local scale, doubts exist about the application of paired catchment results to large catchment or a regional scale. On a regional scale, land use changes are likely to be mosaics with vegetation at different stages of development. Therefore uncertainty exists about the application of small scale experimental results to large catchments (Wilk et al. 2001). An alternative method that could be used to assess the impacts of vegetation changes on large catchments is the use of time-trend studies. However this requires the separation of the impact of vegetation changes from climatic variability. Munday et al. (2001) used a general additive model (GAM) to assess to impact of a

mosaic of vegetation types (pine plantation, eucalypt forests and pasture) on water yield in the Adjungbilly catchment in south eastern Australia. This model simulated the annual average water yield changes in response to the natural ageing of forests and to user defined logging regimes. While a time-trend study with a good vegetation history was used in this study, paired catchment experiments were used to gain an understanding of the impact of pine plantations and the stand age of native vegetation on water yield.

The purpose of this report is to:

1. review the paired catchments methods used to assess the magnitude of annual and seasonal changes in water yield that can be attributed to alterations in vegetation type
2. investigate the possible methods for separating the impacts of climatic variability on water yield form the effects of alterations in vegetation types
3. highlight the knowledge gaps in the literature in relation to the impacts of vegetation type on seasonal water yield and flow regime
4. suggest how generalisation made from paired catchments can be applied to large catchment with a mosaic of vegetation types.

This review includes an additional 56 paired catchments on top on those reviewed by Bosch and Hewlett (1982) bringing the total number of paired catchment experiments reviewed to 150. Details of these experimental catchments can be found in **Appendix A**.

2. Paired catchments

Paired catchment studies have been widely used to assess the likely impact of land use change on water yield around the world. Such studies involve the use of two catchments with similar characteristics in terms of slope, aspect, soils, area, precipitation and vegetation located adjacent 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 change 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:

(i) afforestation experiments;

(ii) regrowth experiments;

(iii) deforestation experiments; and

(iv) forest conversion experiments.

2.1 Methods used to determine annual changes in water yield

Various methods have been applied in the analysis of paired catchment data to assess the impacts of vegetation changes on water yield a various time scales. The most commonly used method is to produce a linear regression between the control and the treated catchment for annual data collected 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 has not taken place. The difference in the observed and the predicted streamflow is then assumed to be due to land use change as the method provides a control over climatic variability (Bari et al. 1996). While the method of linear regression is most commonly used on annual data it has also been used on the components of streamflow, the quick flow response and baseflow (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 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 impacts of afforestation on annual streamflow and the variations on between years due to development of plantations, Scott and Smith (1997) developed an empirical model that predicts the percentage reduction in water yield with time. This work is further discussed in **Section 4**.

2.2 Methods for determining seasonal changes in water yield

Seasonal or monthly analysis of paired catchments data is less common than annual analysis. As with annual analysis the most commonly used method is to use standard linear regression techniques on monthly data (making no adjustments for the serial correlation) to establish pre-treatment relationships between the control and the treated catchments. Lane and Mackay (2001) adopted this method in their analysis of data in the Tantawangalo Creek catchments in New South Wales as insufficient data was available during the pre-treatment year to use annual data to develop the relationships. Scott and Lesch (1997) also used monthly data in their analysis of the Mokobulaan experimental catchments in South Africa. To adjust for the serial correlation of monthly data both streamflow and rainfall data were included as independent variables in a monthly multiple regression. The rainfall term was considered as part of an antecedent wetness index, which considered the wetness index for the previous month and the rainfall in the present month. The analysis of Scott and Lesch (1997) looked at 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 Maroondah experimental catchments in Victoria, Australia. They argued that the short pre-treatment periods in most paired catchment studies, limits the strength of the regression analysis and recommended that monthly data with an explicit seasonal component should be used. In a number of studies in south Western Australia, only three years of pre-treatment data have been used to generate the linear regression on annual flows (Ruprecht and Schofield 1989), casting doubt on the strength of the correlation gained. The advantage of using monthly data is that there are 12 times as many data points, than in the analysis of annual data (Watson et al. 1999). However it is important to note that while the use of monthly data represents more information if the serial correlation is treated, it does not represent 12 times the annual data.

2.3 Types of paired catchment experiments

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 impact on 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.

The paired catchment experiments reviewed in this report can by divided into four broad categories.

1. Afforestation experiments—conversion of sparsely vegetated land to forest. Examples of these can be found in South Africa (Scott et al. 2000), New Zealand (McLean 2001), Australia (Hickel 2001) and in the UK (Kirby et al. 1991, Johnson 1995).
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 clearing of densely vegetated land to grass or pasture. Examples include the Collie catchments in Western Australia (Ruprecht and Schofield 1989, Ruprecht and Schofield 1991a, Ruprecht and Schofield 1991b, Ruprecht et al. 1991, Schofield 1991).
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 provides an example of the conversion of native vegetation to pine in Victoria, Australia (Mein et al. 1988, Nandakumar 1993).

Vertessy (1999) highlighted some of the problems with using regrowth experiments for estimating yield increases. Where a forests are permitted to regenerate only the data obtained in the first few years following treatment are used in building relationships between the percentage change in cover and the change in yield. Three problems were highlighted in relation to the use of such data:

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

The results of various paired catchment experiments are discussed in **Section 4**, following a review of the major hydrological processes in **Section 3**.

3. Hydrological processes in relation to vegetation type

The effects of two main vegetation types on components of the water balance are discussed in the following section. The two main vegetation types considered are grass or pasture and forests.

The water balance equation for a given catchment can be written as:

$$P = ET + Q + D + \Delta S \qquad (1)$$

where P is the precipitation, ET is the actual evapotranspiration, Q in the streamflow, D is the recharge to the ground water and ΔS is the change in soil water storage.

The evapotranspiration and streamflow terms in equation (1) can be rewritten as

$$ET = I + T + E \qquad (2)$$

where I = interception loss, T = transpiration and E = soil evaporation;

$$Q = OF + BF \qquad (3)$$

where OF = overland flow and BF = baseflow

The hydrological processes and water balance components discussed in relation to vegetation types are precipitation, evapotranspiration, interception, transpiration, soil evaporation, infiltration, overland flow, deep drainage, baseflow and recharge.

3.1 Precipitation

Precipitation is the largest term in the water balance equation and varies both temporally and spatially (Zhang et al. 2001). In discussing the impact of vegetation type on precipitation it is important to distinguish between gross precipitation and net precipitation. Gross precipitation is the amount of rainfall (or snow) falling above the vegetation, while net precipitation is the amount of precipitation reaching the ground surface. In most cases gross precipitation can be assumed to be independent of vegetation type (Calder 1998).

Calder (1999) suggests one of the myths associated with forests is that forests increase precipitation. In most cases it is reasonable to assume that vegetation has little or no influence on gross precipitation. However, in some instances there is evidence that forests increase the amount of gross rainfall. It has been suggested that tall trees increase the orographic effect, increasing the amount of gross rainfall. However any increases in gross rainfall are likely to be offset by the increased rate of evapotranspiration of these taller trees, resulting in an overall decrease in water resources. On a continental scale it is thought that vegetation type may well impact on the amount of gross precipitation through land-atmosphere feedbacks (Calder 1996). However, there is no data to show that this effect operates at the catchment scale.

3.2 Evapotranspiration

As described in equation (2) evapotranspiration can be divided into three components: interception, transpiration and soil evaporation. Evapotranspiration is defined as the total process of water transfer into the atmosphere from vegetated land surfaces. The two major components of evapotranspiration (transpiration and interception) are defined and discussed in **Sections 3.2.1 and 3.2.2**. The total amount of evapotranspiration, under different vegetation types is dependent not only on the vegetation type, but also on the soil and climate of the catchment (Calder 1999).

Changes in evapotranspiration due to changes in vegetation can have a significant impact on the water balance. For example when comparing the annual evapotranspiration between forest and grass for catchments with the similar rainfall,

Turner (1991), Holmes and Sinclair (1986) and Zhang et al. (1999) found that forests consistently had higher rates of evapotranspiration than grass.

3.2.1 Transpiration

Transpiration is the process by which water in plants is transferred to the atmosphere in the form of vapour (Ward and Elliot 1995). The amount of transpiration differs with different vegetation types and is controlled by the physiological characteristics of the vegetation, with the majority of transpiration occurring through the stomates, the small pores in the leaf epidermis. The combined effect of large leaf area and more extensive root systems of forests compared to grass or pasture results in much greater transpiration rates (Ward and Elliot 1995). This larger transpiration rates of forests compared to pasture is not only due to the increased leaf area, but is also due to the ability of forest to access deeper water stores.

3.2.2 Interception

Interception loss is the amount of gross rainfall intercepted by leaves or litter and evaporated directly back to the atmosphere. Water that is captured on foliage and evaporated does not contribute to streamflow. Interceptions can be divided into two types:

1. canopy interception
2. litter interception.

The amount of interceptions is largely dependent on the type of vegetation and on the intensity, duration, frequency and form of precipitation (Dingman 1994). Interception is generally proportional to leaf area index (LAI) with forests having a larger LAI then shrubs or grasses. This combined with the greater aerodynamic roughness of forests leads to greater interception loss and reduction in net rainfall under forested conditions (Vertessy 2000).

Using a paired catchment study to determine the impact of replacing native vegetation with pasture on a small catchment in south Western Australia, Ruprecht and Schofield (1989) attributed the initial increase in streamflow (~13% of rainfall) to an decrease in the interception loss as a result of changes in vegetation type. Bari et al. (1996) also observed this response in the March Road catchment in south Western Australia. The difference in interception between forest and grass or pasture impacts on the water balance equation by affecting the evapotranspiration.

Afforestation, deforestation and forest conversion are all likely to alter the water balance through their influence on LAI and interception loss.

3.3 Infiltration

Infiltration is the process by which water arriving at the soil surface (after canopy and litter interception) enters the soil (Dingman 1994). The rate of infiltration is affected by the initial water content and the permeability of the soil. Although the antecedent moisture and permeability are largely determined by rainfall and soil type, vegetation also affects soil moisture levels through transpiration, interception and shading. Soil permeability is also impacted by vegetation through the contribution of organic matter and number of macro and micro-pores that develop around the roots.

The higher transpiration rates of forests results in the initial soil moisture content being considerably lower than under crops or pasture (Ruprecht and Schofield 1989) while the nature of the root structure associated with forests increases the number of macro-pores and the amount of organic matter content under forested conditions leads to higher rates of infiltration under forests than under grass or pasture (Mapa 1995).

3.4 Overland flow

Overland flow occurs when the soil is saturated either from above (Hortonian over land flow) or from below (saturation overland flow) (Dingman 1994). Greater overland flow is generally observed from pastures then from forests. Ruprecht and Schofield (1989) attributed increases in overland flow in deforested catchments to the larger permanent groundwater discharge areas that resulted as a consequence of vegetation removal and decreased evapotranspiration. It is also possible that increased overland flow occurs for pastures relative to forests because of the changes to the infiltration

capacity of the soil. Scott and Lesch (1997) noted that the delayed recovery of streamflow after the clear felling of a plantation catchment in South Africa. They attributed the delayed response to the trees tapping deep soil-water reserves reducing the soil water storage below levels necessary to generate streamflow, indicating that a saturation excess flow mechanism may also operate in this catchment.

3.5 Deep drainage, base flow and recharge

Deep drainage is the water that moves downward through the soil profile below the root zone that cannot be used by transpired by plants (Ward and Elliot 1995). Where there is no lateral flow of water between the root zone and the water table, deep drainage is equivalent to the recharge to the ground water table. Where lateral flow occurs between the root zone and the water table a portion of deep drainage may contribute to baseflow. Baseflow can therefore consist of two components: the discharge from the groundwater table; and the lateral flow of deep drainage that becomes streamflow.

Deep drainage is generally greater beneath pastures than forests, as the deeper roots of forests and increased evapotranspiration utilises more water, reducing deep drainage. In an experimental catchment in Coweeta, USA, Burt and Swank (1992) observed that with the conversion of hardwood to grass the amount of low flow increased, particularly baseflow. This has been observed almost universally in paired catchment studies involving deforestation. The lower evapotranspiration rates and shallower root zones of short vegetation compared to forests results in an increase in the deep drainage and baseflow.

3.6 Soil water storage

The last term in the water balance equation is the change in soil water storage. The soil water storage represents the amount of water stored in the soil profile that can either be transpired or that contributes to baseflow. Over long periods it is reasonable to assume that changes in soil water storage are negligible, if no change to vegetation type has occurs (Zhang et al. 2001) the change in soil water storage term in the water balance equation can be ignored. However, on a seasonal basis the changes in soil water storage may be significant.

3.7 Summary of processes

The above discussion highlights the major hydrological processes in relation to vegetation type. The general conclusions that can be drawn are:

1. Alterations to vegetation type on the local and catchment scale are not likely to impact on gross precipitation; however, regional or continental changes to vegetation may alter gross precipitation.
2. Interception loss is greater for forest than for grasses or pasture. Under deforestation it is likely that the initial increase in water yield is due to a reduction in interception loss.
3. Overland flow or quick flow is less likely to be affected by changes in vegetation cover than baseflow.
4. Changes in water yield as a result of changes in vegetation, particularly permanent vegetation changes are likely to be reflected as changes to baseflow. Larger soil moisture stores and groundwater reserves accumulated in response to removal of forest and decreased evapotranspiration cause the observed increase in baseflow.
5. Under most climatic conditions, evapotranspiration from forests will be greater than from grasses.

4. Changes in water yield due to changes in vegetation type

Water yield changes have been reported at mean annual, annual and monthly temporal scales for paired catchment studies. The majority are reported on an annual basis. The following section summarises the results for previous reviews and uses specific examples from Australia, South Africa and New Zealand to highlight some of the conclusions that can be drawn from paired catchment studies.

4.1 Generalisations based on paired catchment data

A number of reviews have been undertaken to draw generalisations from paired catchment studies, particularly in reference to changes in forest cover on water yield. The first of these was by Hibbert (1967). In this review 39 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
- the response to treatment is highly variable and, for the most part, unpredictable.

Bosch and Hewlett (1982) undertook at further review of paired catchments and in reviewing 94 experimental catchments, they concluded:

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

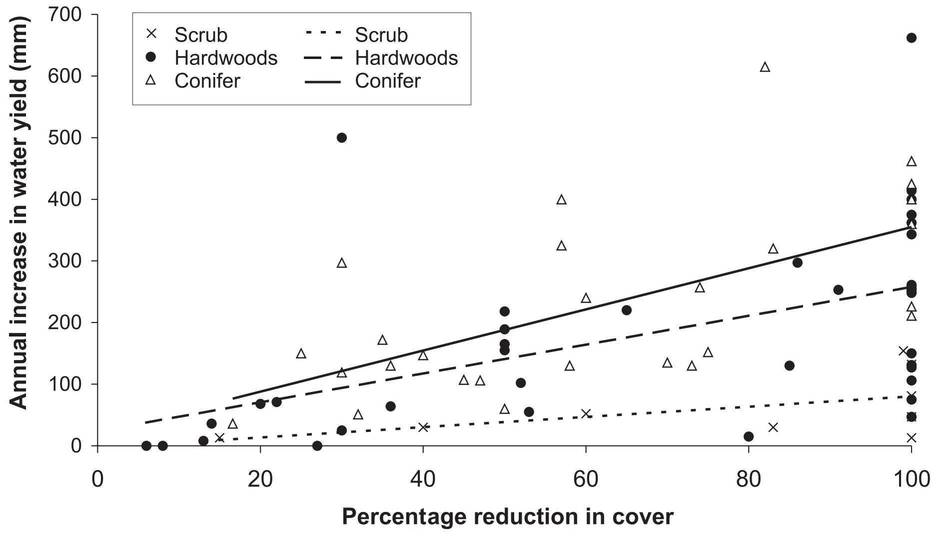

Figure 1: Yield increases following change in vegetation cover (after Bosch and Hewlett 1982). The points represent the maximum annual increase in water yield during the first five years after treatment for cover reduction experiments and maximum decrease (within the time frame of the experiment) in water yield for afforestation experiments.

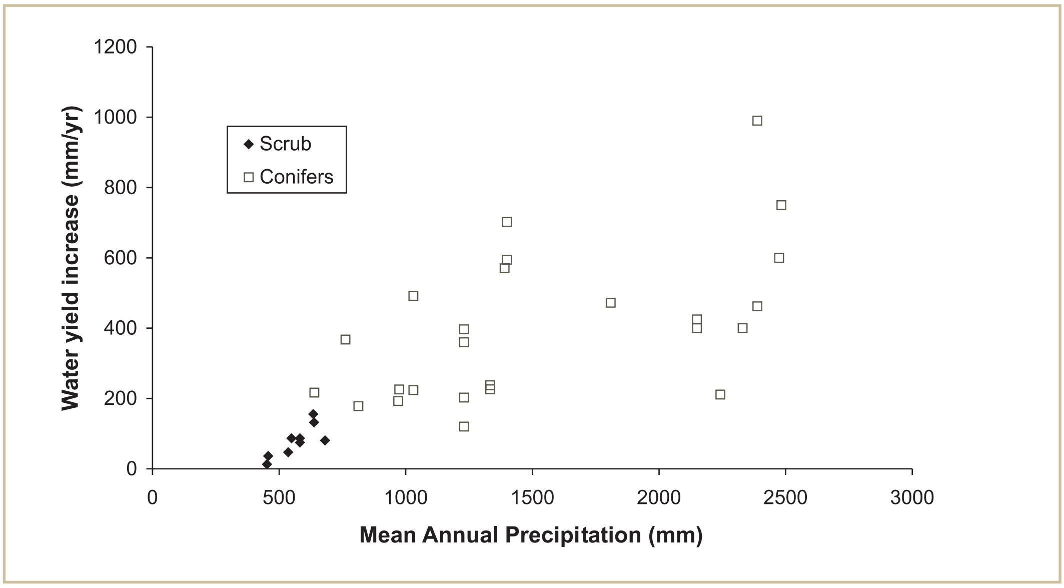

Figure 2: The distribution of water yield change after clear cutting of conifer and scrub (scaled to 100% reduction in cover), as a function of mean annual precipitation (after Bosch and Hewlett 1982).

Figure 1 shows the results of the Bosch and Hewlett review relating the maximum increase in water yield during the first five years after treatment to percentage reduction in cover and the cover type. **Figure 1** illustrates that with an increase in the percentage reduction in cover an increase in annual streamflow occurs.

To explain some of the within group variability evident in **Figure 1**, the results of paired catchment studies involving scrub and conifers were scaled to predict the water yield increases that would have occurred if 100% of catchments had been cleared and these increase were plotted against the mean annual rainfall for the catchments (**Figure 2**).

From this work Bosch and Hewlett (1982) concluded that:

- water yield changes are greatest in high rainfall areas
- the effect of clear cutting is shorter lived in high rainfall areas due to the rapid regrowth of vegetation
- the annual change due to treatment in high rainfall areas appears to be independent of the variation in rainfall from year to year
- changes in water yield are more persistent in drier areas because of the slow recovery of vegetation, and are related to the precipitation in during the year following treatment.

In order to include afforestation experiments in their analysis, Bosch and Hewlett (1982) assumed that the maximum decrease in water yield was analogous to the first year increase in water yield for a deforestation experiment. This allowed general conclusions to be drawn. The use of maximum increase in water yield in the first five years after treatment may also introduce bias into the results as the maximum is likely to be affected by climate.

The reviews of Hibbert (1969) and Bosch and Hewlett (1982) mainly focused on catchments from temperate zone. 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

- 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 water yield may occur, seems to conflict with many of the results of paired catchment studies in temperate zones, in which increases in baseflow is almost uniformly observed (Hornbeck et al. 1993).

Reviews by Stednick (1996) and Sahin and Hall (1996) expanded on the work by Bosch and Hewlett (1982). Stednick (1996) reviewed result of studies from the United States and looked only at annual water yield changes as a result of timber harvesting. Their main focus was on the effect of the percentage of area treated the ability 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 determined by streamflow measurement
- the rationalisation of data suggested this value might change depending on the temperature and precipitation of the area. With a measurable increase in streamflow being observed for treatments of 15% of the catchment areas in the Rocky Mountains, compared with the Central Pains where treatment is required over 50% of the area before changes in water yield can be detected.

Sahin and Hall (1996) used a similar approach to Bosch and Hewlett (1982) in there analysis of 145 experimental catchments, 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 five years after treatment, they used the average water yield changes in up to the first five years after treatment. Using fuzzy linear regression analysis they concluded that for a ten per cent 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
- deciduous hardwoods gave a 17-19 mm increase in water yield.

These estimates are lower than those from Bosch and Hewlett's (1982) review. In the Bosch and Hewlett (1982) analysis adopted the maximum change in water yield in the first five years after treatment, this will lead higher estimate of the reduction in water yield as opposed to the same analysis performed with average increases. However the use of the average of up to the first five years after treatment may be impacted by regrowth of vegetation after clearing.

The results of these reviews are limited by the use of regrowth experiments to build relationships about annual increases in water yield after vegetation change. As discussed in **Section 2.3**, Vertessy (1999) highlights the limitations associated with the use of regrowth experiments for developing relationships between percentage of vegetation cover and water yield. The results of subsequent studies, that look at change in water yield as a function of vegetation age have shown that the maximum change in water yield may not occur in the first five years after treatment. The results from a paired catchments studies in mountain ash forests of Australia indicate that the maximum water yield changes, when old growth forest is replaced by regrowth vegetation is not see until approximately 20 years after treatment as shown by Kuczera (1987). The vigorous regrowth in mountain ash forests will in fact cause a decrease in water yield compared to old growth forests. This concept is further discussed in **Section 4.2**.

In reviewing paired catchment studies both Stednick (1996) and Sahin and Hall (1996) concluded that in summarising the result of catchment experiments, difficulties were experienced because of 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 general discussion about the impacts of land use change on inter-annual water yield (the change in water yield with change in vegetation age) and seasonal flows. While the information contained in previous reviews may be useful for determining the short-term changes in water yield, it does not allow for the likely long-term impact of permanent land use change or the inter and intra annual changes to be investigated.

Taking these factors into account and the limitations of regrowth experiments (**Section 2.3**) the remainder **Section 4** considers the impact of vegetation changes on water yield and flow regime at different temporal scales.

4.2 Mean annual and annual water yield

The main process responsible for changes in water yield as a result of vegetation changes 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 a forested catchment to grass. Their results were based on a series of catchments in Victoria, Australia. As discussed in **Section 3**, when assessing the mean annual changes in water yield the recharge and change in storage terms in the water balance are small compared to the other terms, hence the change in runoff can be predicted through the prediction of change in evapotranspiration.

The concept that under mean annual conditions it is reasonable to assume the that recharge and change in soil water storage are negligible compared to the rainfall, streamflow and evapotranspiration was further explored by Zhang et al. (1999, 2001). They expanded on the work by Holmes and Sinclair (1986) and included results from 250 studies worldwide as opposed to a small number of local catchments. 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 different vegetation types. **Figure 3** shows the Holmes Sinclair relationship (HSR) and the Zhang model. The difference between the grass and forest curve represents the increase 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 Zhang curves.

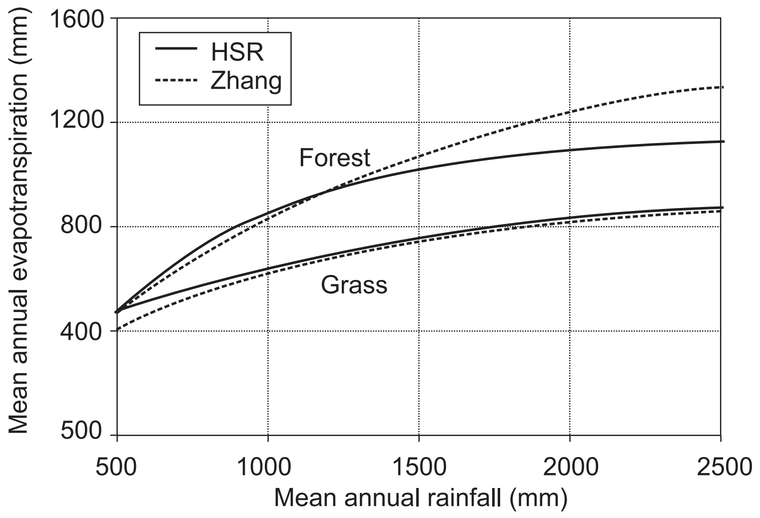

Figure 3: *Relationship between land cover, mean annual rainfall and mean annual evapotranspiration, as predicted by Holmes and Sinclair (1986) and Zhang et al. (2001). Note the HSR is based on local catchments mainly in Victoria, Australia, while the Zhang Model is based on a worldwide database.*

Vertessy and Bessard (1999) adapted the HSR to predict the impact of afforestation on water yield in the Middle Murrumbidgee basin. Equations, based on the HSR were defined to estimate the mean annual runoff from grassland and eucalypt forest and were also adapted to predict the mean annual ET of pine plantations. These were then used in predict the large scale impacts of afforestation on water yields.

The nature of most paired catchment studies does not allow for the long term effects (>10 years) of permanent vegetation changes to be investigated. While the mean annual results based on the HSR or the Zhang model provide a means to assess the impact of permanent land use changes on mean annual flows, they do not provide a method for the assessment of inter-annual variability or the length of time it takes for a catchment to adjust to changes in vegetation type. 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 occurring promptly after forest clearing
- increases could be prolonged by controlling the regrowth (analogous with permanent land use change), when regeneration of forest cover was permitted the increase in streamflow diminished rapidly in about three to ten years
- a small increase or decrease in water yield may persist for at least a decade.

Figure 4 shows the impact of vegetation changes for four catchments in the USA. The differing responses are consistent with the treatments 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 are permitted the water yield increase is reduced. The observed reduction in water yield about 15 years after treatment is due to the increased evapotranspiration of the regrowth compared to the old growth forest. 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, with the clearing of the upper half of the catchment 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 on water year can be seen with water yield returning to pre-treatment levels by year 27 (Hornbeck et al. 1993).

While the regrowth experiments of the types shown in **Figure 4** are useful for looking at the initial increase in water yield and the time taken for a catchment to return to its pre-disturbance state. It provides 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 its pre-treatment state.

There are limited examples of paired catchment studies looking at the impact of permanent land use changes on water yield. A number of paired catchments studied in south Western Australia have focussed on the deforestation of native forest for agricultural land. **Figure 5** shows the results of four

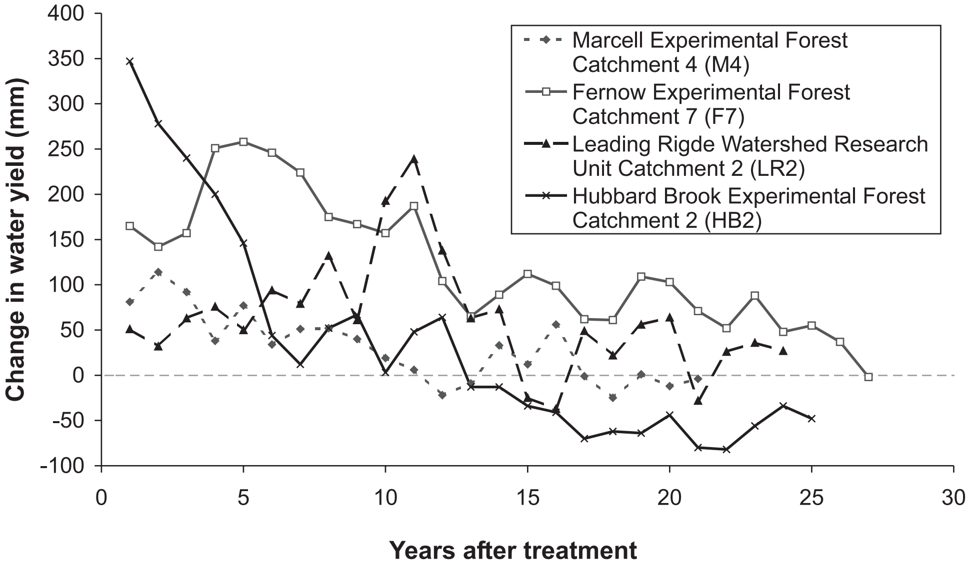

Figure 4: Change in annual water yield for four paired catchment studies in the USA. M4–100% Basal area cut. F7, upper half clear-cut (year 0), herbicides on upper half (2-7), lower half cut (year 4), herbicide on entire catchment (5-7). LR2–Lower 24% clear-cut (year 0), mid slope 27% clear-cut (years 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).

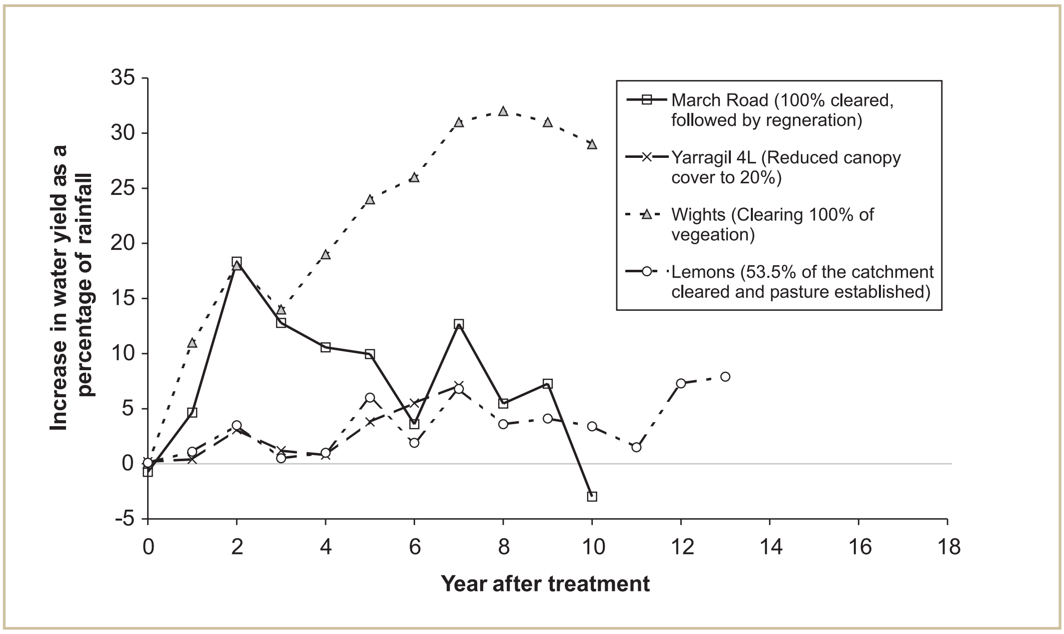

Figure 5: *Water yield increase for paired catchments, south Western Australia. Wights catchment (Ruprecht and Schofield, 1989), Yarragil (Stoneman, 1993), March Road (Bari et al. 1996), Lemons (Ruprecht and Schofield, 1991)*

different paired catchments in the Collie Basin in Western Australia. The catchments in the Collie Basin, experience a Mediterranean climate with a mean annual precipitation ranging from 600 to 1400 mm. Predominate pre-treatment vegetation in these catchments are jarrah (*Eucalyptus marginata*) in the north and karri (*E. diversicolor*) in the south. March Road, Yarragil 4L, Wights and Lemons catchments have mean annual rainfalls of 1050 mm, 1120 mm, 1200 mm, 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 until a new equilibrium is reached (Ruprecht and Schofield 1989). The results of clearing followed by regrowth in the March Road catchment show a similar tend to the regrowth in Hubbard Brook Catchment 2 USA (**Figure 4**), with an initial increase followed by a return to pre-treatment levels.

This highlights the limitations of regrowth studies in predicting the long-term effects of deforestation as the initial increase after clearing are not representative of the long-term increases in water yield. 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 transpires more water compared with old growth forests (Cornish and Vertessy 2001, Vertessy et al. 2001, Roberts et al. 2001). Through the use of 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 flowing 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 m 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:

- the mean annual water 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
- 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. (Vertessy et al. 2001)

The work by Cornish and Vertessy (2001) 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.

Examples of long-term response to permanent vegetation change from grass or pasture to tree plantations can be found in South Africa, New Zealand and Australia. **Figure 5** showed the response of streamflow to the clearing of native vegetation for agriculture for deforestation and regrowth experiments in south Western Australia. South Africa has the longest and most detailed record of paired catchment afforestation experiments, addressing permanent land use 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 low flows as a function of plantation age, species planted and site suitability as shown in **Figure 6**.

The curves in **Figure 6** are similar to that observed in **Figure 5** (particularly for Wights catchment), indicating that the response is similar for both afforestation and deforestation, with a period of transience until a new equilibrium is reached. **Figure 7** shows the results of a deforestation and afforestation experiment in areas of similar rainfall.
A similar change in water yield, under either deforestation or afforestation in the long-term is observed. The time taken to reach this equilibrium is dependent on the treatment, with a new equilibrium being established more rapidly under deforestation then afforestation.

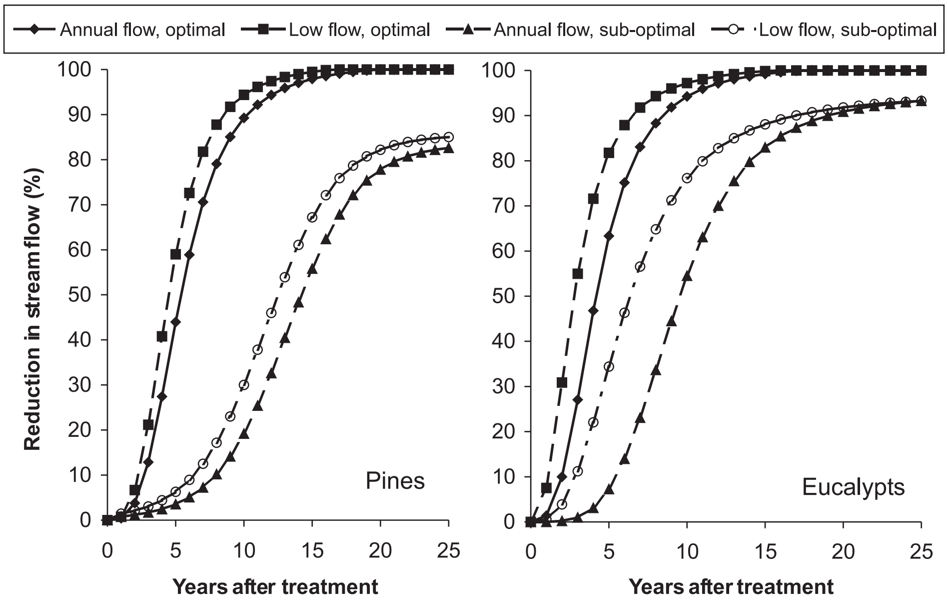

Figure 6: *Generalised curves from estimating the percentage reduction in total and low flow after 100% afforestation with pine and eucalypt afforestation (Scott and Lesch 1997).*

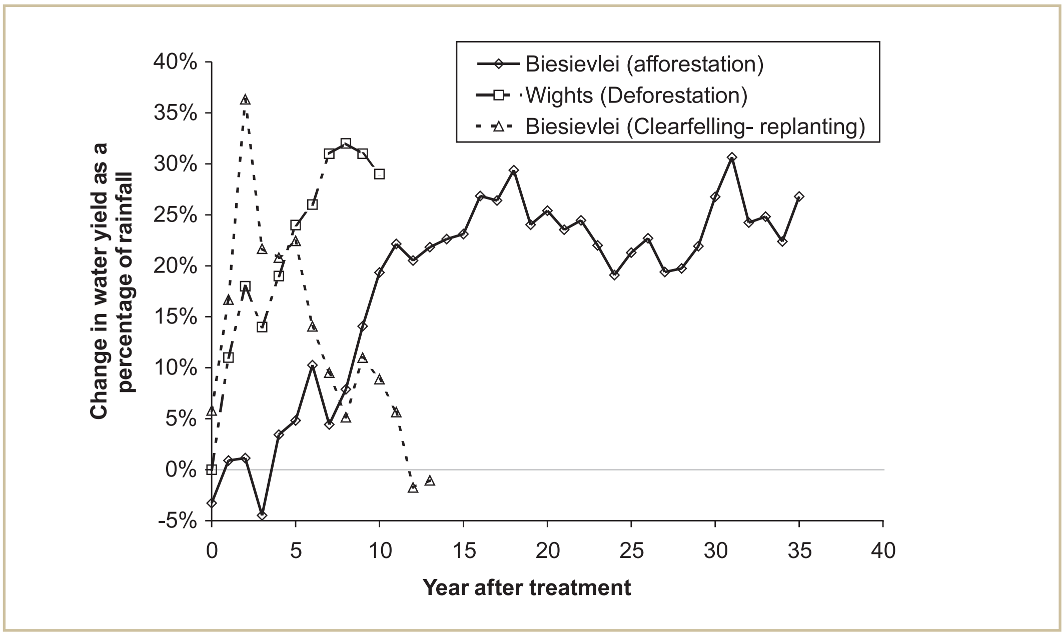

Figure 7: *Change in water yield as a percentage of rainfall for deforestation (Wights catchment, Western Australia. Mean annual rainfall = 1200 mm after Ruprecht and Schofield 1989), afforestation and clear felling-replanting (Biesievlei catchment, South Africa. Mean Annual Rainfall, 1298mm, Scott et al. 2000).*

The results for the Biesievlei catchment, Jonkershoek, South Africa indicate that it will take between 15 and 20 years for the catchment to reach a new equilibrium under afforestation, while the deforestation experiment from Wights catchments in Western Australia, indicates that a new equilibrium is reach in eight to ten years. This casts doubt on the use of the assumption of Bosch and Hewlett (1982) that the maximum reduction in water yield under afforestation is equivalent to the maximum increase in water yield in the first five years after treatments for regrowth and deforestation experiments.

4.3 Annual flow regime

4.3.1 Flow duration curves

The impact of changes in vegetation type on flow regime can be depicted through the use of flow duration curves (FDC). The FDC for a catchment provides a graphical 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 going to be influenced by water resources development (water abstractions, upstream reservoirs etc.) and land-use type (Smakhtin 1999).

The FDC (the cumulative distribution of the river flows) has been used widely as a measure of the flow regime as it provides an easy way of displaying the complete range for flows and how they would be changed under different land use scenarios in different climatic zones.

FDC can be constructed using multiple temporal scales of streamflow data: monthly or daily flows and depicted either using all the flows in a given year (annual flow duration curve) or flows for subset of yearly flows (seasonal flow duration curve). Smakhtin (1999) adopted the following terminology and this terminology has been adopted when discussion the effect of vegetation changes on the FDC for various vegetation change scenarios:

- One-day annual FDC—Constructed using daily data for a complete year
- One-month annual FDC—Constructed using monthly data for a complete year
- One-day seasonal FDC—Constructed using daily data for a given season
- One-month seasonal FDC—Constructed using monthly data for a given season

One of the limitations of using FDC 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 where possible it is important to compare years with similar precipitation, to minimise the variations due to climate (Burt and Swank 1992).

4.3.2 High and low flows

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 flows are the flows within the range of the 70% to 99% time exceeded (Smakhtin 2001), hence this definition has been adopted. High or peak flows have been taken as the flows that occur one to ten per cent of the time.

4.3.3 Impact of vegetation changes on annual FDC, high and low flows

The flow duration curves discussed below are one-day 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 catchment only three examples have been chosen and discussed here. These examples are the Redhill 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.

Figure 8 depicts the change in flow regime for the Redhill catchment in south eastern Australia. The catchment is located in a 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. Redhill has a catchment area of 195 hectares while the control catchment Kylies Run is 135 hectares. Both catchments range in altitude from 590 m to 835 m. The climate of the area is highly variable with a winter dominant rainfall. The mean annual rainfall of the Redhill catchment is 876 mm (Hicke 2001). There is no pre-treatment data available for this paired catchment study and due to differences in soil properties between the two catchments, there was also marked difference between the flow regimes even before the pines are well established at the beginning of the treatment period. It was therefore decided to compare the FDC for years of similar annual rainfall for the treated catchment only. FDC for one and eight 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 results of vegetations change. The one-year and eight-year old pines were chosen as these years have similar rainfalls, 887 mm 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.

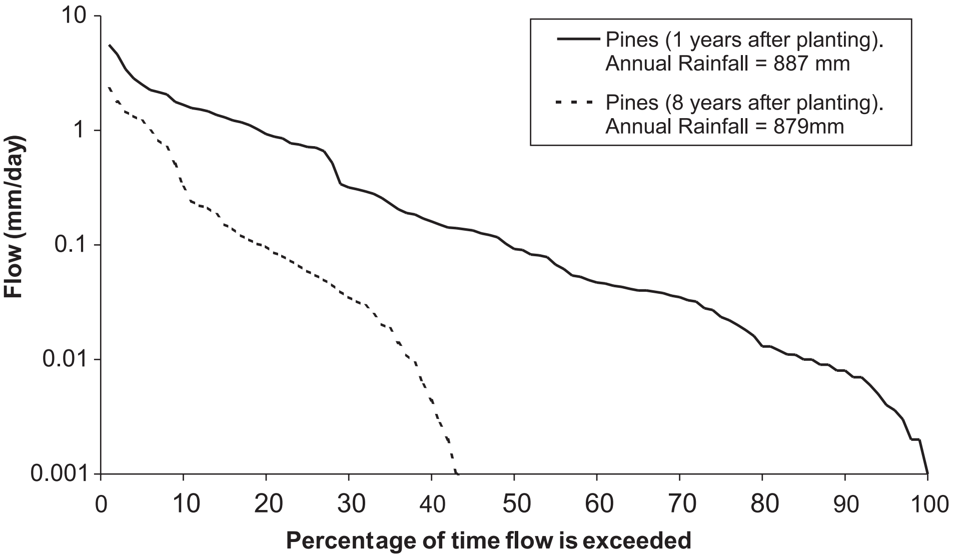

Figure 8: *Flow Duration curves for the Redhill catchment, near Tumut, NSW 1 year old pines and 8 year old pines. (after Vertessy 2000).*

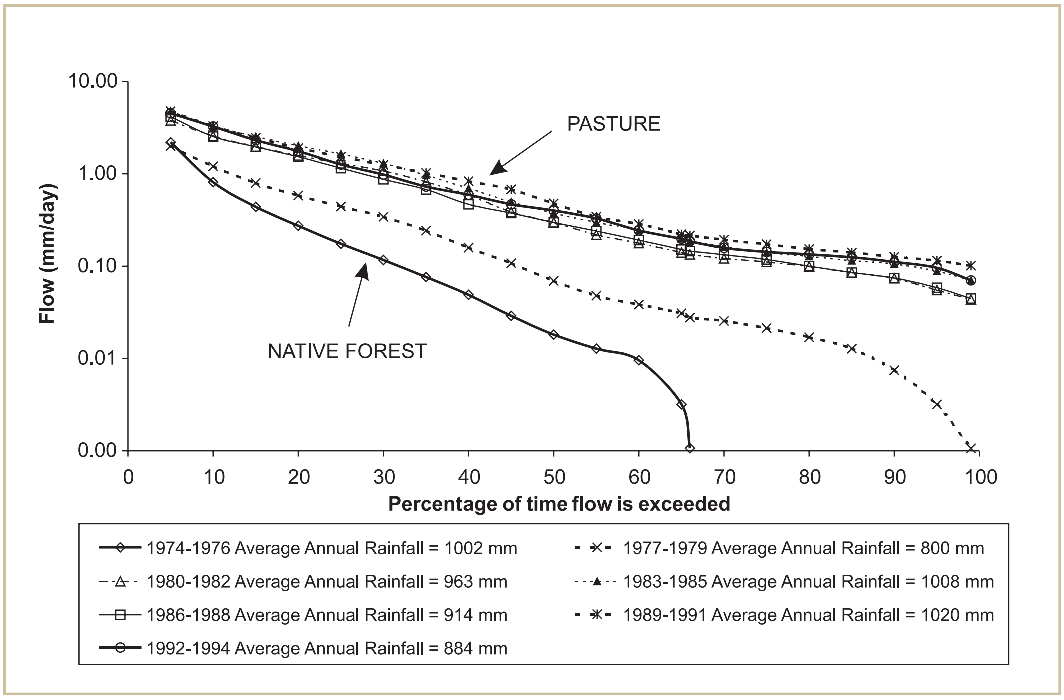

***Figure 9:** Flow Duration curves for the Wights catchment in southwestern Australia. (Based on a water year from April to March).*

Figure 9 depicts the response to conversion of native forest to pasture in the Wights catchment in south Western Australia. As discussed in **Section 4.2** the Wights catchment is part of a series on paired catchment studies in south Western Australia. These catchments have two important local characteristics,

- an increasing soil salinity storage with distance inland; and
- a local groundwater system.

The interplay between the groundwater and vegetation plays in important role in the hydrological response of these catchments to vegetation change. The hydrological response to replacement of native forests by pastures is related to an increase in groundwater discharge area (Schofield 1996).

As with **Figure 8**, it can be seen that all sections of the flow regime are affected by the change in vegetation type. Comparing the FDC for native vegetation (1974-1976) with a period of similar climatic conditions of pasture (1983-1985). We can see that you would expect a 50% reduction in high flows when going to pasture to forest and a 100% reduction in low flows.

Figure 10 depicts an alternate 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 has mean annual rainfalls of 1310mm and 1290mm respectively. The treatment involved the planting 67% of the catchment with *Pinus radiata* (McLean 2001). Unlike the Redhill and Wights catchments the control and treated FDC for the control and treated catchments are similar during the calibration period. Therefore the changes in high and low flows have been assessed through comparison the control to the treated catchment at various stages after treatment. The reductions in low and high flows as similar for all sections of the flow regime with approximately 30% reduction in both low and high flows. This response is typical of many catchments including the mountain ash catchments in Victoria (Watson et al. 1999) and the Biesievlei catchment in South Africa.

Figure 8, **Figure 9** and **Figure 10** depict two possible responses in flow regime as a result of vegetation change. The response seen in the Redhill and Wights catchments are typical of areas were annual evapotranspiration of forests approaches annual precipitation, while the response seen in Glendhu is typical of areas where annual precipitation is greater than the annual evapotranspiration. In the Mountain ash catchments in southern Australia, Watson et al. (1999) noted that in wetter catchments all flows respond to

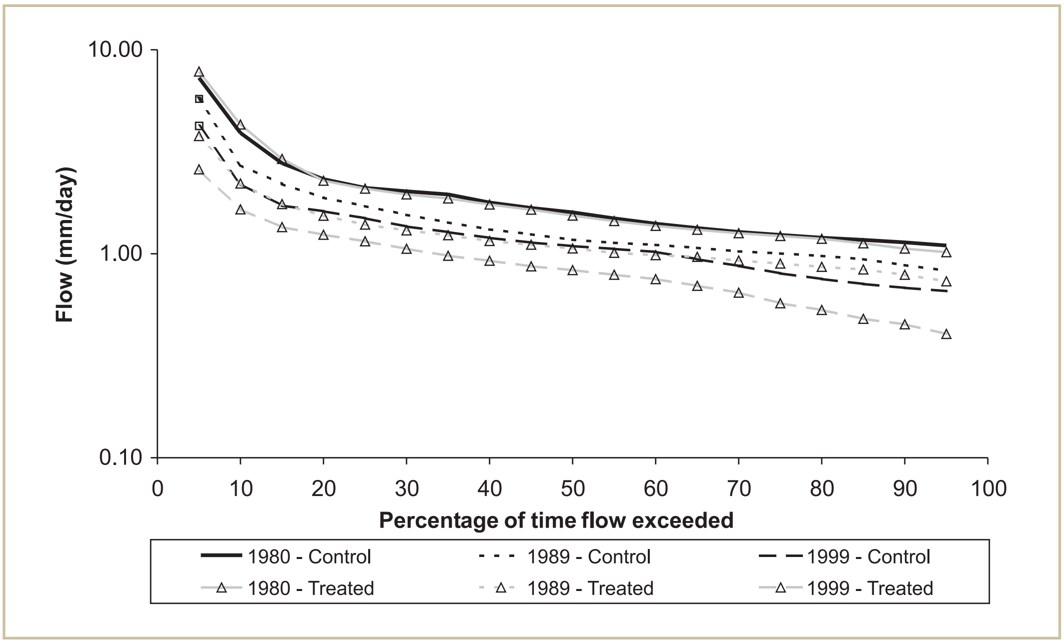

Figure 10: *Flow duration curve from the Glendhu experimental catchments New Zealand. 1980—during the calibration period (both catchments tussock). 1989—6 years after pine plantation established. 1999—16 years after pine plantation established. (McLean 2001)*

climatic and vegetation changes in unison with the changes in the mean flow, however in the drier parts of the study area changes in low flows are accentuated.

4.4 Seasonal water yield and flow regime

As noted earlier, information on the impact of land use change on seasonal or monthly flow is seldom reported in quantitative detail in the literature and generalisations about seasonality of yield changes under different land use have not been made. The majority of the previous work of land use change and water yield has had an emphasis on annual or mean annual water yield. The impact of land use change on seasonal yield can be as important as the impact on annual water yield, particular where flows during the dry season are of importance to downstream water users.

Johnson and Kovner (1956) noted that 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. While on an annual basis the changes in soil moisture between one year and the next can be assumed to be negligible, this is not the case on a seasonal basis. This section will aim to provide a summary of the literature on seasonal 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 for the impact of annual water yield as well as seasonality to be assessed. The results of these studies indicate that variations can be found in seasonal yield but lack quantitative data on the water yield changes. This lack of quantitative data makes it difficult to generalise the results on seasonal water yield between sites.

Hornbeck et al. (1997) looked at annual and seasonal flows for the first year after clear felling in the Hubbard Brook experimental forest. Separating annual yields into growing and dormant seasons allowing contrasting of treatment effects between periods of full leaf and maximum evapotranspiration, and period when deciduous forests are dormant and minimum evapotranspiration. They observed that most of the increases and decrease in annual yield occur during the growing season as shown in **Figure 11**. They concluded that water yield increases were a result of decreased transpiration and primarily occurred as augmentation to low flows, as illustrated by the flow duration curves in **Figure 11**. While this analysis is an obvious thing to do for deciduous catchments the definition of seasons is less obvious for evergreen vegetation.

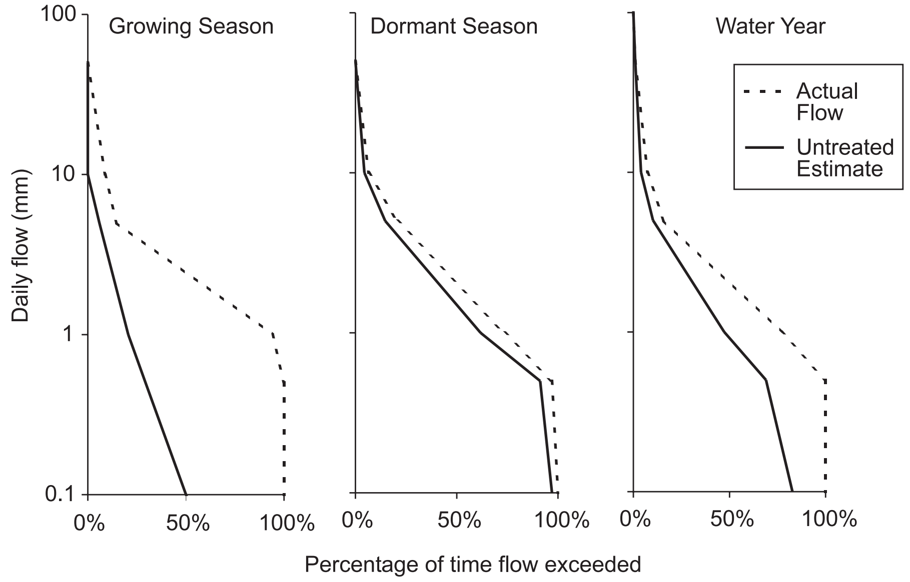

Figure 11: *Flow duration curves for the first year after the clear-felling treatment—Hubbard Brook experimental forest (after Hornbeck et al. (1997)).*

Using a similar approach to the analysis of Hornbeck et al. (1997), McLean (2001) produced flow duration curves to assess the hydrological response during Winter (July–September) and Summer (December–February) due to the conversion of tussock to pine plantations in New Zealand. From this study it was concluded that:

- the differences in summer flows were more variable than the winter differences, due to the high variability in the rainfall over the summer months
- the seasonal effects of land use modifications are not easily identified through the use of flow duration curves.

The difference in the results between the USA catchment, where notable seasonal differences were observed, and those in New Zealand, where seasonal changes could not be detected, 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. However where there is no dormant season, such as in eucalypt or pine plantations, the seasonal changes in water yield are limited more by climatic conditions of the seasons than by changing evapotranspiration rates.

Sharda et al. (1998) used a monthly average dataset to look at the seasonal nature of water yield changes at Glenmorgan Research Farm, south India. It was observed that the major reduction in mean annual flow caused by the blue gum plantation occurred during the months from July through to October, when 60% of the mean annual rainfall occurred (**Table 1**). These results indicate that the major reductions in flow volume occurred during the monsoon (July–October), however the percentage reductions in flows indicate that significant reductions occur in all months of the year. It was also noted that although the reduction in flow in the dry period was small on a volume basis compared to the wet season the percentage reduction in flow is significant in all months. The early and late monsoon periods show different responses in water change yield, which may be related to soil moisture dynamics introducing delays in response time.

TABLE 1. Average monthly reduction in total run-off due to bluegum plantation in the second rotation (after Sharda et al. 1998).

Month	Rainfall (mm)	Flow in Catchment B (mm)		Deficit (Computed—Observed) (mm)	Percentage reduction in flow
		Observed	Computed		
Apr	71.3	3.8	4.9	1.1	22
May	111.1	7	9	2	22
Jun	166.4	16.3	21.8	5.5	25
Jul	233	60.9	78.6	17.7	23
Aug	221.2	61.3	78.4	17.1	22
Sep	133.6	27.3	37.7	10.4	28
Oct	165.1	40.4	58.6	18.2	31
Nov	70	24.1	33.8	9.7	29
Dec	64.9	20.5	27.9	7.4	27
Jan	9.9	7.4	9.6	2.2	23
Feb	5.9	3.9	4.6	0.7	15
Mar	17.9	3.2	4	0.8	20

Similar analysis was carried out on the Glendhu catchment in New Zealand and the Cathedral Peak II catchment in South Africa. The results of this analysis are presented in **Figure 12**.

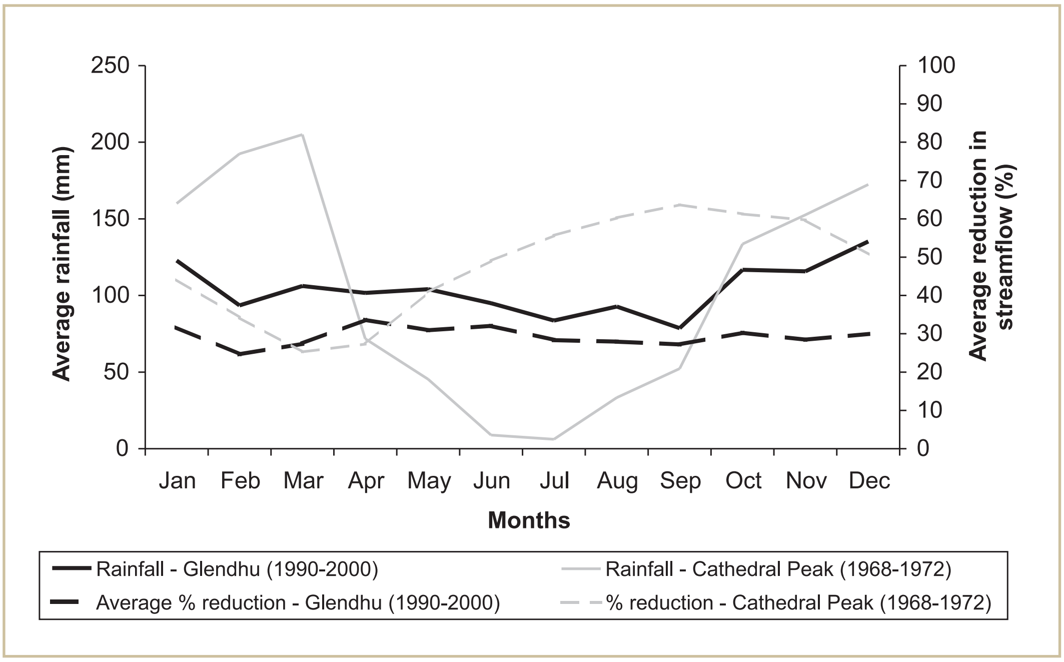

Figure 12: *Average monthly reductions in streamflow from the Glendhu catchment (afforestation with pines 1980) and Cathedral Peak II, South Africa (afforestation 1950-1955).*

Other studies reporting monthly or seasonal results include;

- Lane and McKay (2001) who concluded that there was no clear or persistent seasonal influence on either total streamflow or base flow change following logging
- Ruprecht et al. (1991) observed that the major increase in streamflow occurred from July to October, however increases were still significant in June, November and December. After thinning there was significant flow over the summer and early autumn
- Stoneman (1993)—observed that the largest increases in streamflow occurred between June and October (Winter) with small increases in November and December (Summer).

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 in nature, making it hard to generalise between the results of different studies. While on an annual basis the results of the studies seem to be easily generalised according to vegetation type, this is not the case on a seasonal basis.

Jones and Grant (2001a, 2001b) noted that the nature of the analysis undertaken could impact on the results. This was displayed 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 (2001a, 2001b) concluding both analyses showed that forest harvest has increased peak discharges in small basins by as much as 50% and 100% in large basins. 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.

5. Summary of limitation of paired catchments studies

In the following section the limitations of paired catchment experiments are discussed. These limitations are divided into two sections. The first section summarises the limitations in the analysis of paired catchment data in terms of what has been reported in the literature. The second deals with the limitations associated with the application of paired catchment results to time trend studies.

5.1 Limitations in reported literature

During the review of literature three major limitations were highlighted in relations to the previous analysis of paired catchment data. These have been disused in **Section 4** and are:

- generalisations about annual increases in water yield (Bosch and Hewlett 1982, Stednick 1996, Salin and Hall 1996) are generally only based on short term results of regrowth experiments (maximum change in the first five years after treatment, or first year increases). The results of permanent land use change experiments indicate that it may take longer than five years for the maximum change to be observed and for a new hydrologic equilibrium to be established
- changes in vegetation type will effect not only mean annual flow, but also the variability of annual flow. Peel et al. (2001) noted that the continental differences in the variability of annual runoff were due to two factors, the continental differences in the variability of annual precipitation and the distribution of evergreen and deciduous vegetation
- most studies do not evaluate the seasonal changes in water yield. Where seasonal analysis is carried out the results reported are generally of a descriptive nature
- in order to assess 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 when comparing results between sites, the generalisations are not complicated by conflicting results from different analysis methods.

5.2 Application to large catchments

The major advantage of using paired catchment studies in investigating the impact of vegetation changes on water yield is that the control catchments provide a means of separating out the changes in yield as a result of climate from those due to land use. However, if the results of small experimental catchments cannot be applied to larger non-paired catchments with some degree of confidence, then their application is limited.

5.2.1 Spatial issues

Paired catchment studies provide a good method for determining the relationships between percentage vegetation change and water yield in relatively small catchments. However, methods are needed for scaling these results to larger catchments where the area of subject to land use change is likely to be patchy and relatively small compared to the overall catchment size.

The results summarised in **Section 4** indicate that for any impact of land use 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. Munday et al. (2001) developed a model to simulate the temporal changes in streamflow associated with reafforestation 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 Redhill (for pine plantations) and Karuah (for eucalypt forest). The results indicated that while the trend in streamflow

changes are statistically insignificant, 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.

In determining the impact of forest conversion to agriculture in a large river basin in Thailand, Wilk et al. (2001) commented that the results of small scale studies have shown that a large reduction in forest cover increases the annual streamflow and raised the issue of whether similar results would emerge from large, partly deforested catchments with variable vegetative pattern at different growth stages. Their study concluded that despite a reduction in forest cover from 80% to 30% in the Nam Pong river basin, no change in river discharge could be detected. This is likely to be due to the fact that land use change in large river basins is not uniform in space or time.

At present the impacts on water yield at the whole of catchment or regional scale are limited to mean annual investigations. Scott et al. (1998) used the generalised curves of Scott and Smith (1997) to determine the likely change in water yield on total run-off 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.

There are limited examples of the extrapolation of the generalisations gained through the used of small experimental catchments to the regional scale and how treatments over less than 20% of the catchment impact on water yield. In terms of making predictions it is reasonable to assume that 0% land use change will not cause any change in water yield. Thus forcing the linear relationships suggested by Bosch and Hewlett (1982) thorough the origin would allow predictions to be made if less than 20% of a catchment is subjected to changes in vegetation. The ability to detect the change in water yield is of less importance than how well the magnitude of the water yield change can be predicted. Once the predictions have been made the importance of regional effects can be assessed. Another scale issue that could potentially be significant is the change in geomorphology as you move down from uplands to lowlands.

5.2.2 Climatic Variability

One of the advantages of paired catchment studies is that they allow the removal of 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 land use 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 annual flow duration curves in **Figure 8**, **Figure 9** and **Figure 10**. There is also the potential to use paired catchments to determine the seasonal impacts of vegetation change.

For example, in **Figure 10** a change in the flow duration curve for the tussock catchment (control), between 1980 and 1989 can be seen, despite the fact that no land use change has occurred. The most likely explanation for this is the climate differences between 1980 and 1989, causing a change in the amount of runoff. Where both the flow duration curves for the control catchment and the treated catchment are available, separation of the impact of land use on flow regime is possible. However, for **Figure 7**, where all the flow duration curves have been plotted for the same catchment, how does one separate quantitatively the changes due to land use from the fluctuations due to climate.

Three possible methods that could be used for the removal of climatic variability from non-paired catchments are:

1. the use of a generalised additive model to separate the climate signal from land use from the percentiles of the flow duration curves, either annual or seasonal
2. removing exogenous variable so trends can be more easily identified in the variable of interest (land use change in this case)
3. the use of a rainfall runoff model to determine flows under different land uses for the same climatic period.

6. Summary and conclusions

This review highlights the lack of information available in the literature for examining the impacts of vegetation changes on seasonal yield and flow regime. While the effect of vegetations change on a mean annual basis is well understood, research on seasonal water yield reported in the literature is limited and confusing and is primarily of a descriptive nature.

The processes affected by land use change are reasonably well understood at a mean annual or annual basis, however changes on a seasonal basis and in flow regime are not as well understood, particularly in relation to soil water storage. On a mean annual basis, changes in soil water storage can be assumed to be insignificant in relation to the other terms in the water balance equation; however, this is not the case at a seasonal time scale.

The previous reviews of paired catchment studies have focused mainly on regrowth experiments, where changes in water yield are only observed in the first couple of years following treatment before returning to pre-treatment levels. Given the transient nature of the water yield changes in regrowth catchments the applications of these results to permanent land use changes are questionable. In terms of future land use changes in Australia, the increase in afforestation due to the 2020 Vision is likely to be of a more permanent nature leading to permanent change in water yield and flow regime.

This review raises a number of issues relating to land use change and water yield that need further investigation. These include:

- Can the results of regrowth studies provide relevant information on the effects of permanent land use change or the likely changes in evapotranspiration with time in tree plantations?
- How will the effect of permanent land use change alter over time? Do the generalisations made by Scott and Smith (1997) in **Figure 6** apply to other areas around the world?
- How will vegetation changes affect flow regime? Will these effects vary between regions or will the major changes in water yield be reflected in low or high flows?
- Can the generalisations drawn from paired catchment studies be applied to larger catchments and at regional scales?
- Can the impacts of climatic variability be separated from the effects of land use change?

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Appendix A

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 Streamflow (mm)	Treatment	Calibration period	Source of info
Karuah, NSW, Australia																			
Barratta	36.4		450-940[1]		Moist warm temperate climate.	tall wet sclerophyll forest	Regrowth	1577[2]	588[2]	Crabapple/ Sassafras	14.7/ 25.3		450-940m[1]		1637/1429[2]	456/307[2]	Logging without regeneration burn	1976-1983	Cornish (1993); Cornish and Vertessy (2001)
Bollygum	15.1							1499[2]	500[2]								Logging without regeneration burn	1976-1983	
Coachwood	37.5							1444[2]	373[2]								Plantation established after tractor clearing	1976-1983	
Corkwood	41.1							1639[2]	503[2]								Logging plus regeneration burn	1976-1983	
Jackwood	12.5							1368[2]	313[2]								Logging plus regeneration burn	1976-1983	
Kokata	97.4							1562[2]	518[2]								Plantation established 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 windrowed, 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[1]		Regional rainfall is reasonably uniform throughout the year.	Open Sclerophyll forest	Regrowth			Ceb	21.7						30% of area logged	1986-1989	Lane et al. (2001)
Wicksend	68.2							1100							1100		38% of area logged	1986-1989	Lane et al. (2001)
Tumut, NSW, Australia																			
Redhill	195	9			Temperate with highly variable and winter dominant rainfall.	Pasture	Pines	876		Kylies Run	135	12			876		50ha afforested in 1988 and the remaining area (145ha) afforested in 1989	None	Hickel (2001)

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[1] Elevation Range

[2] Pre-treatment mean (1976/77 to 1982/83)

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 Streamflow (mm)	Treatment	Calibration period	Source of info
Yambula State Forest, NSW, Australia																			
Geebung Creek	80.2		157-331[3]	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) Post Logging Burn (June-July, 1987)	1979-1986	MacKay and Cornish (1982);Moore et al. (1986); Crapper et al. (1989); Roberts (2001); Roberts et al. (2001)
Peppermint Creek	127.5		230-476[3]														Wild Fire - Jan 1979 Integrated Harvest (Dec 1986 - June 1987)	1977-1979	
Grevillea Creek	92.5																Wildfire - Dec 1972 Wildfire - Jan 1979	1977-1979	
Stringybark Creek	140		230-476[3]														Integrated harvesting - May 1978-Jane 1979) Wildfire Jan 1979	1977-1978	
Germans Creek	225.1		230-476[3]														Wildfire - Jan 1979 Salvage Logging: June - Dec 1979	1977-1979	
Wyvuri experimental catchments, Babinda, Queensland, Australia																			
North Creek	18.3	34		W		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); 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); 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		Dry sclerophyll eucalypt forest	*Pinus Radiata*	1400		Ella Creek/Betsy Creek	113.0 /44.3			E	1400		December 1979 vegetation removed leaving 30m buffer strip around stream. Area planted with radiata pine	1975-1979	Bren and Papworth (1991)

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[3] Elevation Range

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 Streamflow (mm)	Treatment	Calibration period	Source of info
North Maroohdah experimental Area, Victoria, Australia																			
Black Spur 1	17	7.1		SW			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); Watson et al. (1999); Watson et al. (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-Jan1982	
Ettercon 2	8.83						Regrowth			Ettercon 3	15.01						Understorey removed - 1979 Infested with Psyllids - 1998	5/8/1971-1979	Watson et al. (1999); Watson et al. (2001)
Ettercon 4	9.03						Regrowth			Ettercon 3	15.01						35% strip thinned Jan 1982-Mar-1982	15-7-1971 - Jan-1982	
Monda 1	6.31				Mediterranean - cool wet winters and hot dry summers	1939 E. Regnans	Regrowth			Monda 4	6.31						79% clearfelled and regenerated with 2000 seedlings /ha 5/12/77-26/4/78 clearfelled 20/3/78 - burnt 17:5-78 - Seedlings	11-6-1970 - 5-12-1978	Jayasuriya and O'Shaughnessy (1988); Watson et al. (1999); Watson et al. (2001)
Monda 2	3.98						Regrowth			Monda 4	6.31						75% clearfelled and regenerated with 5000 seedlings/ha 5/12/1977-26/4/1978 clearfelled 6/3/1978 Burnt 17/5/1978 Planted	11/6/1970-5/12/1977	
Monda 3	7.25						Regrowth			Monda 4	6.31						5/12/1977-26/4/1978 80% clearfelled and regenerated with 500 seedlings/ha 21/4/1978 Burnt 9/5/1978 Planted	11/8/1970-5/12/1977	Watson et al. (1999); Watson et al. (2001)
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	13/7/1971-4/12/1984	

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 Streamflow (mm)	Treatment	Calibration period	Source of info
Coranderrk experimental area, Victoria, Australia																			
Blue Jacket	64.8	36.6		SW	Mediterranean - cool wet winters and hot dry summers	1850 E. Regnans & E. Obliqua	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); Nandakumar and Mein (1997);
Piccaninny	52.8	37.8		S	Mediterranean - cool wet winters and hot dry summers	1850 E. Regnans & 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); 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.	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); Nandakumar (1993)
CA5	17.6	7.6		NW		Mixed Species Eucalypt forest.	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	95.1 107.2 156.2 521.2	5 9 5 2	596 594 640 651	NW SW SW S	1265 1249 1308 1440	209 234 228 318	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								Native Forest until April 1984. Understorey burnt in April 1984	1971-1980	Nandakumar (1993);

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 Streamflow (mm)	Treatment	Calibration period	Source of info
Collie River Basin, Western Australia																			
Dons						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)
Wights	94					Eucalypt Forest	Agriculture	1200		Salmon							100% cleared in Summer 1976-1977	1974-1976	Ruprecht and Schofield (1989)
Balingup Brook Tributary	93.3					Jarrah (Eucalyptus. marginata)	Agriculture	880		Thomson Brook/Ludlow River	10200/1010				950/950		Afforestations	1978-1980 (first 3 years since reforestation)	Borg et al. (1988)
March Road	261		170-230m		Mediterranean climate	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. Nursery raised karri seedlings were hand-planted in the same year of logging.	1976-1982	Bari et al. (1996)
April Road North						Eucalypt Forest	regrowth	1070									Clear felling leaving 100m buffers		
Lewin South						Eucalypt Forest	regrowth	1220		Lewin North							Selection cut and regeneration	1982-1985	Ruprecht and Schofield (1989)
Wellbucket						Eucalypt Forest	regrowth										Selection cut and regeneration. Basal area reduced from 16 m^3/ha to 11m^3/ha. Crown cover reduced from 55% to 22%	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 50m 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 50m buffer strip	1978-1984	Ruprecht et al. (1991)

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 Streamflow (mm)	Treatment	Calibration period	Source of info
India																			
Doon Valley	1.45	5.1		SE		Derived scrub with sal seedlings	E. grandis and E. camaldulensis	1167											Oyebande (1988)
Glenmorgan B	32				montane temperate humid climate	Grassland	Bluegum Rotation 1 then Bluegum rotation 2	1380		Glenmorgan A	32				1380		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	Sharda et al. (1988); Sharda et al. (1998)
Japan																			
Takaragawa-Shozawa	118		1067	SW		60% hardwood, 40% conifers		2153	1783								1948-1954 - 50% volume selected cutting		Bosch and Hewlett (1982)
Kamabuchi No. 2	2.48	36		SE		Artificial forest, standing as groups in hardwood stand, with dense ground cover	Restricted regrowth	2617	2075	No.1							100% clear felled Dec 1947	1940-1947	Nakano (1967)
Kenya																			
Kericho Sambret	702	4.5	2200	NW		Montane forest with bamboo	tea	2236	789								1959-1963 87% Cut for tea garden		Oyebane (1988)
Kimakia	35.2		2438	S		Bamboo forest	Pine	2198	1104								1956 100% cleared, pine planted		Oyebane (1988)
Big Bush, New Zealand																			
DC1	8.57		550	NW	Evenly distributed rainfall throughout the year, mean annual temperature of 10.5 DegC	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 Pinus radiata in September 1981	1975-1980	

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 Streamflow (mm)	Treatment	Calibration period	Source of info
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	Pinus radiata	1350		GH1	218		460-670	N	1350		67% Planted with Pinus radiata in 1982 at 1230 stems/ha	1979-1982	McLean (2001); 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) Rowe and Pearce (1994)
M14	4.62	36	340	SW			Regrowth	2650	1550	M15	2.64	34	335	SW	2650	1550	100% Clearfelled	1977	
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	
Cathedral Peak, South Africa																			
Calth_ii	190	0.45	1845-2454	N	Cold dry winters and hot wet summers	Grassland, woody communities along the streams	Pinus patula (with 20m strip of riparian zone on either side of the stream)	1400	807	Cath_iv	94.7	0.35	1845-2226	N	1400	673	75% afforested	1949-1952	Scott et al. (2000)
Calth_iii	138.9	0.38	1845-2317	N	Cold dry winters and hot wet summers	Grassland, woody communities along the streams	Pinus patula	1400	683	Cath_iv	94.7	0.35	1845-2226	N	1400	673	86% afforested	1951-1960	Dye (1996); Scott and Smith (1997); Scott et al. (2000)
Jonkershoek Forest Research Centre, South Africa																			
Biesievlei	27.2	0.35	372-580	SW	humid mesothermal Mediterranean type	tall open to closed fybos shrubland	Pinus radiata	1298	594	Langrivier	245.8	0.40	366-1460	SW		1653	98% afforested with Pinus radiata	1938-1948	van Wyk (1987); Dye (1996); Scott et al. (2000)
Bosboukoof	200.9	0.26	274-1067	SW	humid mesothermal Mediterranean type	tall open to closed fybos shrubland	Pinus radiata	1127	246	Langrivier	245.8	0.40	366-1460	SW		1653	57% afforestation with Pinus radiata	1938-1940	van Wyk (1987); Scott and Van Wyk (1990) Dye (1996); Scott et al. (2000)
Lambrechtsbos A	31.2	0.45	366-1067	SW	humid mesothermal Mediterranean	tall open to closed fybos shrubland	Pinus radiata	1145	564	Langrivier	245.8	0.40	366-1460	SW		1653	89% afforested with Pinus radiata	1946-1972	van Wyk (1987); Scott et al. (2000)

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 Streamflow (mm)	Treatment	Calibration period	Source of info
Lambrechtsbos B	65.5	0.46	300-1067	SW	humid mesothermal Mediterranean type	tall open to closed fybos shrubland	Pinus radiata	1145	518	Langrivier	245.8	0.40	366-1460	SW		1653	825 afforested with Pinus radiata (20m buffer on stream banks)	1947-1964	van Wyk (1987); Scott and Van Wyk (1990); Dye (1996); Scott and Smith (1997); Scott et al. (2000)
Tierkloof	157.2	0.49	280-1530	SW	humid mesothermal Mediterranean type	tall open to closed fybos shrubland	Pinus radiata	1319	1077	Langrivier	245.8	0.40	366-1460	SW		1653	36% afforested with Pinus radiata	1938-1956	van Wyk (1987); Scott et al. (2000)
Uitsoek State Forest, South Africa																			
Mokobulaan A	26.2	0.23	1292-1433	E	Sub Tropical with 80%of the average annual rainfall of 1167mm falling within the summer months of October to March. Rainfall runoff ratio 0.18	sub-climax grassland, North Eastern Mountain Sourveld, maintained by regular burning and grazing	Eucalypts	1166	197	Mokobulaan C	36.9	0.26	1341-1494	E	1199	118	100% afforested with Eucalyptus grandis	1956-1968	Van Lill et al. (1980); Dye (1996); Scott and Lesch (1997); Scott and Smith (1997); Scott et al. (2000)
Mokobulaan B	34.6	0.22	1318-1486	E			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); 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 Eucalyptus grandis in 1983	1975-1981	Scott and Smith (1997); 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)

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 Streamflow (mm)	Treatment	Calibration period	Source of info
Adirondacks, New York, USA																			
Sacandaga	127000		575			Northern hardwoods with conifers		1143	770								1912-1950, basal area increased from 17 to 28 m^2 ha^{-1}		Bosch and Hewlett (1982)
Alum Creek, Ark., USA																			
WS2	1	15	412	NE		pine with hardwood understory		1333	153	WS1	1	15		NE	1333		1970, 45% thinned, undergrowth killed by herbicide application	Clearcut sprayed annually for 3 years	Rogerson (1971)
WS3	1	15	412	NE		pine with hardwood understory		1333	153	WS1	1	15		NE	1333		7-1970, 100%		
Beaver Creek, Arizona, USA																			
WS 3	147		1573	W		Juniper-pinyon forest	Regrowth	453	22	Beaver Creek 2	51		1591	NW	466	25	1968 - 83% of trees killed by herbicide	1958-1962	Baker (1984); Baker (1986)
WS1	134		1595-1790	W			Grass	457	20	Beaver Creek 2	51		1591	NW	466	25	1963 - large pinyon pine and juniper trees removed. Area planted with grass		Baker (1986)
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)
Castle Creek, Arizona, USA																			
West Fork	364.2	12.6	2165	NW		Predominately ponderosa pine with an understory of Gamble oak	Regrowth	686	50.8	East Creek	471	13.8	2388-2616	N14W	686	76.2	one-sixth area harvested, remainder thinned for optimum growing conditions	1955-1964	Rich (1972); Baker (1999)
Workman Creek, Central Arizona																			
North Fork	100.4		2010-2356	SW	Cold moist winters, dry war springs and hot moist summers.	Ponderosa pine On the moist sites, Douglas fir and white fir are important	grassland	835	87	Middle fork	210.9		2010-2356		835	86	1953 - riparian cut of broadleaf species 1958 - convert moist site (mostly Douglas fir and white fir to grassland. 1966 convert dry site (mostly	1938-1952	Rich and Gotterfried (1976)

TREATED CATCHMENT										CONTROL CATCHMENT								
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South Fork	128.7		2010-2356	SW			Ponderosa pine	835		Middle fork	210.9		2010-2356		835	86	1953 - Start single tree selection harvest 1966 - convert to pure ponderosa pine with basal area of 9.2 m2/ha	1938-1952	Rich and Gottfried (1976)
Central New York, USA																			
Cold Spring Brook	391		565	S	Continental type climate	mixed hardwoods and conifers	mixed hardwoods and conifers	1030	616	Albright Creek	1830						1934, 35% reforested with conifers		Schneider and Ayer (1961)
Sage Brook	181		525	SE				974	535								1932, 47% reforested with conifers		
Shacklam Brook	808		520	S				1030	627								1931-1939, 58% reforested with conifers		
Coshocton, Ohio, USA																			
172	18	22.8	306-393	S		30% hardwood in 1938	100% hardwood/ white pine	970	300	196	122.6	14	276-361	SE	970		1938-1939, 10% reforested, mostly pine		Harrold et al. (1962)
Coweeta, North Carolina, USA																			
Coweeta 1	16.2	34	705-988	S	marine with cool summers, mild winters, and adequate rainfall during all seasons	Oak-hickory forest	White Pine	1727	787								1956 - entire catchment clear-cut and white pine seedlings planted	1944-1953	Swank and Miner (1968); Swank et al. (1987)
Coweeta, 10	86	24	742-1159	SSE		Oak-hickory forest	Regrowth										Exploitive selective logging during the period 1942-1956 with a 30% reduction in total watershed basal area		Swank and Crossley (1987)
Coweeta, 13	16.1	19	725-912	ENE		Second regrowth stand with a scattering of overmature trees	Regrowth	1829	872	WS18	12.5		726-993	NW	1939	1034	Sept 1939-Jan 1940 all woody vegetation was cut (no material removed); 1962 Regrowth cut	1936/37-1939/1940	Swank and Helvey (1973); Swank et al. (1987)
Coweeta, 17	13.4	57	760-1021	NW		Oak-hickory forest	White Pine	1930	868								All shrub and forest vegetation cut Jan-March 1942 Annual sprout growth cut 1943-1955 1956 white pine planted	1938-1941	Swank and Miner (1968); Swank et al. (1987)
Coweeta, 19	28.3	32	796-1119	NW		Oak-hickory forest	Regrowth	2032	1219	WS21	23.9		823-1174	N	2083	1321	Dec 1948-March 1949 all laurel and rhododendron cut close to ground (22% of basal area)	1941-1948	Johnson and Kovener (1956)

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Coweeta, 22	34	35	847-1244	N		Oak-hickory forest											All woody vegetation within alternate 10m strips deadened by chemicals in 1955; reduced total basal area by 50%		Swank and Crossley (1987)
Coweeta, 28	144	31	964-1551	E		Oak-hickory forest											Multiple use demonstration comprising of commercial harvest with clear-cutting on 77ha, thinning on 39ha of the cove forest and no cutting on 28 ha; products removed		Swank and Crossley (1987)
Coweeta, 3	9.2	32	739-931	E	marine with cool summers, mild winters, and adequate rainfall during all seasons	Oak-hickory forest	Regrowth		1814	607							All vegetation cut and burnt or removed from the watershed in 1940. Unregulated agriculture on 6ha for a 12 year period, followed by planting yellow poplar and white pine		Swank and Crossley (1987)
Coweeta, 37	43.7	33	1280	NE		Second regrowth stand with a scattering of overmature trees		2244	1515	Coweeta 36	49		1021-1542	ESE	2222	1675	100% vegetation cut in 1963 (no products removed)	1943/1944-1957/1958	Swank and Helvey (1973)
Coweeta, 40	20	42	1035	SE		Oak-hickory forest											Commercial selection cut with 22% of basal area removed in 1955		Swank and Crossley (1987)
Coweeta, 41	29	46	1065	SE		Oak-hickory forest											Commercial selection cut with 35% of basal area removed in 1955		Swank and Crossley (1987)
Coweeta, 6	9	35	793	NW		oak - hickory forest	Grass	1854	838	WS14/WS18	61/13		707-992/993-726	NW/NW	1876/1939	988/1034	1942 - 12% of catchment along stream was cut (Regrowth) 1958 - merchantable timber removed 1959 - reminder of catchment cleared and grass sown. Grass herbicide in 1966 and 1967 Grass herbicide in 1966 and 1967		Hibbert (1969); Burt and Swank (1992)

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Coyote Creek, Oregon, USA																			
Coyote 1	69		730-1065			Douglas fir, mixed conifers		1230	627	Coyote 4	49		730-1065				50% selection cut 1971	1963-1970	Jones (2000)
Coyote 2	68		730-1065			Douglas fir, mixed conifers	Regrowth			Coyote 4	49		730-1065				25-30% Patch cut 1971	1963-1970	Jones (2000)
Coyote 3	50		730-1065			Douglas fir, mixed conifers				Coyote 4	49		730-1065				100% clear-cut 1971	1963-1970	Jones (2000)
Eastern Tennessee, USA																			
White Hollow	694		410	SE		65% mixed hardwoods and pine in 1934	Regrowth	1184	460								1934-1942, 34% reforested with pines		Bosch and Hewlett (1982)
Fox Creek, Oregon, USA																			
FC1	59		840-925		The maritime climate has wet, mild winters and dry, cool summers	Douglas Fir, western hemlock	Regrowth	2730	1750	Fox 2	253		840-1988				1969-17, 25% clear-cut in 3-4ha units	1958-1964	Stednick (1996); Jones (2000)
FC3	71		840-950				Regrowth	2730	1750	Fox 2	253		840-1988				1970-1972, 25% clear cut in 8-10 ha units	1958-1969	Jones (2000)
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); Troendle and King (1985)
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); Troendle and King (1985)
Fool Creek	289		2896-3505	SW		lodgepole pine and spruce-fir	Regrowth	762	283	East St Louis Creek	803		2896-3719				1954-1956, 40% commercial cut in strips.	1943-1953	Alexander et al. (1985)
Grant Memorial Forest, Georgia, USA																			
WS14	32.5		165	SW		Fully forested piedmont land	loblolly pine			WS15	42.5						100% catchment cleared Oct 1974-Jan 1975. Jan 1976 Loblolly pine planted	1973-1974	Hewlett et al. (1984); Hewlett and Doss (1984)
H.J. Andrews Experimental Forest, USA																			
HJ1	96	28	460-990	W	typically wet in winter and dry in summer	Old growth Douglas fir	Regrowth	2286		HJ 2	60		530-1070	NW	2286		100% clear-cut (1962-1966)	1952-1961	Jones (2000); Rothacher (1970)
HJ10	10.1		425-700	S			Regrowth	2286		HJ 2	60		530-1070	NW	2286		100% clear-cut (1975)	1968-1974	Jones (2000)
HJ3	101	32	490-1070	NW			Regrowth	2286		HJ 2	60		530-1070	NW	2286		25-30% Patch cut 1963	1952-1958	Jones (2000); Rothacher (1970)
HJ6	13		880-1010	S	typically wet in winter and dry in summer	Old growth Douglas fir	Regrowth	2286		HJ 8	21.4		960-1130	S	2286		100% Clear-cut (1974)	1963-1973	Jones (2000)
HJ7	15.4		910-1020	S			Regrowth	2286		HJ 8	21.4		960-1130	S	2286		50% Clear-cut in 1974 and in 1984	1963-1973	Jones (2000)

TREATED CATCHMENT										CONTROL CATCHMENT									
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Hubbard Brook Experimental Forest																			
WS2	15.8	20-30%	503-716m	S31E		even aged deciduous hardwoods	Regrowth	1219		WS3	42.4		527-732	S23W	1219		Clearfelling and herbiciding (1965-1968)	7 years	Martin and Hornbeck (1989); Federer et al. (1990); Hornbeck et al. (1997); Hornbeck et al. (1987)
WS4	36		422-747	S40E			Regrowth	1219		WS3	42.4		527-732	S23W	1219		Strip cut in three phases during the autumns of 1970, 1972 and 1974	1960-1969	
WS5	22		488-762	S			Regrowth	1219		WS3	42.4		527-732	S23W	1219		Whole tree harvesting 1983-1984.	1963-1983	
Leading Ridge Experimental Forest, USA																			
LR2	43		360	NE		Central hardwoods	Regrowth	1004	321	LR 1	123		800-1450	SE			1967 - clearcut lowest 9ha 1971-1972 Clearcut mid-slope 11ha 1974 Herbicide lower and mid-slope areas 1975-1976 Clearcut 17ha on upper slope 1977 - Herbicide all clearcut areas 1976-1977 Clear cut on 45 ha		Dietterick and Lynch (1989); Lynch and Corbett (1990); Hornbeck et al. (1993)
LR 3	104		340																
Natural Draniages, Arizona, USA																			
A	5		1420	SE		Marginal chaparral	Regrowth	452	34								1954, 100% chemically controlled		
C	5		1420	SE				452	34								1954 100% chemically controlled		
Northern Mississippi, USA																			
WSII	1			E		Mixed hardwood	Regrowth	1354											
WSIII	1			E															
Alsea River Basin, Oregon, USA																			
Deer Creek	303		312			60% douglas fir and 40% alder	Regrowth	2474	1906	Flynn Creek	202						1966-1967, 25% clear-cut in patches, roads constructed	1959-1965	Harris (1977)
Needle Branch	70		312			85% alder and maple before cutting. 13ha in the headwaters had been previously logged in early 1950's	Regrowth	2483	1886	Flynn Creek	202				2483	1974	82% clear-cut, burned in 1967	1959-1965	Harris (1973); Harris (1977)

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Placer Country, USA																			
Watershed B	17.2					Oak woodland	Grass			Watershed A	19.1						1966 - Conversion to grassland commenced	1956-1965	Burgy and Papazafiriou (1971)
Watershed C	5		168	N		Oak woodland	Grass	635	145	Watershed A	19.1						Vegetation conversion to grassland commenced in 1963.	1956-1962	Burgy and Papazafiriou (1971)
San Dimas, Calif., USA																			
Monroe Canyon	354		840	S		Chaparral with woodland riparian vegetation along streams	Regrowth										1958 - 1.7% cut (Riparian vegetation)		Bosch and Hewlett (1982)
Three Bar, USA																			
B	1 9		1080	N		Chaparral	Grass	582	11								1960 - converted to grass	1956-1959	Hibbert (1971)
C	3 9		1160	N		Chaparral	Grass	638	58	D	36.2	34					1965 - converted to grass	1956-1959	Hibbert (1971)
F	27.7	41	168	N		Chaparral	Grass	681	36								1969 - chaparral cleared grass planted	1964-1969	Davis (1984)
Upper Bear Creek Ala., USA																			
XF1	53					Pine and hardwood	Pine	1397									1971-1972, 30% clearcut, additional 22% selective cut, burned residual poisoned pines planted 1969-1970 85% conversions to pine after commercial clearcut		Bosch and Hewlett (1982)
XF2	53																		
Fernow Experimental Forest, USA																			
Fernow 1	30		755	NE	rainy and cool climate	Mixed hardwoods	Regrowth	1524	584	Fernow 4	39			SE	1422	60	1957-1958 85% basal areas clearcut		Patric and Reinhart (1971); Hornbeck et al. (1993)
Fernow 2	15		780	S				1500	660								1957-58 36% are clearcut 1957-58 13% basal area removed by selection cut		
Fernow 3	34		805	S				1473	762								1963 - 8% Removed by same method 1968 - 6% of basal area removed, same method 1969-1970 - 91% clearcut		

TREATED CATCHMENT										CONTROL CATCHMENT									
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Fernow 5	36		780	NE				1500	607								1957-1958 20% basal area removed by selection cut 1968 - treatment repeated (14%)		
Fernow 6	22		805	SE				1469	788								1964 - lower 50% cut, regrowth not permitted 1968 - upper 50% cut	1956-1963	
Fernow 7	24		800	NE				1440	493								1963 - upper 50% clearcut. 1967 - lower 50% clearcut	1956-1963	
Wagon Wheel Gap, USA																			
B	81		3110	NE		Aspen and Conifer		536	158	A	90		3110	SE	534	153	1919 - Clearcut of watershed	1912-1919	Van Haveren (1988)
Western Tennessee, USA																			
Pine Tree Branch	36		160	E		Mixed hardwoods	Regrowth	1230	255								1946 - 75% reforested mostly pines		Bosch and Hewlett (1982)
White Spar, USA																			
B	39		1160	N		Chaparral	Regrowth	549	34								1967 - shrub on 15% chemically treated 1974-1976, shrub on 20% chemically treated		Bosch and Hewlett (1982)
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); 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)

Integrated catchment management in the Murray–Darling Basin

A process through which people can develop a vision, agree on shared values and behaviours, make informed decisions and act together to manage the natural resources of their catchment: their decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Our values

We agree to work together, and ensure that our behaviour reflects that following values.

Courage

- We will take a visionary approach, provide leadership and be prepared to make difficult decisions.

Inclusiveness

- We will build relationships based on trust and sharing, considering the needs of future generations, and working together in a true partnership.
- We will engage all partners, including Indigenous communities, and ensure that partners have the capacity to be fully engaged.

Commitment

- We will act with passion and decisiveness, taking the long-term view and aiming for stability in decision-making.
- We will take a Basin perspective and a non-partisan approach to Basin management.

Respect and honesty

- We will respect different views, respect each other and acknowledge the reality of each other's situation.
- We will act with integrity, openness and honesty, be fair and credible and share knowledge and information.
- We will use resources equitably and respect the environment.

Flexibility

- We will accept reform where it is needed, be willing to change, and continuously improve our actions through a learning approach.

Practicability

- We will choose practicable, long-term outcomes and select viable solutions to achieve these outcomes.

Mutual obligation

- We will share responsibility and accountability, and act responsibly, with fairness and justice.
- We will support each other through the necessary change.

Our principles

We agree, in a spirit of partnership, to use the following principles to guide our actions.

Integration

- We will manage catchments holistically; that is, decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Accountability

- We will assign responsibilities and accountabilities.
- We will manage resources wisely, being accountable and reporting to our partners.

Transparency

- We will clarify the outcomes sought.
- We will be open about how to achieve outcomes and what is expected from each partner.

Effectiveness

- We will act to achieve agreed outcomes.
- We will learn from our successes and failures and continuously improve our actions.

Efficiency

- We will maximise the benefits and minimise the cost of actions.

Full accounting

- We will take account of the full range of costs and benefits, including economic, environmental, social and off-site costs and benefits.

Informed decision-making

- We will make decisions at the most appropriate scale.
- We will make decisions on the best available information, and continuously improve knowledge.
- We will support the involvement of Indigenous people in decision-making, understanding the value of this involvement and respecting the living knowledge of Indigenous people.

Learning approach

- We will learn from our failures and successes.
- We will learn from each other.