Land Use and Water Resources:
Hydrological Effects of Different Vegetation Covers
SMF2167: Report No 5

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Landcare Research Contract Report: LC0203/027

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DATE: November 2002

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1. Introduction

Project 2167: Land Cover Effects on Water Availability is funded by a grant from the Ministry for the Environment's Sustainable Management Fund. The purpose of the project is to provide information and tools that will assist water and land managers in making the best allocations of water resources for all end-users.

A series of annotated bibliographies have been prepared as part of the project that provide hydrological information on *Pinus radiata (*radiata pine) plantations (Rowe et al. 2001b), Douglas fir (*Pseudotsuga menziesii)* forests and plantations (Rowe et al. 2001a), and New Zealand land-use studies (Rowe et al. 2001c). As the project is dominated by concerns about the effects of plantation forestry, the first two bibliographies concentrate on the two main species planted in New Zealand – radiata pine and Douglas fir – and include much information from overseas work. The third bibliography provides a New Zealand context and includes the New Zealand studies in the earlier reports plus references pertaining to other land uses such as pasture, and native tussock grasslands and forests.

This report summarises the information in those bibliographies examining differences in water yield between catchments with different vegetation covers, e.g., indigenous forests, exotic plantations, grasslands, and pasture; single catchment studies where a land use changes over time; and studies with a focus on processes such as interception or transpiration. Studies of management of pasture and forest cover, such as grazing regimes and forest thinning, are also included. The Hydrological Cycle provides the framework for organising the data into the different factors contributing to the water balance.

2: Background

There are worldwide concerns that increased establishment of plantations of exotic forest species for wood fibre production, either as a result of conversion of native forests and scrublands or afforestation of pasture and native grasslands, may have a detrimental effect on the environment. New Zealand is no different to most other countries in this regard.

Controversy has surrounded the effects that plantation establishment might have on water resources since the late 1940s. In one of the earliest reports published, Smith (1946) gave anecdotal evidence of reduced streamflows emanating from the Maramarua Forest in Auckland and at Tairua Forest in the Coromandel Peninsula as a consequence of planting radiata pine. At about the same time ,however, conflicting reports were coming from South Africa where it was reported that water use by pines (and other conifers) was little different from that by sclerophyllic scrub, both having low transpiration rates, and that eucalypts and wattles 'squander water if available' and 'should not be planted in water catchment areas' (Henrici 1947). Wicht (1949) recommended that afforestation in South Africa should be restricted to high rainfall areas as plantations of indigenous or exotic species were likely to use more water than the scrub. A later report by Rycroft (1952) found that planting *P. radiata* there had little effect on streamflows over the first 12 years of a rotation.

Recently, attention has focused on the following concerns:

- harvesting trees will cause accelerated erosion and sedimentation problems
- plantations are a monoculture, which decreases biodiversity
- acidification and compaction will degrade soil quality
- streams will dry up after planting forests, especially in the low-flow season.

However, there is evidence to show that for forest management, in general:

- erosion and sedimentation issues are short term only, and when taken over the full rotation, plantation forests are less damaging than other land uses (e.g., McLaren 1996, Phillips et al. 1990)
- plantations do sustain a wide-ranging biological diversity (e.g., Allen et al. 1995; Ledgard 1995)
- changes to soil quality may be positive (e.g., Davis & Lang 1991) and may often lead to improvements in hydrological properties (R.J. Jackson, unpublished data).

The main concern raised when proposals are made to establish plantation forests in the headwaters of catchments is that there could be diminished water yields. In water-short areas, conflicts can then arise between foresters who need to 'use' rain water to meet the biological needs of trees for growth, and downstream-users who require water for municipal, stock-water and irrigation supplies, or to sustain minimum levels in rivers for recreation, or to maintain in-stream habitats, especially at times of seasonally low flows. The economic benefits of water to tree growth have been well demonstrated. For example, it has been estimated in an irrigation and tree growth trial in Australia that a 500 mm increment in available water (between the limits of 500 and 1500 mm) will produce 11 m^3/ha of merchantable timber annually (Cromer et al. 1982). Water managers then have the unenviable task of allocating scarce resources to all users. Conflicts in the allocation process can lead to litigation in the Environmental Court.

The draft National Agenda for Sustainable Management Action Plan (MfE 1999) states 'There has been a substantial research effort in New Zealand and overseas on studying the impacts of changing land use on water yield, such as afforestation. This research is at a point where a guideline needs to be produced.' This report, and others in the series, while aimed at providing a foundation to reduce conflicts between land and water managers, could assist in the preparation of such a guideline.

2.1 SMF Project 2167: Land Cover Effects on Water Availability

Workshops in Nelson (March 1999 sponsored by Tasman District Council, Landcare Research, New Zealand Hydrological Society; Rowe 1999) and Rotorua (May 1999, New Zealand Forest Research Institute, Site Management for Sustainable Forestry) identified that water resource issues were still in the forefront of the list of concerns held by land managers (foresters, agriculturalists, etc.), water resource managers (regional and district councils) and other water users (recreationalists, environmentalists, etc.). Discussion with people outside these workshops indicated that these concerns were highly relevant. The principal questions confronting water resource managers were:

- What is the effect of a particular land use on useable water resources?
- How do I allocate scarce water resources when land-use change affects availability?
- What information, resources, and tools are available to help me with these questions?

In 1999, Tasman District Council and Landcare Research applied to the Ministry for the Environment's Sustainable Management Fund for funding to undertake a review of available literature, gather hydrological and land-use data from New Zealand catchments, and to develop a decision support resource to enable water and land managers to make more informed decisions on water resource allocations. The successful application resulted in this project, SMF2167: Land Cover Effects on Water Availability.

2.2 The New Zealand plantation forest estate

Whereas, three decades ago, conversion of native forest was the norm and planting of pastoral land was not favoured, there has been a major switch in recent years as a result of changes in Government policy. At 1 April 1999, the New Zealand exotic forest estate covered 1.73 million hectares (m ha), 6% of New Zealand's land area. Radiata pine (*Pinus radiata* D. Don) is the number one plantation species grown comprising more than 1.56 m ha, over 90% of the total plantation area (NZFI undated). For a commercial radiata pine plantation, rainfall must be at least 600 mm and less than 2500 mm/year (Boomsma & Hunter 1990) and most is grown below about 1000 m altitude. Douglas fir (*Pseudotsuga menziesii*) is the next most significant species planted, 86 000 ha, and is found mainly in the lower South Island or at higher altitudes, often above 1000 m.. Indeed, Douglas fir is becoming increasingly popular in the South Island where it represents a growing percentage of the southern plantation estate (Belton & Law 1996). About 82 000 ha of other species are grown, including eucalypts (NZFI undated).

Between 1992 and 1999, new exotic forest plantations were being established at over 60 000 ha per year, peaking in 1994 when about 96 000 ha were planted. Rates have dropped, however, and the provisional estimate for 1999 was about 25 000 ha (NZFI undated). Most of the new plantings are into improved (45%) and unimproved (45%) pasture, with the balance into scrubland (12%) (MAF 2000).

2.3 Sources of hydrological data

Reviews of catchment experiments from worldwide surveys have been presented by Hibbert (1967) and Bosch & Hewlett (1982); Stednick (1996) has done a similar study for the USA. Reviews by Fahey (1994), Fahey & Rowe (1992), McLaren (1996) and Rowe et al. (1997) have a New Zealand focus while Cornish (1989) presents a review with an Australian focus which includes a significant section on radiata pine.

Catchment studies at Glendhu (Otago), Maimai (West Coast), Donald Creek and Moutere (Nelson), Ashley (Canterbury) and Purukohukohu (Central North Island) provide the bulk of the information on the hydrology of New Zealand forests, but for radiata pine plantations or native forests, not Douglas fir plantations. Apart from Moutere and Ashley, these are higher rainfall areas where concerns about water yields are not high. This is in contrast to, say, Nelson and the east coasts of both islands where water is often scarce in summer and the most relevant data come from studies at Donald Creek, Moutere and Ashley. Hydrological studies at Makara (Wellington), Puketurua (Northland), Ashley, Moutere and Purukohukohu are the main sources of pasture catchment data while Glendhu provides information about native tussock grasslands.

To supplement the New Zealand reports, information has been gathered from overseas. For example, plantations of radiata pine are grown extensively in Australia (Boomsma & Hunter 1990), south-west South Africa, and Chile. In Chile alone there were 2 m ha in radiata pine in 1995 (Huber & Iroume 2001), which is 25% more that the New Zealand radiata pine estate in 1999. To a lesser extent pine plantations have been established in Spain and around the Mediterranean. Little information from New Zealand studies is available on the hydrology of Douglas fir—which, although a native of North America, can be found in significant-sized plantations in Australia and Europe. Also, New Zealand studies on gorse, bracken and large catchments are limited in number and there are some relevant studies from overseas that can be considered.

Thus, there is potentially a wealth of information to supplement that found from New Zealand sources. Searches of the literature in worldwide databases, mainly using CAB Abstracts, were carried out to identify this additional material which has been compiled into the three bibliographies (Rowe et al. 2001a, 2001b, 2001c).

2.4 Caveats on data

In compiling this report, differing types of data have been extracted from the original documents—tables, figures and text. Many studies give data for periods other than one year and we have adjusted these data to annualise he information; where the time period was less than about 6 months we have, generally, not used the data, as extrapolation to one year could be suspect because of seasonal rainfall variations. Thus, there will be errors inherent in the data presented, hopefully not significant ones, but it is considered that these will be of more value added to the overall dataset than if they had been left out altogether. In some cases, values have been extracted from figures, so inaccuracies will also occur here.

For some studies we have made estimates of mean canopy parameters where data are given as a range for more than one year but the hydrology is given as annual means. Where parameters are given for the start or end conditions, or for one year during a study with no progression reported throughout the study as the canopy changes, these canopy data are used throughout the course of that work. If stand ages are not given but planting dates are, we have assumed that the age the year after planting is one year, which ignores the age of the seedling when planted (which may be 1- or 2 years old). In some cases, data from multi-year studies are presented for all years where given.

Where data has been obtained from a number of reports from an author(s), a particular event is only presented once in any statistical relationship or figure.

We have also made some calculations, such as determining actual values where percentages are given, making estimates of catchment losses from precipitation and streamflow values, etc. Any errors made in these calculation are ours and cannot be attributed back to the original authors. Before citing any of the data in this report, it is advisable to source the original reports to verify the information and assumptions.

2.5 Abbreviations

BA	Basal area
DBH	Diameter at breast height
ET	Evapotranspiration
EVAP	Evaporation
ISC	Interception storage capacity
IL	Interception loss
%IL	Interception loss as a percentage of P
LAI	Leaf area index
MAP	Mean annual precipitation
PTTN or P	Precipitation (= rainfall and/or snowfall)
SFLO	Streamflow (= runoff = water yield)
SF	Stemflow
%SF	Stemflow as a percentage of P
SM	Soil moisture
SPH	Number of stems per hectare
TF	Throughfall
%TF	Throughfall as a percentage of P
TRANS	Transpiration

2.6 Statistical tests

Linear regression analyses and the calculations of confidence limits have been carried out after Freese (1967). Other statistical functions used are those in the Corel Quattro Pro spreadsheet package. All significance tests have been applied at the 95% level.

2.7 Units

A plethora of units are used in hydrological studies and reports, especially those predating the major change to SI units in the 1960s and 1970s but also including many reports emanating from the United States today. Some of the data presented here may still be in the original units; most have been converted, but there are still multiple ways of presenting values: e.g., L/s/ha, m^3/s/ha, L/s/km^2, and mm/day all describe the rate of flow from a specific catchment area.

Some conversions that may be useful are:

1 m^3/s = 1000 L/s
1 L/s = 0.001 m^3/s

1 mm = 10 m^3/ha
1 m^3/ha = 0.1 mm

1 mm/day = 0.1157 L/s/ha
1 L/s/ha = 8.64 mm/day

1 L/s/ha = 100 L/s/km^2
1 L/s/km^2 = 0.01 L/s/ha

1 cfs/mile^2 = 0.1093 L/s/ha where cfs is cubic-feet/second

3. The Hydrological Cycle

The New Zealand climate is dominated by maritime influences as anti-cyclones moves eastwards across the region at roughly weekly intervals. Low pressure troughs separating the anti-cyclones bring periods of unsettled weather. Northern districts are also be affected by cyclones which originate in tropical waters to the north and northwest (Robertson, 1960).

Evaporation from the sea surface is the major source of precipitation over the land (Fig. 3.1). The hydrological cycle over land can be expressed in the form of the water balance, which can be written as:

$$\mathrm{SFLO} = \mathrm{PTTN} - (\mathrm{IL} + \mathrm{TRANS} + \mathrm{E} + \mathrm{G}) \pm \triangle\mathrm{SM} \qquad (3.1)$$

where SFLO is streamflow or runoff, PTTN is precipitation, IL is interception, TRANS is transpiration, E is evaporation from the soil, G is the loss to deep groundwater storage, and $\triangle$SM is the change in soil moisture storage over the measurement period.

Interception is a loss of precipitation to any system before it can be utilised by any crop (including forests). This is evaporation from the wet vegetation canopy storage, and consists of extensive evaporation from the canopy while precipitation is still falling and that moisture held on the canopy at the cessation of precipitation. Transpiration is evaporated water that is extracted from the soil by the vegetation and is limited by the soil water content. Some transpiration takes place during a precipitation event but there is evidence from sapflow measurements that it is reduced while the canopy is wet compared to dry weather conditions. Precipitation that drains through the soil to the groundwater store may be available for stream runoff or lost to deep storage.

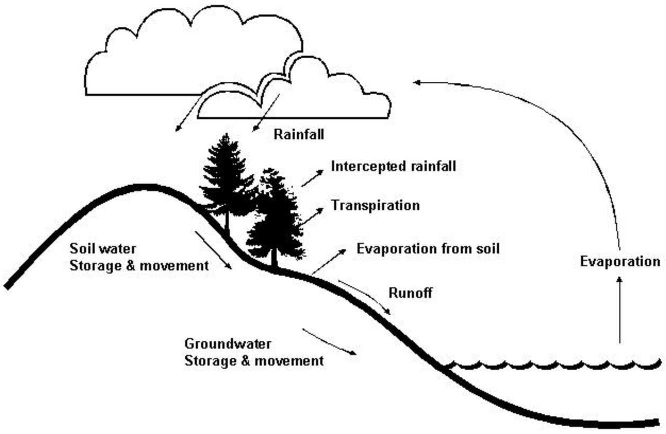

Fig. 3.1 The hydrological cycle

4. Forests and Rainfall

That the presence of forests might result in increased rainfall has been debated since the 19th century and contributes significantly to the myths and folklore concerning land use and water (Penman 1963; Pereira 1973, 1989; Bruijnzeel 1990; Calder 1999). Pereira (1989) notes:

> *The worldwide evidence that hills and mountains usually have more rainfall and more natural forests than do adjacent lowlands has historically led to confusion of cause and effect. Although the physical explanations have been known for more than 50 years, the idea that forests cause or attract rainfall has persisted. The myth was created more than a century ago by foresters in defence of their trees .... The myth was written into the textbooks and became an article of faith for early generations of foresters.*

Bands et al. (1989) make the following points:

> *Forests are associated with high rainfall, cool slopes or moist areas. There is some evidence that, on a continental scale, forests may form part of a hydrological feedback loop with evaporation contributing to further rainfall. On the Southern African subcontinent, the moisture content of air masses is dominated by marine sources, and afforestation will have negligible influence on rainfall and macroclimates. The distribution of forests is a consequence of climate and soil conditions — not the reverse.*

Most researchers (e.g., Penman 1963; Pereira 1973, 1989; Bands et al. 1989; Bruijnzeel 1990; amongst others) conclude that generally there is little, if any, evidence that forests can increase rainfall. There are possible exceptions where forests can "strip" moisture from clouds in coastal fog belts (Penman 1973; Bruijnzeel 1990) and can increase snow storage (Penman 1973). Recent work using global climate models has suggested there may be a slight increase in rainfall brought about by the presence of forests, but it seems as though this needs to be at a large areal scale, say of the Amazon Basin or the Sahel, but in any case will be relatively small and is likely to be compensated for by increased evaporation (Calder 1999). Calder (1999) also states *Although the effects of forests on rainfall are likely to be relatively small, they cannot be totally dismissed from a water resources perspective*, and concludes, *Further research is required to determine the magnitude of the effect, particularly at the regional scale.*

4.1 Conclusion

New Zealand weather is strongly controlled by maritime influences. Therefore, it is highly unlikely that native and plantation forests will cause an increase in rainfall.

5. Fog

Cotton & Anthes (1989) define fog as occurring when a large number of water droplets are suspended in air close to its saturation point. Alternatively, fog can be defined as cloud with its base near the ground surface.

The literature searches produced no information on radiata pine plantations and the significance of fog deposition. However, studies from fog-prone areas in Oregon and California showed that the capture of fog by Douglas fir forest (mainly old-growth forests) canopies significantly enhanced precipitation, of the order of 400–900 mm/year (Azevedo & Morgan 1974; Harr 1982; Ingwersen 1985). Thus, in a fog-prone environment, forests do have the potential to increase precipitation reaching the ground, but this is unlikely to be a significant factor in the water balance of New Zealand forests.

In New Zealand, Campbell & Murray (1990) carried out a weighing lysimeter study at Glendhu in upland east Otago. The lysimeter contained native snow tussocks representative of the surrounding area. Forty-one of 249 events may have contributed fog interception – the total was about 1% of precipitation. Another Otago study near Dunedin (Cameron et al. 1997) found that fog deposition rates may be of the order of 0.05 mm/hour. Here, it is unlikely that a change in land cover will significantly change the runoff regime by changing fog deposition rates; much larger changes are to be expected from changed evaporation rates. Extra runoff is estimated to be no more than 2% of total rainfall (Fahey et al. 1996).

5.1 Conclusion

Only in exceptional areas where fogs are frequent is there a possibility that fog may be a significant factor in a catchment water balance in New Zealand.

6. Dew

Dew accumulates on the vegetation and ground surfaces when air is cooled to the temperature at which it reaches saturation.

In one of the few studies in the literature of dew accumulation by trees, Fritschen & Doraiswamy (1973) measured dew accumulation on a single 28-m-tall Douglas fir tree in a weighing lysimeter at Washington in the United States Pacific Northwest. Dew accumulation on 2 clear days was equivalent to 0.37 and 0.63 mm and represented 15 and 20%, respectively, of the daily tree evaporation. They felt that under the climatic conditions experienced at the site, dew formation could play a significant part in the hydrologic balance of Douglas fir trees.

The lysimeter study of the water relations of snow tussock by Campbell & Murray (1990) at Glendhu in upland east Otago recorded 24 dew events. In all of these events, the lysimeter lost weight, indicating that condensation was not recorded as a weight gain.

6.1 Conclusion

Only in exceptional areas where dew occurs frequently is there any possibility that it may be a significant factor in a catchment water balance in New Zealand.

7. Interception Storage Capacities

In the first stage of the process of interception, precipitation not passing directly through canopy gaps to the ground is collected by the vegetation canopy. Water is stored on the vegetation surfaces until it falls off at drip points once that part of the canopy is more or less saturated, or it is evaporated back to the atmosphere during or after the storm ceases. The canopy may dry out a number of times during a storm if the evaporation rate is greater than the precipitation rate.

Interception storage capacity (ISC) is the amount of precipitation that can be held by the vegetation. It has been determined in a number of ways including:

1 The threshhold value of precipitation below which no throughfall occurs (Rogerson & Byrnes 1968)
2 Extrapolation of the upper envelope of the throughfall–precipitation data points for storms > 2.5 mm to find ISC = PTTN at the point where TF = 0 (Leyton et al. 1967)
3 Extrapolation of a line of slope (1 − stemflow fraction) along the upper envelope of a plot of throughfall and precipitation back to the point PTTN = 0 where the ISC is considered to be the negative throughfall amount (Gash & Morton 1978; Pearce & Rowe 1981; Kelliher et al. 1992b)
4 Extrapolation of the throughfall–precipitation relationship to find the amount of rain required before throughfall begins, i.e., ISC = PTTN where TF = 0 (Rutter 1963; Rowe 1975, 1979, 1983; Singh 1977; and many others).

Table 7.1 lists those values for interception storage capacity available from the literature searches. It appears that the Douglas fir stands have the highest ISC at about 2–4 mm, native evergreen forests are next at about 2 mm, and pine plantations have the smallest ISC, often about 1 mm but up to 2.5 mm. It is noteworthy that Pearce & Rowe (1981) and Rowe (1979) calculated ISC for the same beech-podocarp-hardwood stand at Maimai near Reefton on the West Coast, but using methods 3 and 4, respectively, over the same sampling periods. The difference in the results (Table 7.1) indicates that estimating ISC is not a precise science.

The interception storage capacity of the forest floor has largely been ignored. Putuhena & Cordery (1996) have measured forest floor interception storage capacity of about 2.8 mm for radiata pine compared to 1.7 mm for eucalypt.

7.1 Conclusion

Canopy interception storage capacity tends to be of the order of 2 mm for most of the woody vegetation types listed here. Forest floor ISC is largely unknown.

Table 7.1 Interception storage capacities (ISC) for some vegetation types found in New Zealand exotic species plantations, native forest and scrub stands.

Vegetation type	Age (year)	Stand density (SPH)	ISC (mm)	Source
Radiata pine	16	1708	2	Crockford & Richardson 1990
Radiata pine	31		2.5	Bell & Gatenby 1969
Radiata pine	7	450	0.4	Kelliher et al. 1992b
Radiata pine	26	733	0.9	Huber & Oyarzun 1983
Radiata pine	9	1392	1.3	Oyarzun et al. 1985
Radiata pine	9	443	1.1	Oyarzun et al. 1985
Radiata pine	26	733	2.2	Oyarzun et al. 1985
Radiata pine	12	754	0.6	Whitehead et al. 1989
Douglas fir	23	535	3.6 ± 0.7	Aussenac & Boulangeat 1980
Douglas fir	23	1030	3.7 ± 0.8	Aussenac & Boulangeat 1980
Douglas fir	23	2229	3.9 ± 0.8	Aussenac & Boulangeat 1980
Douglas fir	27	785	2.07–2.58	Bouten et al. 1996
Douglas fir	Mature		3.3–5	Krygier 1971
Douglas fir	41		1.2	Robins 1974
Mountain beech	Mature		2.7	Rowe 1975
Beech-podocarp-hardwood	Mature		2	Rowe 1979
Beech-hardwood	Mature		2	Rowe 1983
Beech-podocarp-hardwood	Mature		1	Pearce & Rowe 1981
Kanuka	16–40		2	Rowe et al. 1999
Snow tussock	Mature		0.6	Campbell & Murray 1990

8. Interception – Throughfall

During the interception process, precipitation is redistributed by the vegetation canopy so that:

Precipitation = Throughfall + Stemflow + Interception loss

Throughfall is that portion of precipitation that reaches the ground either as drip from a vegetation canopy or as direct fall through a canopy gap. It is generally measured using raingauges or troughs of varying designs.

In this section, where possible, studies identified as determining throughfall by single trees have not been included as it is difficult to relate this to a plantation/land-use situation. Nonetheless, some may have been inadvertently included as sampling methods were not always explicit.

8.1 Radiata pine

Annual throughfall under radiata pine canopies has been measured in many studies worldwide. New Zealand data are listed in Table 8.1, and the full data listed in Appendix 28.1 are summarised in Fig. 8.2. Some data are for studies that have gone on for more than one year and data are provided for each year, while other data are averages for more than one year.

New Zealand measurements cover the annual precipitation range from about 800 to 1600 mm. Both Australian and Chilean data overlap the New Zealand range, with that from Australia extending the dataset at the low end of the precipitation scale and that from Chile adding information beyond the upper end of the New Zealand dataset.

The highly significant linear relationship found between throughfall and precipitation using all data (Fig. 8.2) is given as Eqn 8.1. Equations 8.2 to 8.4 give the throughfall–precipitation relationships for Australia, New Zealand and Chile datasets, respectively. Data from New Zealand compared with Chile or Australia are not significantly different from each other; the 95% confidence limits of the regression coefficients overlap and slope-test F-values were 0.4 for Australia/New Zealand and 1.0 for Chile/New Zealand comparisons, respectively, while $F_{\text{tab, 95\%}} = 4.0$ (Freese 1967). The Australia/Chile relationship could be considered different, however, as $F = 6.0$ cf. $F_{\text{tab, 95\%}} = 4.0$.

All $\quad TF = -120 \pm 50 + 0.80 \pm 0.03 \times P \quad SE = 90;\ r^2 = 0.97;\ n = 75$ pairs (8.1)
Australia $\quad TF = 5 \pm 95 + 0.66 \pm 0.10 \times P \quad SE = 65;\ r^2 = 0.93;\ n = 17$ pairs (8.2)
New Zealand $\quad TF = -60 \pm 250 + 0.73 \pm 0.22 \times P \quad SE = 125;\ r^2 = 0.79;\ n = 16$ pairs (8.3)
Chile $\quad TF = -140 \pm 90 + 0.81 \pm 0.05 \times P \quad SE = 85;\ r^2 = 0.97;\ n = 38$ pairs (8.4)

Table 8.1 Throughfall under radiata pine canopies in New Zealand.

Source	Location	Age (year)	BA (m^2/ha)	Density (SPH)	PTTN (mm)	TF (mm)	TF (%)
Baker et al. 1985	Auckland	14	42	2100	895	512	57
Baker et al. 1986	Auckland	14	29.9	2000	822	551	67
Baker et al. 1986	Auckland	14	36.1	2000	822	484	59
Baker et al. 1986	Auckland	14	38.9	2000	822	484	59
Baker et al. 1986	Auckland	14	47.5	2000	822	459	56
Duncan 1980	Nelson	4		1500	1265	1088	86
Duncan 1980	Nelson	6		500	1238	1028	83
Duncan 1980	Nelson	7		500	938	750	80
Duncan 1980	Nelson	8		500	800	608	76
Fahey 1964	Otago	30	102	2080	1227	587	48
Fahey et al. 2001	Hororata	18	46	650	950	715	75
Jackson 1985	Ashley	mixed			855	556	65
McGregor 1983*	Central NI						75
Will 1959a	Kaingaroa	28		300	1854	1346	73
Will 1959a	Kaingaroa	29		300	1168	800	68
Will 1959b	Rotorua	7		3700	1510	905	60
Will 1959b	Rotorua	39		250	1510	989	65

* McGregor’s (1983) study was for a number of storms only and could not be converted to an annual basis.

Fig 8.2 also shows the error bands in which it is expected that 95% of all the data points will fit. It can be seen perhaps more clearly in Fig. 8.3, that for any given annual precipitation amount, the measured values fall into a band about ± 200 mm wide from the estimate using the worldwide relationship. Thus, for any stand without measured values, the true value may lie up to 200 mm from that predicted by Eqn 8.1.

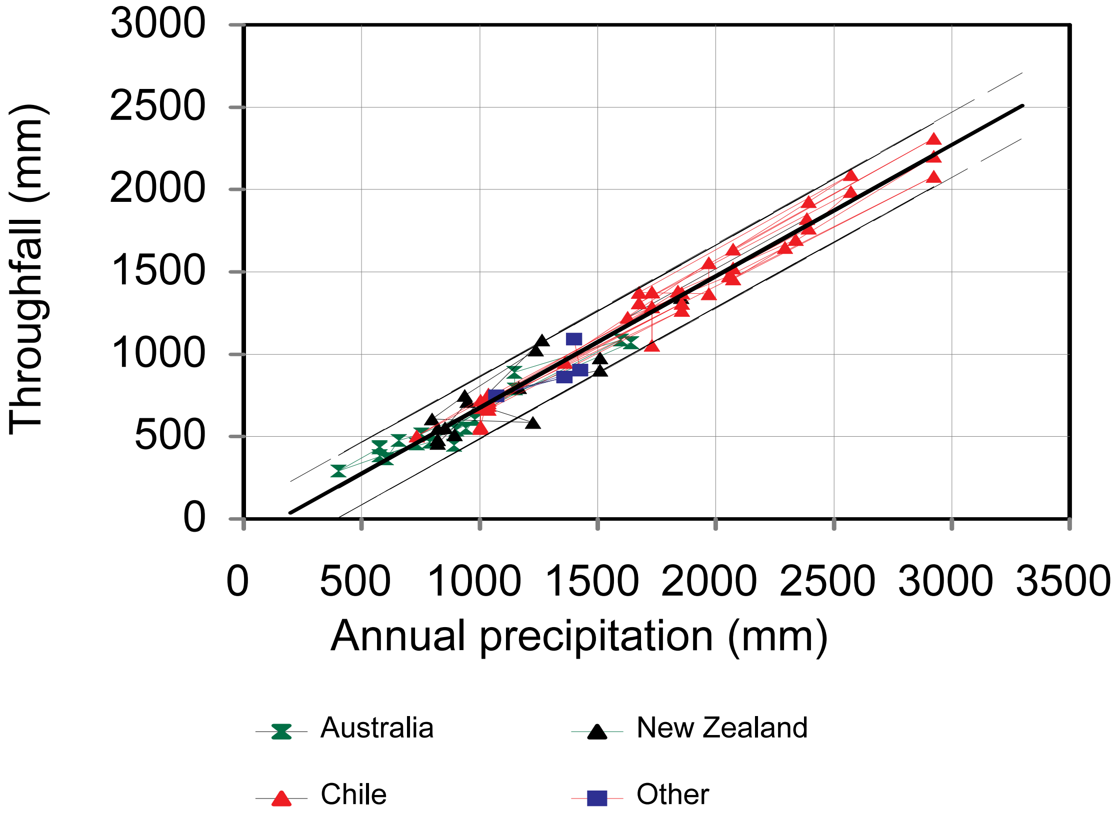

Fig. 8.2 The relationship between annual throughfall under the canopy of radiata pine plantations and precipitation using data from sites throughout the world.

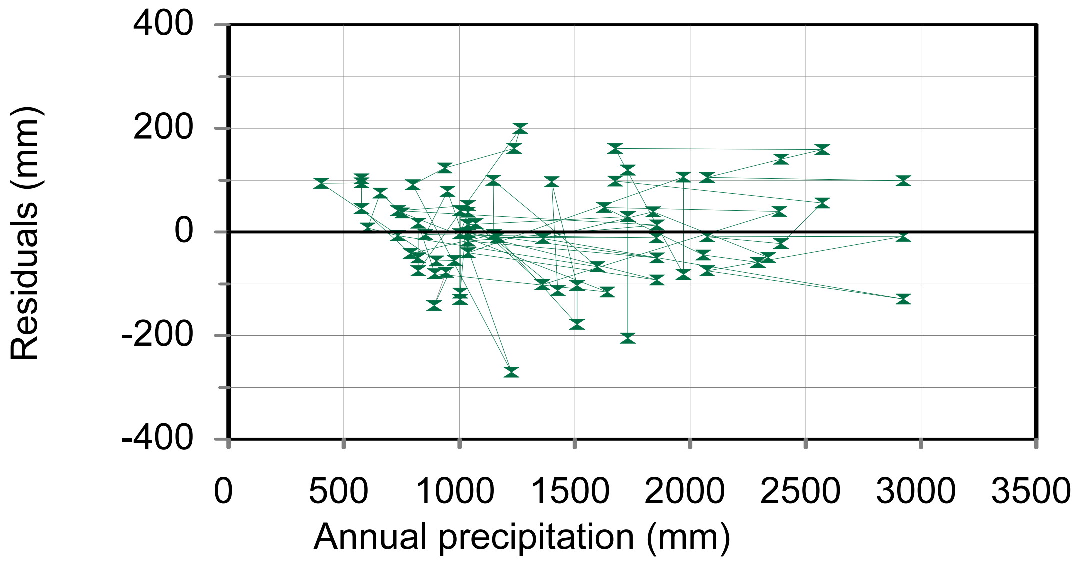

Fig 8.3 Residuals from measured throughfall values and those calculated from Eqn 8.1.

Attempts to improve the worldwide linear relationship by including stand age (Age, Eqn 8.5) or basal area as a measure of stand density (BA, Eqn 8.7) in the prediction equations proved unsuccessful as the regression coefficients for these added variables were not significantly different from zero. It is possible that these were not significant relationships because the length of time for the trees to mature is different in different countries; e.g., rotations are about 25 years in New Zealand and 40 years in South Africa. To try and overcome the age factor, and because there is a greater increase in biomass over the first 15 years or so as the plantation grows from seedlings towards a closed canopy state, an alternative regression equation was determined for the stands less than 15 years old (Age15, Eqn 8.6). Although in this instance an effect was detected, the overall regression was not as good as the other equations as shown by the r^2 values, possibly because thinning and pruning has a backwards effect on biomass for an increase in stand age, which is more sensitive in this smaller dataset than in the context of a whole rotation, as shown by Eqn 8.5.

$$\text{TF} = -90 \pm 70 + 0.80 \pm 0.04 \times \text{PTTN} - 2 \pm 3 \times \text{Age} \qquad \text{SE} = 90;\ r^2 = 0.97;\ n = 75 \text{ pairs} \quad (8.5)$$

$$\text{TF} = -100 \pm 180 + 0.74 \pm 0.09 \times \text{PTTN} - 13 \pm 11 \times \text{Age15} \qquad \text{SE} = 90;\ r^2 = 0.92;\ n = 30 \text{ pairs} \quad (8.6)$$

$$\text{TF} = -140 \pm 60 + 0.81 \pm 0.03 \times \text{PTTN} + 0.01 \pm 0.30 \times \text{BA} \qquad \text{SE} = 90;\ r^2 = 0.97;\ n = 60 \text{ pairs} \quad (8.7)$$

When expressed as a percentage of precipitation, throughfall (%TF) exhibits a wide scatter of points (Fig. 8.4) with a mean for the New Zealand data of 67 ± 5% compared to 70 ± 2% for the worldwide data. Linear regression analysis showed that only 19% of the variance in the data could be explained by precipitation, which had a regression coefficient of only 0.0055 (Eqn 8.8), although this is significantly different from zero. Dividing the data in Table 8.1 into two sets at the PTTN = 1000 mm mark gave mean %TF of 66 ± 6% and 69 ± 10% for the < 1000 mm and > 1000 mm samples, respectively. These mean %TF's are not significantly different from each other and indicate that there is no significant trend when we try and relate percentage throughfall to precipitation for radiata pine stands in New Zealand.

$$\%\ \text{TF} = 61.8 \pm 50 + 0.0055 \pm 0.003 \times \text{PTTN} \qquad \text{SE } 7.3;\ r^2 = 0.19;\ n = 75 \text{ pairs} \quad (8.8)$$

Adding basal area to the analysis made a small improvement in the statistical significance of the percent throughfall–precipitation relationship with r^2 increasing from 0.19 to 0.25. Adding age caused r^2 to decrease from 0.19 to 0.18. Neither regression coefficient for these factors was different from zero.

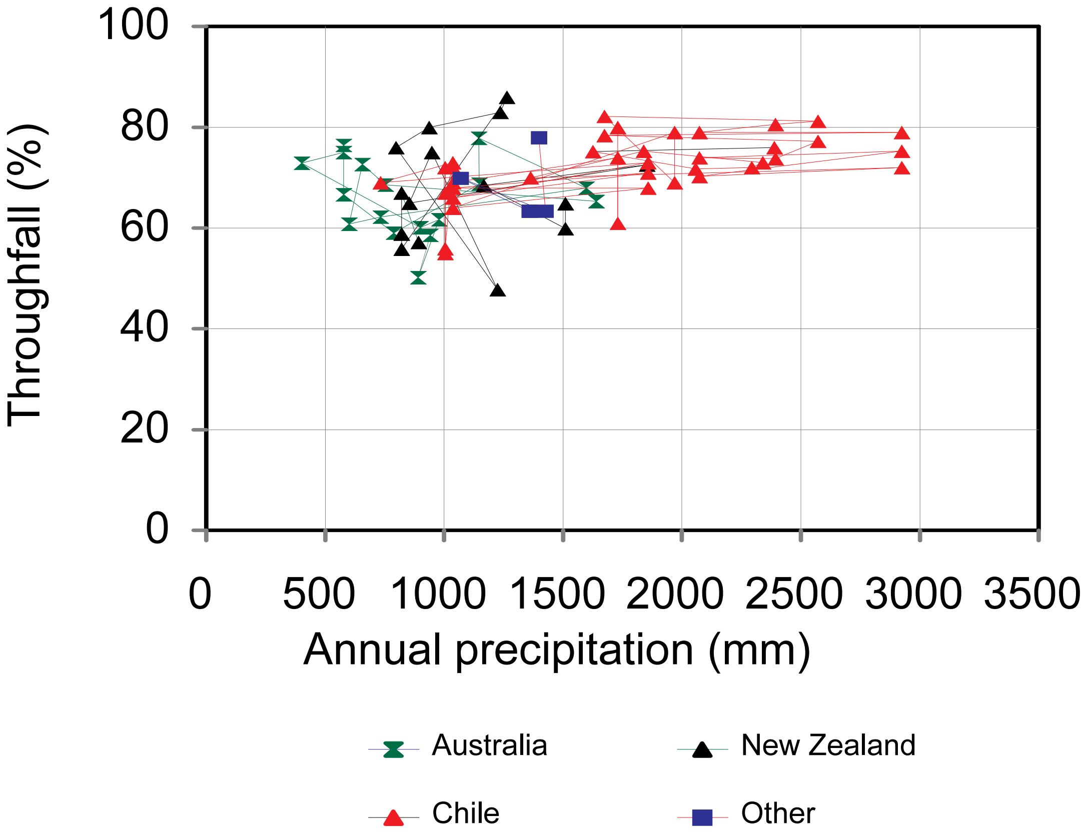

Fig. 8.4 The same data as in Fig. 8.2, but with radiata pine annual throughfall expressed as a percentage of annual precipitation.

A number of regression equations relating throughfall for radiata pine stands to precipitation have been noted in the literature (Table 8.2). The range in linear regression coefficients for canopy throughfall relationships listed in Table 8.2 is 0.695 to 0.84 with a mean of 0.79, which is slightly higher than for the New Zealand annual relationship in Eqn 8.3.

Table 8.2 The relationship between throughfall and precipitation for some radiata pine stands

Sampling regime	Age (year)	Stand density (SPH)	Equation	Source and Comment
Storm	25		$TF = 0.71 \times PTTN - 0.66$	Blake 1975
Storm	5		$TF = 0.84 \times PTTN - 3.21$	Blake 1975
Storm	7	450	$TF = 0.74 \times PTTN$	Kelliher et al. 1992b; No intercept given
Storm	7	450	Slash TF = 0.72 × Canopy TF	Kelliher et al. 1992b; No intercept given
Storm		550	$TF = 0.82 \times PTTN - 0.094$	McGregor 1983; Winter only
Storm		550	Slash TF = 0.852 × Canopy TF − 0.125	McGregor 1983; Winter only
Daily	10	1480	$TF = 0.79 \times PTTN - 0.1$	Pienaar, 1964
Daily	15		$TF=(1-(0.47\times C + 0.48^{(-0.40\times P/C)}))\times PTTN$	Putuhena & Cordery 2000; Canopy fraction 0.71
Weekly	26	733	$TF = 0.799 \times PTTN - 0.748$	Huber & Oyarzun 1983
Weekly	10	1745	$TF = 0.695 \times PTTN - 0.45$	Langford & O'Shaughnessy 1977
Weekly	33		$TF = 0.837 \times PTTN - 1.45$	Smith 1974

In their studies, McGregor (1983) and Kelliher et al. (1992b) show there can be significant interception by slash and understorey. Putuhena & Cordery (2000) also noted that forest floor interception can be significant, rising to 13% of precipitation at age 15 years for a stand in New South Wales.

8.2 Douglas fir

Thirty-one studies were identified that have data for throughfall under Douglas fir canopies but only three were in New Zealand (Appendix 28.2). Will (1959a) took throughfall measurements as part of a nutrient cycling study in several conifer stands at Kaingaroa Forest in the Central North Island, Hogg et al. (1978) made short-term measurements of throughfall in a plantation near Dunedin, and Fahey et al. (2001) carried out a comparative study with radiata pine at Hororata in Mid-Canterbury (Table 8.3).

Table 8.3 Throughfall under Douglas fir canopies in New Zealand

Source	Location	Age (year)	Height (m)	BA (m^2/ha)	Density (SPH)	PTTN (mm)	TF (mm)	TF (%)
Fahey et al. 2001	Hororata	18	11	38	1350	1030	690	67
Fahey et al. 2001	Hororata	54	28	67	550	910	600	66
Hogg et al. 1978*	Otago	50	38		440	283	134	47
Will 1959a	Kaingaroa	33	27		1240	1448	800	55
Will 1959a	Kaingaroa	34	27		1240	1930	927	48

* Hogg et al. (1983) measured 23 storms only in an area of MAP about 690 mm.

Many of the overseas studies are for short periods and thus may not be suitable for converting to annual values without the probability of introducing significant errors. Notwithstanding these concerns, all data are shown in Fig. 8.5, and for the older plantation stands the regression equation is given in Eqn 8.9.

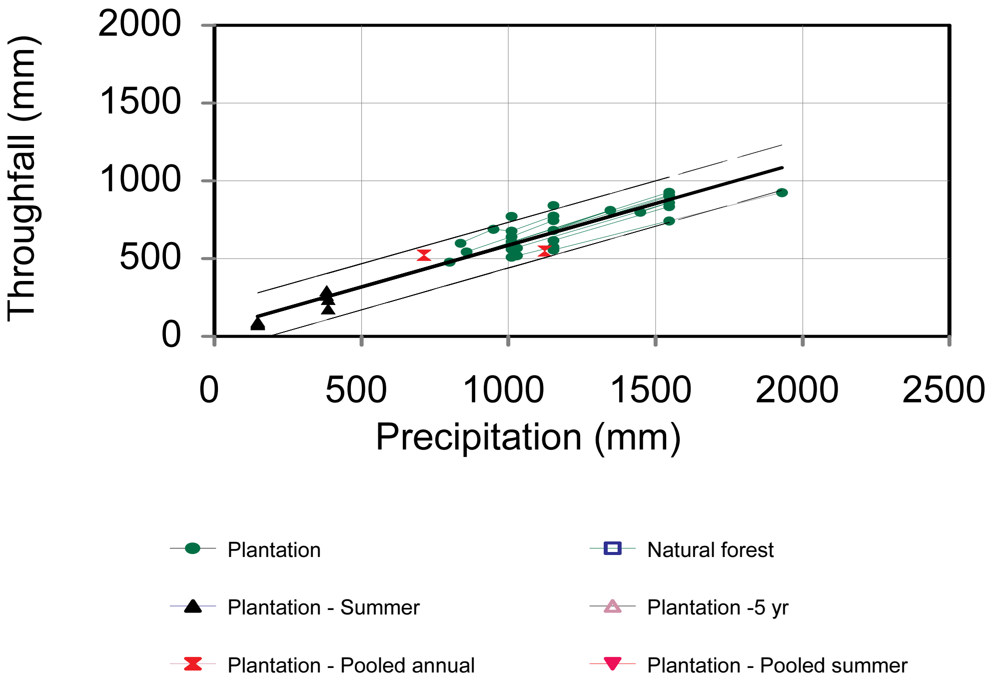

Fig. 8.5 Throughfall under Douglas fir canopies. Precipitation for the short-term studies have been converted on a pro-rata basis to annual amounts. The pooled data are where a number of stands have been averaged and no individual stand data given. Data for the one natural forest and the one 5-year-old-plantation are not included in the regression line.

It is noteworthy that Eqn 8.9 has a much lower regression coefficient than in Eqns 8.1 to 8.4 for radiata pine. Moreover, a comparison between Eqns 8.1 and 8.9 indicates the slopes were significantly different ($F = 71$; $F_{\text{tab, 95\%}} = 6.9$). This means that the canopy architecture of Douglas fir stands (possibly crown density) allows more interception of precipitation than radiata pine plantations. However, there are no interception storage capacity assessments nor biomass estimates given for the Douglas fir plantations to verify this.

All data TF = −50 ± 50 + 0.54 ± 0.05 × PTTN SE = 85; $r^2 = 0.92$; n = 48 pairs (8.9)

While 92% of the variance in the data is explained by Eqn 8.9, there is still a wide scatter of points and throughfall measurements will generally fall in an envelope ± 150 mm from the predictions using Eqn 8.9 (Figs 8.5 and 8.6).

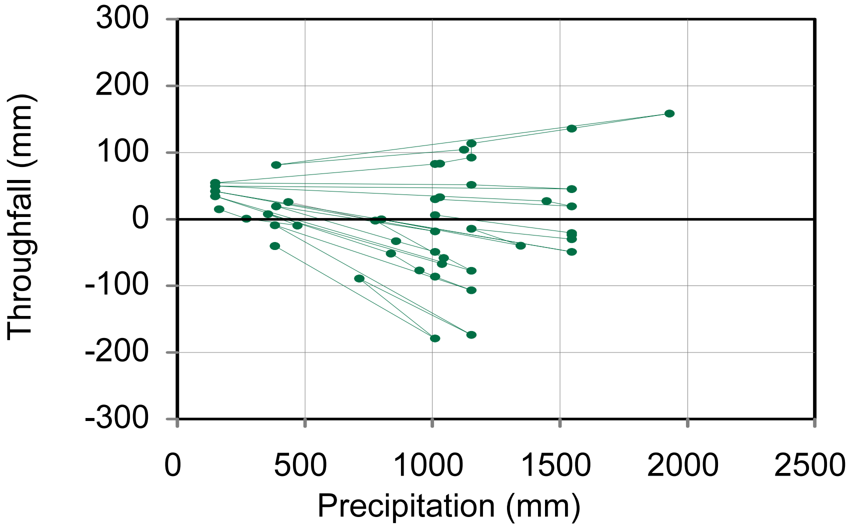

Fig. 8.6 Residuals between measured throughfall and that calculated using Eqn 8.9 for Douglas fir

While the New Zealand data fall within the scatter in Fig.8.5, the four data points (as shown later in Fig. 8.7) exhibit a strange trend not shown by other vegetation types. We can only surmise that the data points of Will (1959a) are an aberration in the overall dataset, perhaps because the data are averages from only two throughfall gauges, which were not representative of the plantation as a whole. The average throughfall for the five studies listed in Table 8.3 is 57 ± 8%, a mean value lower than for the radiata pine data given earlier but the confidence limits do overlap; for all the studies the mean throughfall was 61 ± 3%. There was no correlation between %TF and either precipitation ($r^2 = 0.02$; n = 52 pairs) or stand density ($r^2 = 0.01$; n = 40 pairs).

Only two studies, one in a plantation and one in a natural forest, gave relationships between short-term throughfall and precipitation (Table 8.4). The slope coefficients are in the same range as for the radiata pine studies and that for the natural forest stand is at the top of the range.

Table 8.4 The relationship between throughfall and precipitation for two Douglas fir stands

Sampling regime	Age (year)	Stand density (SPH)	Equation	Source
Weekly	39-46	668	$TF = 0.604 \times PTTN - 0.72$	Langford & O'Shaughnessy 1977
Summer storms	Old growth		$TF = 0.831 \times PTTN - 1.17$	Rothacher 1963

8.3 New Zealand native forests

Throughfall under native forest canopies has been studied at six locations (Table 8.5) and the data obtained from these are shown in Fig. 8.7. The trend is for throughfall to be smaller under the native forest canopies than for pine plantations for a given annual precipitation total. Equation 8.10 has a regression equation calculated using data from the six sites and, although a statistically significant relationship exists ($r = 0.94$ cf. $r_{tab} = 0.811$), there is little value in using it for prediction purposes because of the high error limits on the intercept and the slope coefficient, which is partly a reflection of the small sample size.

$$TF = -560 \pm 710 + 0.986 \pm 0.47 \times PTTN \qquad SE = 125;\ r^2 = 0.89;\ n = 6 \text{ pairs} \qquad (8.10)$$

Table 8.5 Annual throughfall under New Zealand native forest canopies

Source	Forest type	PTTN (mm)	TF (mm)	TF (%)
Miller 1963	Hard beech	1350	760	56
Aldridge & Jackson 1973	Hard beech	1530	742	48
Rowe 1983	Beech-hardwood	1490	1035	69
Rowe 1975*	Mountain beech	1313	790	60
Rowe 1979	Beech-podocarp-hardwood	2073	1513	73
Jackson & Aldridge 1973	Kāmahi	1099	525	48

* Summer only

On a percentage of precipitation basis, these studies have an average %TF of 59 ± 8%. There is some seasonal variation in throughfall under beech-podocarp-hardwood forest at Maimai near Reefton as throughfall was 68% of precipitation in winter and 77% in summer (Rowe 1979). At Donald Creek in Nelson where precipitation is lower, monthly throughfall under a beech-hardwood forest ranged between a summer minimum of 63% and a winter maximum of 75% (Rowe (1983).

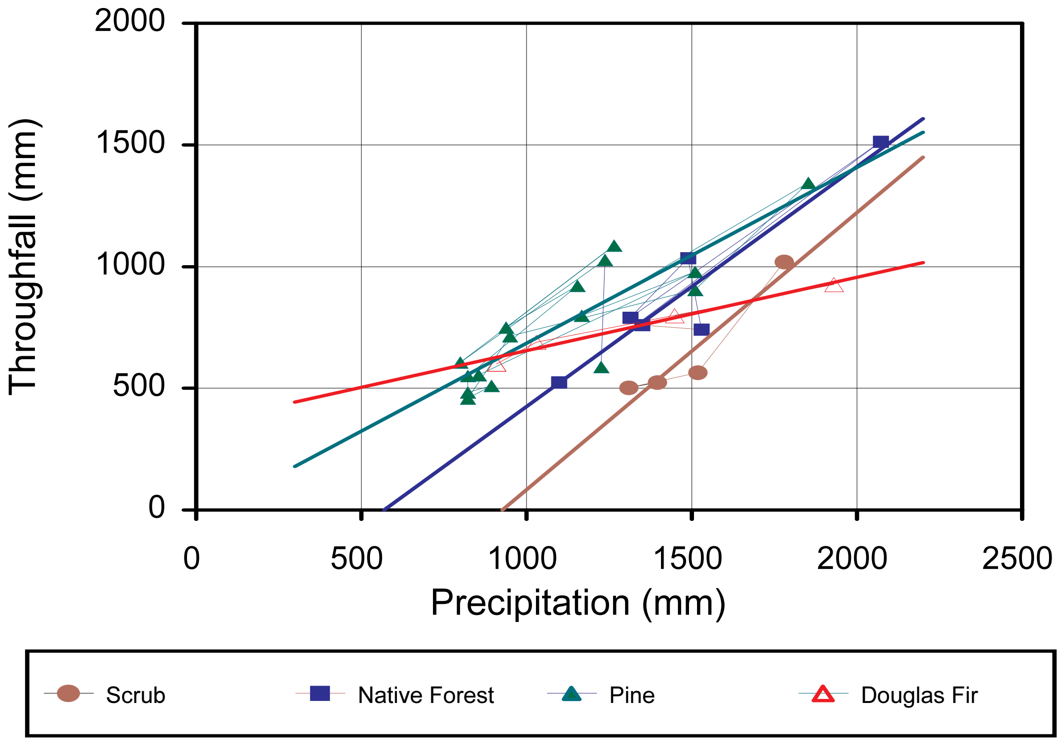

Fig. 8.7 Canopy throughfall for New Zealand vegetation types. Scrub includes gorse, mānuka and kānuka, and the native forest types are those listed in Table 8.5.

A number of studies have reported throughfall as a function of precipitation for short time periods (Table 8.6) with regression coefficients in the range 0.48 to 0.84, which may reflect the diversity of the stands.

Table 8.6 Throughfall–precipitation relationships for New Zealand native forests

Sampling regime	Stand	Equation	Source and comment
Storm	Hard beech	TF = 0.526 × PTTN + 0.01	Aldridge & Jackson 1973
Storm	Kāmahi	TF = 0.480 × PTTN + 0.07	Jackson & Aldridge 1973
Storm	Mountain beech	TF = 0.69 × PTTN – 1.9	Rowe 1975; Summer
Storm	Beech-podocarp-hardwood	TF = 0.84 × PTTN – 1.60	Rowe 1979; Winter
Storm	Beech-podocarp-hardwood	TF = 0.75 × PTTN – 1.51	Rowe 1979; Summer
Storm	Beech-hardwood	TF = 0.78 × PTTN – 0.83	Rowe 1983; Winter
Storm	Beech-hardwood	TF = 0.73 × PTTN – 0.90	Rowe 1983; Summer
Weekly	Native	TF = 0.60 × PTTN – 3.71	Blake 1975
Monthly	Beech-hardwood	TF = 0.78 × PTTN – 7.5	Rowe 1983; Winter

Sampling regime	Stand	Equation	Source and comment
Monthly	Beech-hardwood	$TF = 0.70 \times PTTN - 5.2$	Rowe 1983; Summer

8.4 Scrubland species

Studies in New Zealand have been carried out mainly on gorse, kānuka and mānuka. The compilation here (Table 8.7) includes data from two studies in Spain on gorse.

Table 8.7 Throughfall under scrub species canopies.

Source	Scrub type	PTTN (mm)	TF (mm)	TF (%)
Aldridge & Jackson 1968	Mānuka	1310	503	38
Blake 1965	Mānuka	1397	525	38
Rowe et al. 1999	Kānuka	1780	1020	57
Egunjobi 1971	Gorse	1519	565	37
Soto & Diaz-Fierros 1997	Gorse	1517	830	55
Soto & Diaz-Fierros 1997	Gorse	1063	606	57
Calvo de Anta et al. 1979	Gorse			48

Fig. 8.7 shows the New Zealand data which fit Eqn 8.11 (barely not significant at the 95% level as $r = 0.947$ cf. $r_{tab} = 0.950$), and have a mean throughfall of 48 ± 11% of precipitation. However, because of the wide confidence limit of the parameters, the same comments apply with respect to the utility of this equation as for the native forest species.

$$TF = -1060 \pm 1780 + 1.14 \pm 1.18 \times PTTN \qquad SE = 100;\ r^2 = 0.90;\ n = 4 \text{ pairs} \qquad (8.11)$$

There are also a number of throughfall–precipitation relationships determined for these scrub studies (Table 8.8) the regression coefficients ranging from 0.28 to 0.63, a much lower range than for all the forest stands.

Table 8.8 Throughfall – precipitation relationship for scrubby vegetation

Sampling regime	Vegetation type	Equation	Source
Storm	Gorse	TF = 0.23 × PTTN − 0.05	Aldridge 1968
Storm	Gorse	TF = 0.59 × PTTN − 1.88	Blake 1975
Storm	Gorse	TF = 0.63 × PTTN − 2.50	Soto & Diaz-Fierros 1997
Storm	Mānuka	TF = 0.454 × PTTN − 0.025	Aldridge & Jackson 1968
Storm	Mānuka	TF = 0.441 × PTTN + 0.037	Blake 1972
Storm	Mānuka	TF = 0.44 × PTTN − 0.10	Blake 1975
Storm	Native scrub	TF = 0.47 × PTTN + 0.09	Blake 1975

8.5 Comparative studies

Among the studies reported, there are only two that can be considered comparative for species relevant to New Zealand when measurements are made in the different stands at the same time. Throughfall from Douglas fir and radiata pine stands has been measured by Langford & O'Shaughnessy (1977) in Victoria and by Fahey et al. (2001) in Mid-Canterbury at Hororata (Table 8.9). Both studies indicate that throughfall under radiata pine is greater than under Douglas fir.

Table 8.9 Comparative throughfall studies (Hororata: Fahey et al. 2001; Victoria: Langford & O'Shaughnessy 1977)

	Douglas fir				Radiata pine			
	Age (years)	PTTN (mm)	TF (mm)	TF (%)	Age (years)	PTTN (mm)	TF (mm)	TF (%)
Hororata	18	1030	690	67	18	950	715	75
Hororata	54	910	600	66				
Victoria	43			58	13			68
Victoria	Weekly TF = 0.604×PTTN − 0.72				Weekly TF = 0.695×PTTN − 0.45			

8.6 Conclusions

Annual throughfall

Annual throughfall as a percentage of precipitation is shown in Table 8.10 for both the New Zealand and the worldwide data (including New Zealand) datasets. There is little difference in the comparisons for each vegetation type as the confidence limits overlap, but it must be emphasised that the New Zealand data are a subset of the worldwide data. There is a tendency for throughfall to be greater under the pine stands than for Douglas fir or native forest, and for there to be smaller amounts under scrub, although here there are very wide confidence limits about the mean.

Table 8.10 Summary of throughfall studies: mean throughfall as a percentage of precipitation with 95% confidence limits, and the number of data points given in parentheses.

Species	New Zealand studies	Worldwide
Radiata pine	67 ± 5 (16)	70 ± 2 (75)
Douglas fir	57 ± 8 (5)	61 ± 3 (54)
Native forest	59 ± 8 (6)	
Scrub	48 ± 11 (4)	50 ± 7 (7)

Annual throughfall–precipitation relationships

These relationships are given in Table 8.11 for the worldwide data for radiata pine and Douglas fir and for New Zealand data for all vegetation types except Douglas fir (which had insufficient good data available); they are also plotted in Fig. 8.8. The worldwide regression relationships for the two plantation species are statistically different from each other. For prediction purposes the equations have potential errors of about ± 150 mm about the prediction for any given annual precipitation regime.

The regression coefficients for the native forest and scrub relationships are not those expected in the real world, being close to or greater than 1 and with extremely wide confidence limits, which is a reflection on the small sample sizes available.

Table 8.11 Annual throughfall–precipitation relationships for vegetation types found in New Zealand

Vegetation type	Equation	
Radiata pine – worldwide	$TF = -120 \pm 50 + 0.80 \pm 0.03 \times P$	$r^2 = 0.97$; n = 74 pairs
Radiata pine – New Zealand	$TF = -60 \pm 250 + 0.73 \pm 0.22 \times P$	$r^2 = 0.79$; n = 16 pairs
Douglas fir – worldwide	$TF = -50 \pm 50 + 0.54 \pm 0.05 \times P$	$r^2 = 0.92$; n = 48 pairs
New Zealand native forest	$TF = -560 \pm 710 + 0.986 \pm 0.47 \times P$	$r^2 = 0.89$; n = 6 pairs
New Zealand scrub	$TF = -1060 \pm 1780 + 1.14 \pm 1.18 \times P$	$r^2 = 0.90$; n = 4 pairs

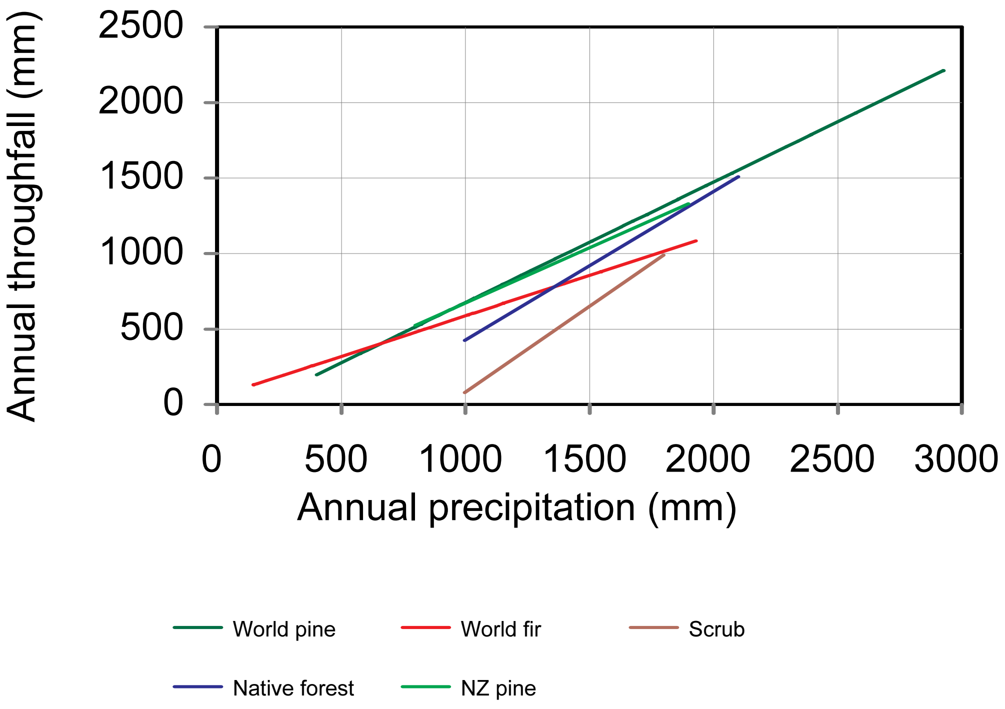

Fig. 8.8 Linear regression relationships between annual throughfall and precipitation. Pine is radiata pine and fir is Douglas fir.

9. Interception – Stemflow

Stemflow is generally by far the smallest component of the interception balance and is the intercepted water that reaches the ground via movement down the stems of trees or shrubs, although it may have as its source direct precipitation or water movement down branches. While throughfall is measured as the other main component of precipitation reaching the ground, stemflow is often ignored or allowance made (e.g., Fahey 1964; Rowe 1983; and many others). Its importance comes in the redistribution of precipitation where it can be concentrated in an area immediately surrounding the trunk and being made available to the tree/shrub.

When measured, stemflow is usually trapped by narrow collars sealed to the tree trunks and led off into containers. The measured volumes may be related to ground area on the basis of plot area, tree canopy projection, or summed according to stem size distributions for a given area.

9.1 Radiata pine

Only one study in New Zealand explicitly reports measured stemflow with rainfall for radiata pine plantations (Fahey et al. 2001) so we have to rely on Australian (11 values) and Chilean (46 values) information to put this in the wider context (Fig. 9.1; data in Appendix 28.3). These points fit Eqn 9.1 which explains only 57% of the variance in the data and they have very wide 95% confidence limits reflecting the scatter of the data (more than ±100 mm about the calculated line (Figs 9.1 and 9.2)). Inclusion of stand density into the equation improves the explained variance by 8% but the coefficient on SPH is not statistically significantly different from zero (Eqn 9.2).

$SF = -60 \pm 45 + 0.11 \pm 0.03 \times PTTN$ SE =64; $r^2 = 0.57$; n = 58 pairs (9.1)

$SF = -100 \pm 55 + 0.12 \pm 0.03 \times PTTN + 0.04 \pm 0.05 \text{ x } SPH$ SE = 61; $r^2 = 0.65$; n = 52 pairs (9.2)

The average stemflow as a percentage of precipitation is: Worldwide 6.7 ± 1.1%; Australia 4.3 ± 1.6%; Chile 7.3 ± 1.3%; New Zealand 5.6%. The overall greater stemflow in the Chilean data may reflect the generally wetter environments in which most of the data were collected (Fig. 9.3).

The lone New Zealand value fits the trend line in Eqn 9.1 and sits within the percent stemflow scatter in Fig 9.3.

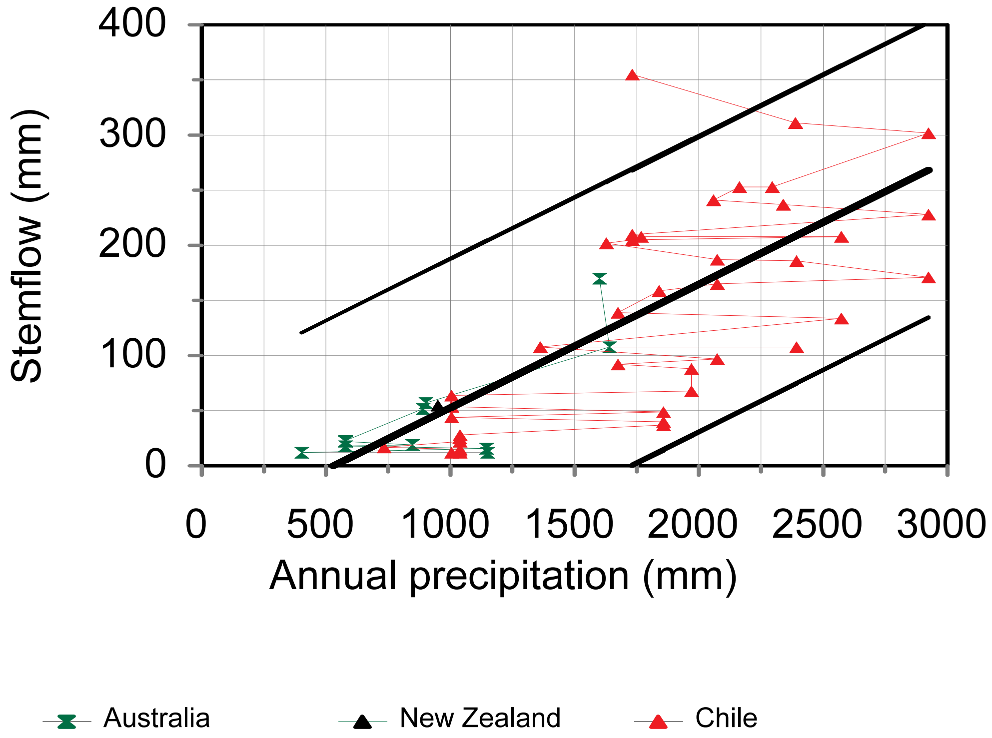

Fig. 9.1 Stemflow by radiata pine plantations in Australia, Chile and New Zealand.

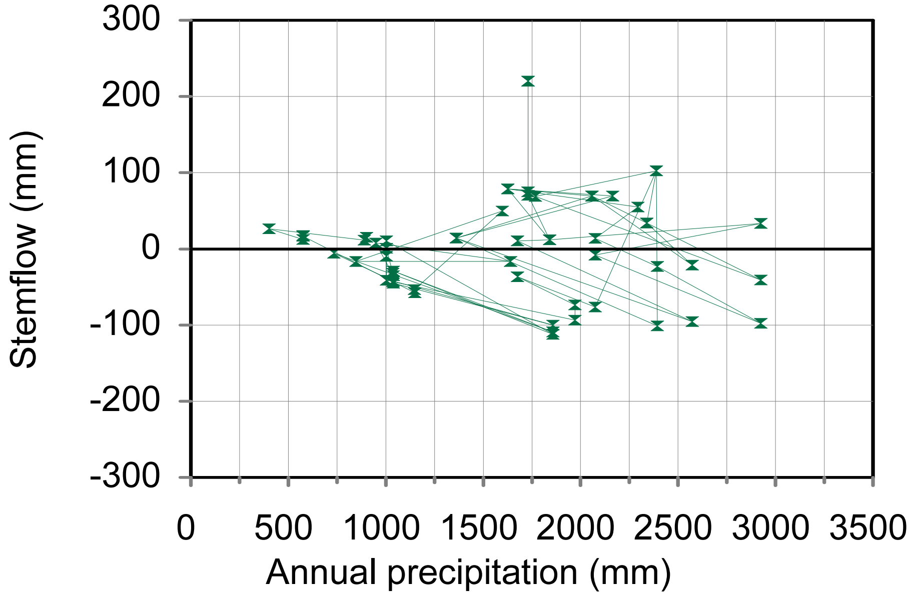

Fig. 9.2 The residuals between measured and that calculated by Eqn 9.1 for radiata pine plantations worldwide.

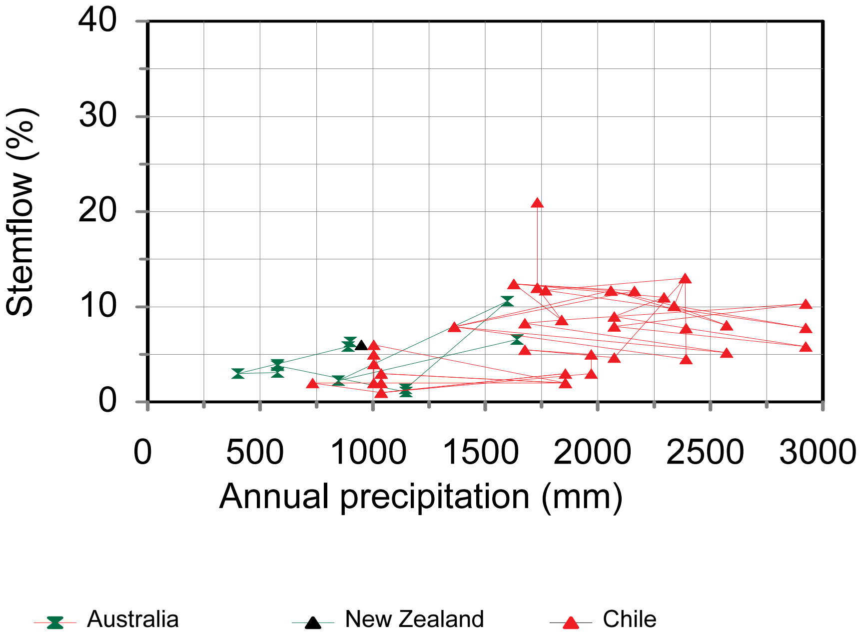

Fig. 9.3 The same data as in Fig. 9.1 but this time with stemflow as a percentage of precipitation.

A number of linear relationships between stemflow and precipitation have been determined (Table 9.1). All linear relationship except for Smith (1974) have regression coefficients less than about 0.17 indicating that stemflow will be less than 17% of precipitation; making an allowance for the intercepts could lower this by about 2–3% per year depending on the number of events in the storm relationships.

Table 9.1 Stemflow-precipitation relationships for radiata pine stands for short time periods.

Sampling interval	Age (year)	Density (SPH)	Equation	Source
Storm	5		$SF = 0.17 \times PTTN - 0.52$	Blake 1975
Storm	25		$SF = 0.07 \times PTTN - 0.19$	Blake 1975
Storm	7	450	$SF = 0.05 \times PTTN - 0.18$	Kelliher et al. 1992b
Storm	7	450	$SF = 0.08 \times PTTN - 0.16$	Kelliher et al. 1992b
Storm	13		$SF = -2.55 + 2.14 \times \log PTTN$	Myers & Talsma 1992
Storm	12	754	$SF = 0.11 \times PTTN - 0.22$	Whitehead et al. 1989
Daily	15		$SF = 0.038 \times PTTN$	Putuhena & Cordery 2000
Weekly	26	733	$SF = 0.127 \times PTTN - 0.806$	Huber & Oyarzun 1983
Weekly	33		$SF = 0.23 \times PTTN - 0.036$	Smith 1974
Weekly	39-46	1745	$SF = 0.141 \times PTTN - 1.04$	Langford & O'Shaughnessy 1977

9.2 Douglas fir

Stemflow measured under two Douglas fir plantations by Fahey et al.(2001) is the only published New Zealand data and appears to be at the low end of the range for Douglas fir as shown in Fig. 9.4. The relationship between stemflow and precipitation is:

$SF = -1 \pm 25 + 0.08 \pm 0.03 \times PTTN$ SE = 34; $r^2 = 0.58$; n = 32 pairs (9.3)
$SF = -60 \pm 35 + 0.09 \pm 0.02 \times PTTN + 0.03 \pm 0.01 \times SPH$ SE = 31; $r^2 = 0.75$; n = 28 pairs (9.4)

Comparing the stemflow–precipitation relations for radiata pine (Eqn. 9.1) and Douglas fir (Eqn 9.2) shows no statistically significant difference between the two ($F_{slope} = 2.06$; $F_{level} = 2.66$; $F_{tab} = 3.95$).

Unlike radiata pine, the Douglas fir data presented here have a positive relationship with stand density as shown by Eqn 9.4. This is further reinforced by the %SF stemflow relationships, where the relationship with precipitation is essentially non-existent (only 0.8% of the variance could be explained by the data). There is a good relationship with stand density alone (Eqn 9.5; Fig. 9.5), and the inclusion of the precipitation term with stand density leads to a minor improvement in explained variance but again no significance can be attributed to the precipitation term (Eqn 9.6).

$\%SF = 2.85 \pm 2.0 + 0.004 \pm 0.01 \times SPH$ SE = 2.4; $r^2 = 0.59$; n = 28 pairs (9.5)
$\%SF = 1.60 \pm 3.2 + 0.004 \pm 0.01 \times SPH + 0.001 \pm 0.002 \times PTTN$ SE = 2.4; $r^2 = 0.61$; n = 28 pairs (9.6)

As a percentage of annual precipitation, average stemflow on a worldwide basis is 7.5 ± 1.3%. Fahey et al.'s (2001) data are 3.9% and 4.9% for the two measured stands.

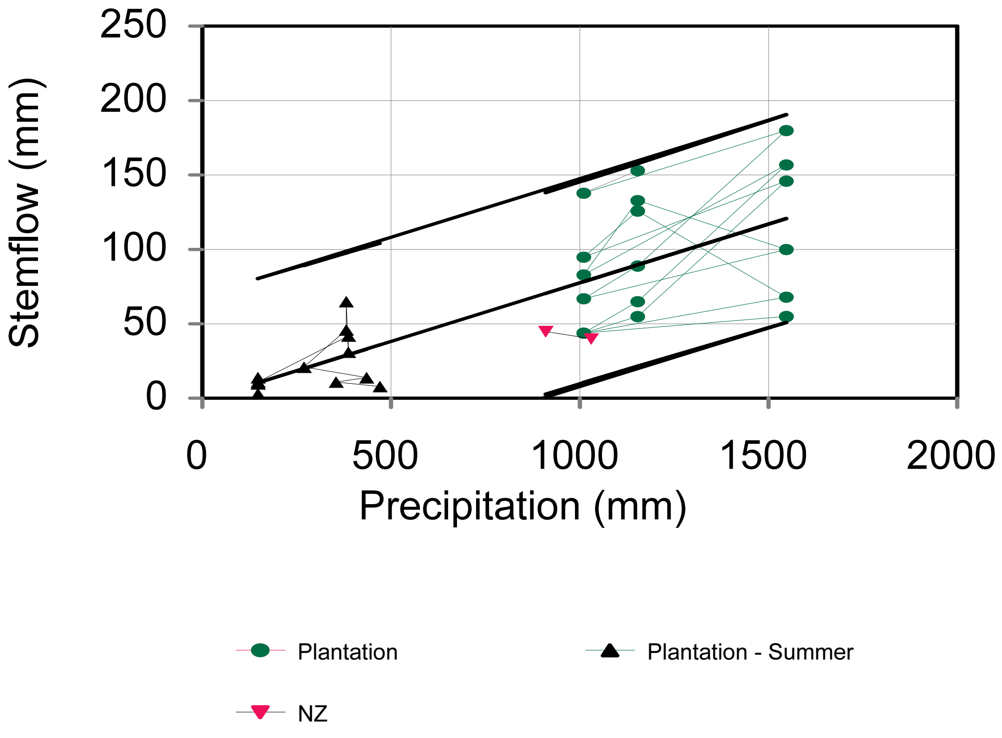

Fig 9.4 Stemflow measured in a number of Douglas fir plantations.

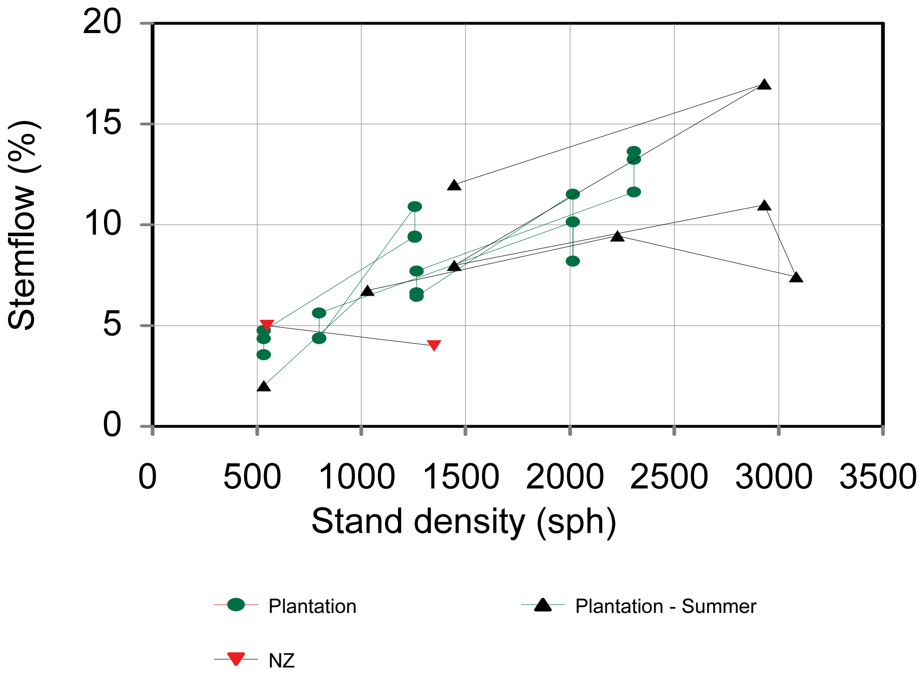

Fig 9.5 The relationship between stand density and stemflow as a percentage of precipitation for Douglas fir stands.

Only one study has presented a short-term relationship between stemflow and precipitation (Langford & O'Shaughnessy (1977) (Table 9.2).

Table 9.2 Short-term stemflow–precipitation relationships for Douglas fir and New Zealand vegetation studies

Vegetation	Sampling interval	Age (year)	Density (SPH)	Equation	Source
Douglas fir	Weekly	40–48	668	SF = 0.161 × PTTN − 0.60	Langford & O'Shaughnessy 1977
Native forest	Storm			SF = 0.04 × PTTN − 0.15	Blake 1975
Kāmahi	Storm			SF = 0.318 × PTTN − 0.89	Jackson & Aldridge 1973
Hard beech	Storm			SF = 0.184 × PTTN − 0.33	Aldridge & Jackson 1973
Mānuka	Storm	58	40 000	SF = 0.324 × PTTN − 0.05	Aldridge & Jackson 1968
Mānuka	Storm			SF = 0.425 × PTTN − 0.050	Blake 1975
Mānuka	Storm			SF = 0.38 × PTTN − 0.01	Blake 1975
Native scrub	Storm			SF = 0.30 × PTTN − 0.56	Blake 1975
Gorse	Storm			SF = 0.07 × PTTN − 0.28	Blake 1975

9.3 New Zealand vegetation

Apart from the Fahey et al. (2001) study referred to earlier, there are few stemflow data available for New Zealand vegetation. The data presented in the literature are listed in Table 9.3 and the variable nature of these is shown further in Fig. 9.6 and by the range in the regression coefficients of the short-term stemflow–precipitation relationships in Table 9.2. Because of this variability it is difficult to make any generalisations, and it may be that differing measurement techniques and methods of attributing the collections to ground areas may contribute to some of the variability. However, the average %SF for the four native forest stands in Table 9.3 is 11% and for the three scrub stands is 18%, but for both vegetation types there is a very wide spread of values.

Table 9.3 Stemflow for New Zealand vegetation classes

Source	Vegetation	P (mm)	SF (mm)	SF (%)
Blake 1965	Mānuka	1397	435.9	31.2
Aldridge & Jackson 1968	Mānuka	1310	297.5	22.7
Rowe et al. 1999	Kānuka	1780	20.0	1.1
Aldridge & Jackson 1973	Hard beech	1530	272.0	17.8
Rowe 1975	Mountain beech	1314	16.7	1.3
Rowe 1979	Beech-podocarp-hardwood	2073	30.0	1.4
Jackson & Aldridge 1973	Kāmahi	1099	386.8	25.3
Fahey et al. 2001	Radiata pine	1030	58.0	5.6
Fahey et al. 2001	Douglas fir	1030	40.0	3.9
Fahey et al. 2001	Douglas fir	910	45.0	4.9

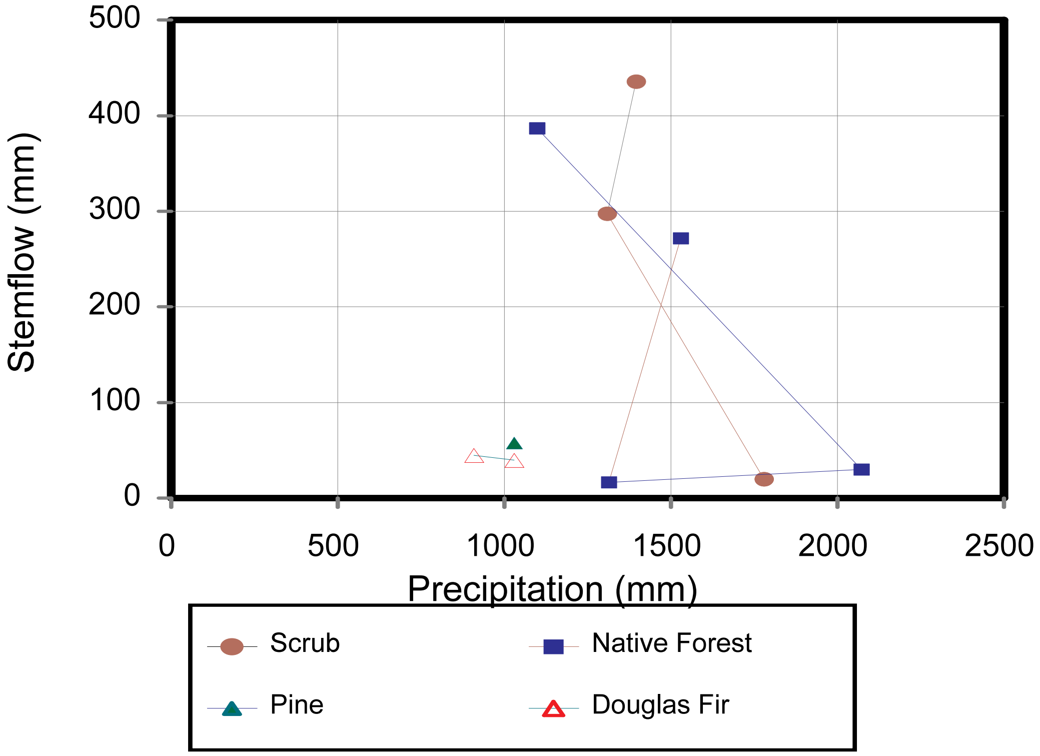

Fig 9.6 Measured stemflow for some New Zealand vegetation types.

9.4 Comparative studies

Amongst the studies reported, there are only two that can be considered comparative for species relevant to New Zealand when measurements are made concurrently in the different stands. Stemflow from Douglas fir and radiata pine stands has been measured by Langford & O'Shaughnessy (1977) in Victoria and by Fahey et al. (2001) in Mid-Canterbury at Hororata (Table 9.4). These studies suggest no clear trend.

Table 9.4 Comparative stemflow studies (Hororata: Fahey et al. 2001; Victoria: Langford & O'Shaughnessy 1977)

	Douglas fir		Radiata pine	
	Age	SF%	Age	SF%
Hororata	18	3.9	18	5
Hororata	54	5.7		
Victoria	43	14.1	13	10.6
Victoria	Weekly SF = 0.161×PTTN – 0.60		Weekly SF = 0.141×PTTN – 1.04	

9.5 Conclusions

Annual stemflow

Annual stemflow as a percentage of precipitation is shown in Table 9.5. Stemflow from radiata pine and Douglas fir plantations is similar at about 7% of precipitation for the worldwide data; the few New Zealand plantations have lower stemflow than this average. New Zealand native forest and scrubland data have very much higher levels although there are very wide extremes.

Table 9.5 Mean percentage stemflow for New Zealand vegetation classes

Species	Worldwide studies	New Zealand studies
Radiata pine	6.7 ± 1.1	5.6
Douglas Fir	7.5 ± 1.3	4.4
Native forest		18
Scrub		11

Annual stemflow–precipitation relationships

Relationships between stemflow and precipitation have only been established for the worldwide datasets for radiata pine and Douglas fir, and they are not statistically different from each other. Too few New Zealand data are available for other species to determine if meaningful relationships exist.

Radiata pine $SF = -60 \pm 45 + 0.112 \pm 0.026 \times PTTN$
Douglas fir $SF = -1 \pm 25 + 0.079 \pm 0.025 \times PTTN$

There are limitations to the use of these equations for predictive purposes in that predictions have a potential error of ±150 mm from the estimate.

10. Interception Loss

Interception loss is not a measured quantity. It is found by calculating the difference between the quantity of precipitation outside the canopy and that reaching the ground as throughfall (including direct precipitation) and stemflow. Often the latter is not measured and estimates are made explicitly. In some cases stemflow appears to be ignored, which would mean interception loss is overestimated. This report only considers data presented as interception loss or calculated by LKR where both throughfall and stemflow are given by the author(s).

10.1 Radiata pine

Interception loss is only reported from three studies in New Zealand (Duncan 1980, 1995a; Pearce et al. 1987; Fahey et al. 2001) and this is supplemented mainly by seven studies in Australia and many experiments in Chile (Appendix 28.4). All data are shown in Fig. 10.1 and are fitted by the linear Eqn 10.1, which explains only 46% of the variance in the data. Addition of stand age or density did not improve the relationship.

$$IL = 125 \pm 55 + 0.12 \pm 0.03 \times PTTN \qquad SE = 90;\ r^2 = 0.46;\ n = 67 \text{ pairs} \qquad (10.1)$$

Again, there is quite a range in the data as demonstrated by the wide confidence limits on the equation parameters, the 95% confidence limits in Fig. 10.1, and by the calculated residuals from the regression line (Fig. 10.2), which are in a band about ± 200 mm about the regression line. This is similar in magnitude to the range in throughfall readings because interception loss is almost the complement of throughfall, stemflow tends to be much smaller than either of these terms. In percentage terms, however, the scatter is much greater because interception loss is generally smaller than throughfall. When separated by country, the New Zealand data did not fit a significant relationship, neither slope nor intercept being significantly different from zero.

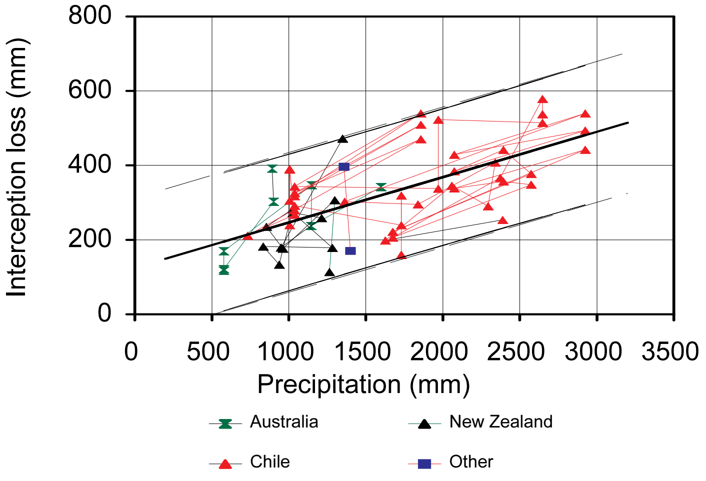

Fig 10.1 Annual interception loss – precipitation relationship for radiata pine.

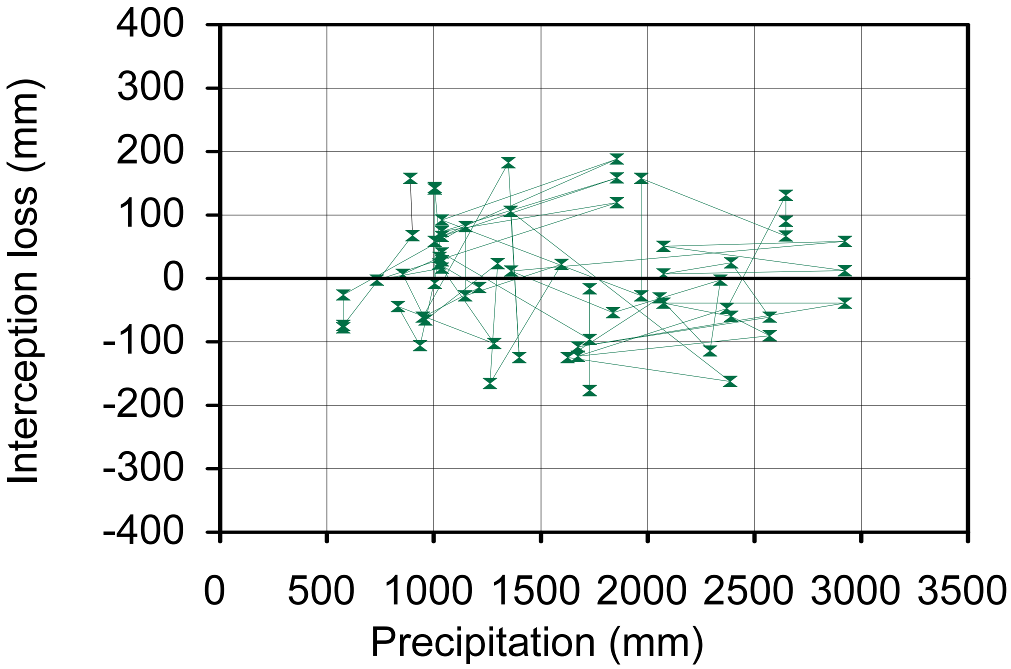

Fig. 10.2 The residuals from the regression relationship between interception loss and precipitation for radiata pine (Eqn 10.1).

A number of regression relationships between interception loss and precipitation have been determined and these are listed in Table 10.1. Generally the intercepts are of the order of 0.1 to 0.25.

Table 10.1 Relationships between interception loss and precipitation for radiata pine stands.

Sampling regime	Age (years)	Density (SPH)	Equation	Source
Storm			$IL = 0.274 \times P + 1.454$	Blake 1972
Storm	5		$IL = 0.23 \times P + 1.05$	Blake 1975
Storm	25		$IL = 0.20 \times P + 0.94$	Blake 1975
Storm	13		$IL = 195 \times P^{-0.81}$	Myers & Talsma 1992
Storm	7	450	$IL = 0.19 \times P$	Kelliher et al. 1992b; no intercept given
Daily	10	1480	$IL = 0.0907 \times P + 0.44$	Pienaar 1964
Weekly	10	1745	$IL = 0.164 \times P +1.49$	Langford & O'Shaughnessy 1977

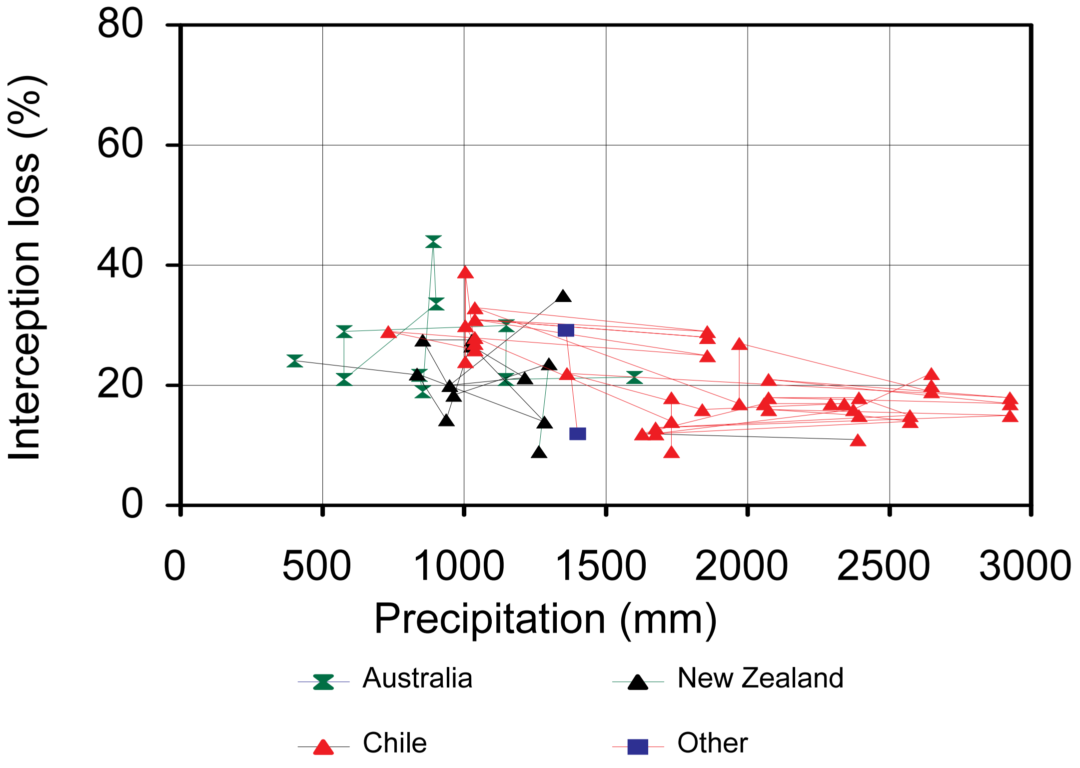

Fig 10.3 Annual interception loss – precipitation relationship for radiata pine. The same data as in Fig. 10.1 but this time expressed as percentage of precipitation.

In terms of percentages of precipitation, interception loss (%IL) for all data averaged 22.0 ± 1.8%. When broken down by country these were: Australia 26.0 ± 4.5%; New Zealand 21.6 ± 4.1%; Chile 22.0 ± 1.8%; all country means are not statistically different from each other. There was no relationship with stand density or age, and that with precipitation, although statistically significant, only explained 24% of the variance in the data and had wide confidence limits limiting its usefulness as a planning tool (Eqn 10.2). Turner & Lambert (1987) obtained significant relationships between %IL and stand basal area with or without precipitation. An analysis here could find no correlation ($r^2 = 0.0004$) with basal area alone, or in the combined relationship where the BA coefficient was not different from zero.

$$\%IL = 30.5 \pm 4.1 - 0.0055 \pm 0.0025 \times P \qquad SE = 6.6\ ;\ r^2 = 0.24;\ n = 67 \text{ pairs} \qquad (10.2)$$

10.2 Douglas fir

Data on interception loss is available for one New Zealand study (Fahey et al. 2001) and plantations mostly in Europe (Fig. 10.4). Some datasets are for the whole year and others for summer only. Regression relationships determined for the separate datasets were not different from each other, so a single relationship using all data was found between interception loss and precipitation (Eqn 10.3). The relationship is significantly different from that for radiata pine (Eqn 10.1) in both slope and intercept.

Adding age or stand density parameters made little difference to the relationship, increasing the explained variance by about 1%.

$$IL = 2 \pm 50 + 0.33 \pm 0.05 \times P \qquad SE = 75;\ r^2 = 0.83;\ n = 38 \text{ pairs} \qquad (10.3)$$

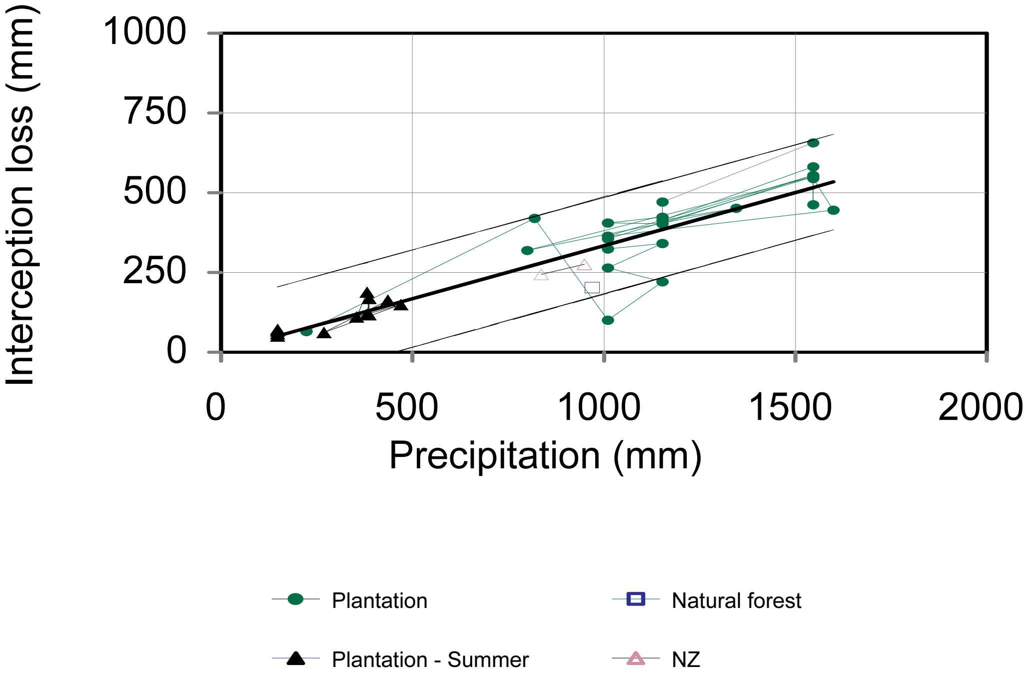

Fig 10.4 Interception loss by Douglas fir plantations and a natural forest.

Only two relationships between interception loss and short-term precipitation were found, and these are listed in Table 10.2.

Table 10.2 Interception loss – precipitation loss for two Douglas fir stands

Sampling regime	Age (year)	Density (SPH)	Equation	Source
Weekly	40–48	668	IL = 0.235 × P + 1.32	Langford & O’Shaughnessy 1977
Monthly			Il = 0.83 + 0.283*P	Rutter et al. 1975

Interception loss for the 42 studies (Fig. 10.5) averaged 33.5 ± 2.7%. This is considerably higher than the 22% estimated for radiata pine and only a little higher than the two New Zealand sites at 28% and 29% (Fahey et al. 2001). However, there was no correlation between %IL and either precipitation or stand density, with less than 1% of the variance being explained in each case.

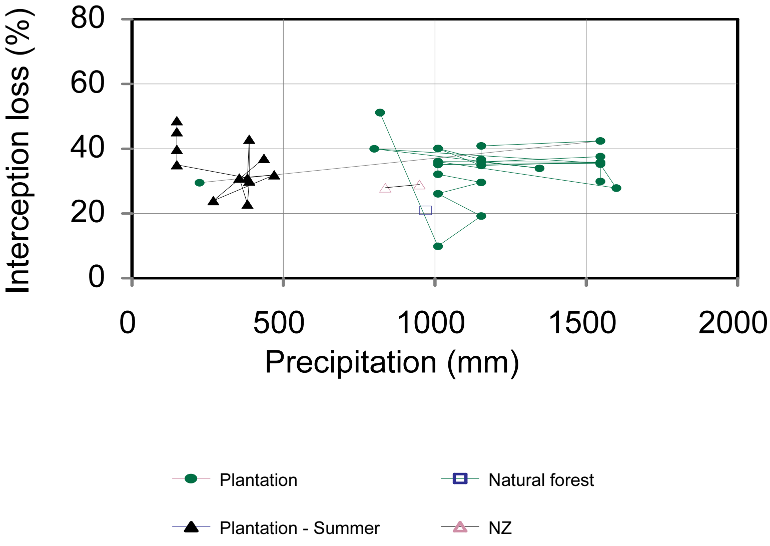

Fig 10.5 Interception loss as a percentage of precipitation for Douglas fir.

10.3 New Zealand vegetation

Interception loss from New Zealand native vegetation studies is shown in Fig 10.6 and listed in Table 10.3, together with the data from plantations shown previously. This list includes one value for snow tussock where interception loss was 21% of the 1040 mm precipitation (Campbell & Murray 1990). As for the radiata pine data earlier, the native forests studies did not show a significant linear relationship between interception loss and precipitation although trend lines are shown in Fig. 10.6.

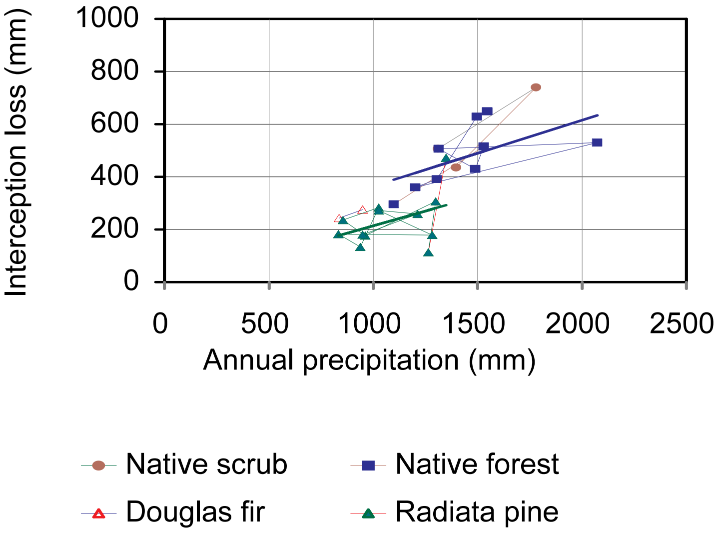

Fig. 10.6 Interception loss data for New Zealand vegetation. Note that the trend lines shown for the native forest and radiata pine stands are not statistically significant.

Table 10.3 Interception loss data for a number of New Zealand vegetation types

Source	Vegetation	P (mm)	IL (mm)	IL (%)
Aldridge & Jackson 1968	Mānuka	1310	507	39
Rowe et al. 1999	Kānuka	1780	740	42
Blake 1965	Mānuka	1397	436	31
Jackson & Aldridge 1973	Kāmahi	1099	296	27
Aldridge & Jackson 1973	Hard beech	1530	516	34
Rowe 1983	Beech-hardwood	1490	430	29
Rowe 1975	Mountain beech - summer	1314	507	39
Rowe 1979	Beech-podocarp-hardwood	2073	530	26
Bargh 1977	Broadleaved forest	1202	361	30
Jackson 1972	Broadleaved forest	1305	392	30
Petch 1984	Native forest	1497	629	42
Petch 1984	Native forest	1546	649	42
Fahey et al. 2001	Douglas fir	837	244	28
Fahey et al. 2001	Douglas fir	950	276	29
Pearce et al. 1987	Radiata pine	1350	472	35
Duncan 1980	Radiata pine	1265	114	9
Duncan 1995a	Radiata pine	1300	307	24
Duncan 1995a	Radiata pine	963	177	18
Duncan 1995a	Radiata pine	855	236	28
Duncan 1995a	Radiata pine	1028	284	28
Duncan 1995a	Radiata pine	938	134	14
Duncan 1995a	Radiata pine	834	183	22
Duncan 1995a	Radiata pine	1284	179	14
Duncan 1995a	Radiata pine	1027	273	27
Duncan 1995a	Radiata pine	1214	259	21
Fahey et al. 2001	Radiata pine	950	180	20
Campbell & Murray 1990	Snow tussock	1040	220	21

On a percentage basis, interception loss for New Zealand stands exhibits a wide scatter of points (Fig 10.7). Interception loss appears to be highest from native scrub stands at 37 ± 6% although that is no different statistically from the native forest data (33 ± 4%). Interception loss is lowest from the radiata pine stands at 21.6 ± 4.1% but this dataset is dominated by 10 years' work up to age 14 from Moutere in Nelson by Duncan (1995a). In some of these years the stand had approached canopy closure; other data were obtained after two thinning operations.

A number of interception loss – precipitation relationships have been reported in the literature for New Zealand vegetation types. (Table 10.4).

Seasonal variations have been identified for beech-podocarp-hardwood forests at Maimai on the West Coast where interception loss was 30% in summer and 21% in winter (Rowe 1979). Similarly at Donald Creek in Nelson, seasonal variation (Eqn 10.4) was between peak monthly interception loss of 35% in summer and the minimum 22% in winter for a beech-hardwood forest where the mean canopy evaporation rate was 0.53 mm/hour in summer and 0.39 mm/hour in winter (Rowe 1983).

$$\%I/R = -5.9 \times [\sin(30X + 10.0)] + 29.1 \qquad (10.4)$$

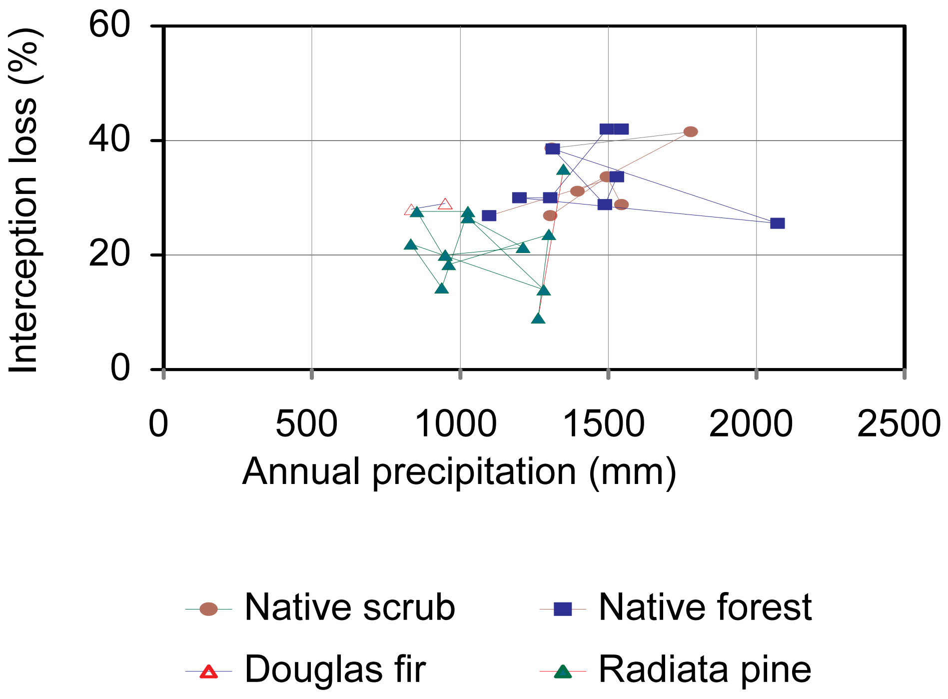

Fig 10.7 Percentage interception loss for New Zealand vegetation classes.

Table 10.4 Storm interception loss precipitation relationships

Sampling regime	Vegetation class	Equation	Source
Storm	Native forest	IL = 0.060 × P + 1.568	Blake 1972
Storm	Native forest	IL = 0.14 × P + 0.66	Blake 1975
Storm	Hard beech	IL = 0.292 × P + 1.04	Aldridge & Jackson 1973
Storm	Kāmahi	IL = 0.202 × P + 0.81	Jackson & Aldridge 1973
Storm	Kauri	IL = 0.43 × P + 1.01	Blake 1975
Storm – winter	Beech-hardwood	IL = 0.20 × P + 0.83	Rowe 1983
Storm – summer	Beech-hardwood	IL = 0.25 × P + 0.93	Rowe 1983
Monthly – winter	Beech-hardwood	IL = 0.20 × P + 7.90	Rowe 1983
Monthly – summer	Beech-hardwood	IL = 0.28 × P + 4.9	Rowe 1983
Storm	Mountain beech	IL = 1.9 × P + 0.29	Rowe 1975
Storms	Mānuka	IL = 0.268 × P + 1.52	Aldridge & Jackson 1968
Storms >4 mm	Mānuka	IL = 0.155 × P + 0.072	Blake 1972
Storms	Mānuka	IL = 0.18 × P + 1.19	Blake 1975
Storms	Kānuka	IL = 0.36 × P + 2.0	Rowe et al. 1999
Storm	Gorse	IL = 0.454 × P + 1.52	Blake 1972
Storm	Gorse	IL = 0.33 × P + 2.57	Blake 1975

10.4 Bracken

No studies have been carried out on bracken-only in New Zealand. However, McGregor (1983) does present some data on interception by combined bracken/logging slash in the central North Island. Information from the United Kingdom shows that:

1: Over 4 months in summer understorey bracken intercepted 64 mm (12.7%) of 503 mm throughfall from a *Quercus* canopy (Carlisle et al. 1967). This was 3.7% of the annual precipitation.
2: Interception losses were 40.1% of precipitation (Pitman & Pitman 1986)
3: Over 5 months with precipitation 462 mm, IL was 225 mm, which was 48.7% for the period and 20% of the annual total (Williams et al. 1987)
4: Maximum water storage was 0.467 X LAI (Pitman 1989).

10.5 Comparative studies

Among the studies reported, there are only two that can be considered comparative for species relevant to New Zealand when measurements are made in the different stands at the same time. Interception loss estimates for Douglas fir and radiata pine stands have been made by Langford & O'Shaughnessy (1977) in Victoria and by Fahey et al. (2001) in Mid-Canterbury at Hororata (Table 10.5). These studies also suggest that interception loss is greater from Douglas fir stands.

Table 10.5 Comparative interception loss studies (Hororata: Fahey et al. 2001; Victoria: Langford & O'Shaughnessy 1977)

	Douglas fir		Radiata pine	
	Age	IL%	Age	IL%
Hororata	18	30	18	19
Hororata	54	22		
Victoria	43	27.9	13	21.4
Victoria	Weekly IL = 0.235×PTTN + 1.32		Weekly IL = 0.164×PTTN + 1.49	

10.6 Conclusions

Annual interception loss

Annual interception loss as a percentage of precipitation is shown in Table 10.6. Interception loss, at about 22% of precipitation, is smallest from radiata pine and the one tussock grassland site. Douglas fir plantations, New Zealand native forests and scrubland data have, on average, similar levels of losses (at about 35% of PTTN). In a rainfall regime of about 1000 mm, these levels of loss equate to about 220 mm for radiata pine and 350 mm for Douglas fir, native forest and scrubland species. Overseas studies have indicated that interception losses could be as much as 45% or so of growing season precipitation.

Table 10.6 Mean annual percentage interception loss for New Zealand vegetation classes

Species	Worldwide	New Zealand
Radiata pine	22.0 ± 1.8	21.6 ± 4.1
Douglas fir	33.5 ± 2.7	28.5
Native forest		33 ± 4
Scrub		37 ± 6
Tussock grassland		21.3

Annual interception loss – precipitation relationships

Relationships between annual interception loss and annual precipitation have only been established for the worldwide datasets for radiata pine and Douglas fir. Too few New Zealand data are available in other datasets to determine if meaningful relationships are present.

Radiata pine	$IL = 125 \pm 55 + 0.12 \pm 0.03 \times P$
Douglas fir	$IL = 2 \pm 50 + 0.33 \pm 0.05 \times P$

Although they are statistically significantly different from each other, there are limitations to the use of these equations for predictive purposes in that predictions have large potential errors (Table 10.7.

Precision

We can estimate the magnitude of interception loss for the above relationships and also the potential for error. These are listed in Table 10.7, which indicates that interception losses will be greater in percentage terms for areas with lower precipitation, and that errors can be of the order 100 mm or 30%.

Table 10.7 Potential errors in estimates of interception loss

Annual precipitation (mm)	600	800	1000	1500
Radiata pine interception (mm, % of P)	200, 33	220, 28	245, 25	305, 20
Potential error (mm, % of IL)	±75, 37	±80, 36	±85, 35	±100, 33
Douglas fir interception (mm, % of P)	250, 41	310, 39	380, 38	545, 36
Potential error (mm, % of IL)	±80, 32	±90, 29	±90, 24	±125, 23

11. Interception Models

Apart from simple regression relationships between interception components and precipitation with or without stand parameters, a number of process-based models on interception have been developed since the late 1960s. Rutter et al. (1971) produced one of the first and this was developed further by Rutter et al. (1975). These models tend to be data-demanding, needing a number of micrometeorological parameters such as radiation, surface temperature, vapour pressure, aerodynamic resistance, etc., which are not always readily available.

The analytical model of Gash (1979) is a simplification of the Rutter model and has been used in many studies worldwide and in New Zealand. Pearce & Rowe (1981) applied a modification of the Gash model to the evergreen beech-podocarp-hardwood forest at Maimai, near Reefton on the West Coast. Here, daily data were used instead of storm data and the canopy is multi-storeyed, so results within 12% of measured data were considered reasonable. Use of the Gash model by Rowe (1983) for the beech-hardwood forest at Donald Creek in Nelson over one year gave results within 6% and 8% of the measured losses for summer and winter, respectively. Pearce et al. (1980) also used Gash's model to demonstrate that evaporation of intercepted water from the canopy during the night is a significant part of the overall interception losses. McGregor (1983) used the model in a study of the interception loss from the bracken and slash understory of a pine forest at the Purukohukohu Basin in the central North Island.

A canopy water balance model that has interception and evaporation components has been developed in New Zealand (Kelliher et al. 1990; Whitehead & Kelliher 1991a, 1991b; Whitehead et al. 1989). This model combines the Penman-Monteith equation for estimating transpiration from a dry canopy and the Rutter model to estimate evaporation from the wet canopy (interception loss). The model then demands many micrometeorological data parameters.

12. Transpiration = Dry Canopy Evaporation

This section covers transpiration by vegetation, sometimes called dry canopy evaporation. Data included here are meant to be for dry weather conditions only, but some wet weather data may be included where no explicit mention is made of weather conditions in the original text.

A variety of techniques have been used to measure transpiration including sap flux (Hatton & Vertessy 1990; Miller 2000; Fahey et al. 2001), micrometeorology (Greenwood et al. 1981; Swanson 1981; Hatton & Vertessy 1990; Kelliher et al. 1990; Arneth et al. 1998); soil water balance changes (Jackson 1983; Pearce et al. 1987), and lysimeters (Fritschen et al. 1977; Campbell 1989). These differing measurement techniques may introduce into the dataset additional, and not insubstantial, variation that is instrument related. For example, Hatton & Vertessy (1990) noted that sapflow transpiration estimates for radiata pine trees were 30–35% greater than estimates obtained using Bowen Ratio equipment, and Cohen et al. (1985) found sapflow estimates were 29–53% higher than estimates from a porometer system.

12.1 Resistances

The Penman-Monteith method for estimating evaporation from dry canopies requires estimates of micro-meteorological parameters such as radiation, surface temperature, and aerodynamic resistance. Table 12.1 presents some necessary parameter values for making evaporation estimates.

Table 12.1 Approximate parameter values for various vegetation surfaces. Source: Pearce & Rowe (1979); Murray et al. (1991).

Parameter	Open water	Grass	Tussock	Field crop	Forest
Roughness length (m)	0.001	0.01		0.1	1
Aerodynamic resistance Rs (s/m)	200	30–115	7	50	5.5–12
Surface resistance Ra (s/m)	0	40–50	160	60	75–120
Rs/Ra	0	0.3		1.2	10

12.2 Daily transpiration

New Zealand studies giving daily transpiration data for radiata pine have been published by Jackson (1983), Kelliher et al. (1990), Whitehead & Kelliher (1991b), Whitehead et al. (1994), Arneth et al. (1998) and Miller et al. (1998). For the most part, the data are one-day spot values but averages of several days supplement these data. Fig. 12.1 is a plot of the data available and this is supplemented by those from a number of Australian studies (all data are listed in Appendix 28.5).

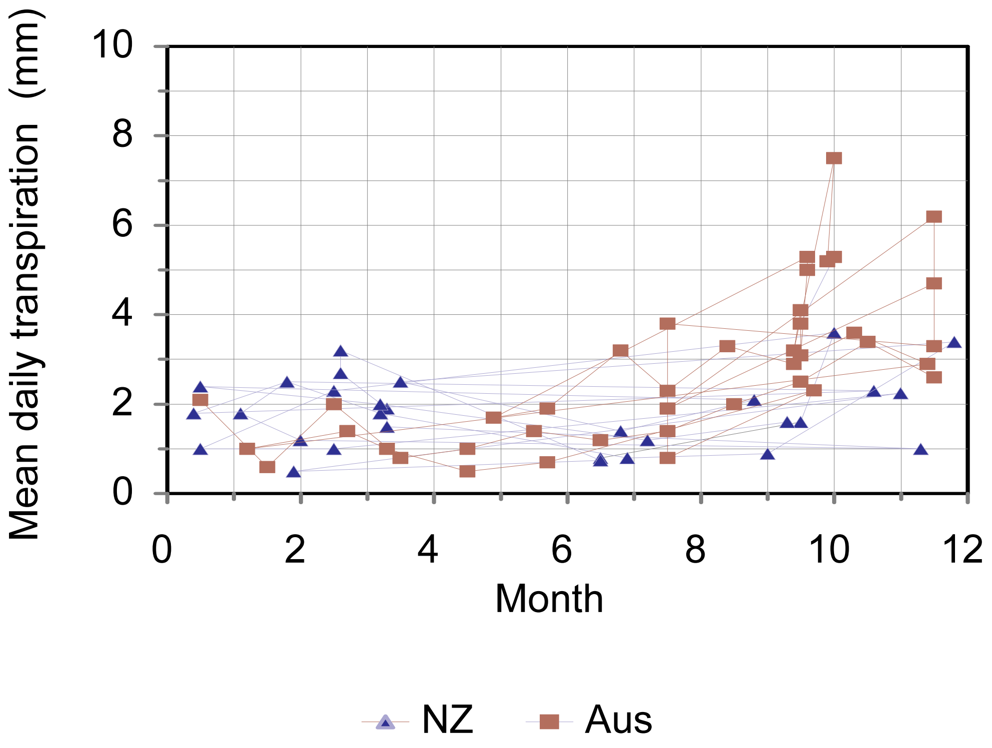

Fig. 12.1 Daily transpiration for radiata pine stands in New Zealand and Australia.

Figure 12.1 shows minimum transpiration occurs in winter at about 0.5–1.5 mm/day, which agrees with generalised data for Ashley Forest (Jackson & Rowe 1997a). Generally the annual maximum occurs in spring/early summer after which soil moisture deficits affect the ability of the trees to get water for evaporation. Pearce et al. (1987) measured transpiration rates at Mangatu Forest of <1 mm/day in winter and 2.5–3.5 mm/day in summer when soil moisture was not limiting.

The wide variation in the values for a given time of the year will reflect the soil moisture regime at the time of sampling. As an example of the influence of soil moisture, Greenwood et al. (1981) carried out linear regression analyses of the soil water content in the top 2 m of the soil and transpiration between November and May, and between June and October (the equations were not given). For observations in the dry season, 93% of the variation in the relationship was accounted for. In the wet season, the significant regression still accounted for 59% of the variation. Teskey & Sheriff (1996) noted transpiration dropped from 6.8 mm/day in late spring to 1.4 mm/day by the end of summer as the soil dried out. Few data in Fig. 12.1 had associated soil moisture data for which an analysis could be carried out.

A small number of measurements of daily transpiration have been reported for Douglas fir (McNaughton & Black 1973; Black et al. 1980; Kelliher et al. 1986; Granier 1987) but there are more which have been simulated using various models. The measured data are generally for the Northern Hemisphere summer and cover the range from 4.8 mm/day under wet soil and sunny conditions (McNaughton & Black 1973) down to about 1 mm when the soil has dried out and the trees are under moisture stress (Black et al. 1980). These data are within the envelope of the radiata pine measurements and are also listed in Appendix 28.5. Daily transpiration rates have also been determined for two South Island beech forests in New Zealand (Table 12.2).

Table 12.2 Daily transpiration for some New Zealand vegetation classes

Vegetation class	Period	Transpiration (mm/day)	Source and comment
Beech forest	Mid-March	1.7–2.4	Kelliher et al. 1992a; Eddy correlation
Beech forest	June–August	0.5–0.6	Benecke & Evans 1987; Porometry, rain-free days
Beech forest	December–March	3.0–3.2	Benecke & Evans 1987; Porometry, rain-free days

One comparative study was found where measurements of transpiration were made for differing vegetation classes within days of each other and these data are given in Table 12.3 (Denmead 1969); no work was found when differing vegetation classes were examined concurrently.

Table 12.3 Comparison between daily transpiration for radiata pine and wheat October–November. The daily range is given in parentheses.

Vegetation class	Transpiration (mm/day)
Wheat	3.9 (2.5–4.3)
Radiata pine	5.4 (3.8–7.5)

12.3 Seasonal transpiration

Myers & Talsma (1992) present one of the few studies with seasonal trends for transpiration of radiata pine. Monthly mean daily water use (= evaporation) data are given for five stands with combinations of irrigation and fertiliser, including a control stand. Data for the irrigated and non-irrigated stands without fertiliser treatments are shown in Fig. 12.2. All stands were similar in their winter water use rates (about 1.0–1.7 mm/day) but there were wide differences in summer; the fertilised stands reached maximum rates of about 8.2 mm/day compared to about 6.8 mm/day for the non-fertilised stand (Fig 12.2), a reflection probably of greater biomass as a result of fertilisation. The two lines in Fig. 12.2 should approximate the envelope of transpiration rates for the range of soil moisture from wet to dry conditions for most stands.

A similar study undertaken by Swanson (1981) at Whakarewarewa near Rotorua also provided data for Douglas fir. Sapflow measurements were made for radiata pine stands with four combinations of ages and planting density and for two Douglas fir stands. For radiata pine, the mean daily rates vary from about 1 mm/day in winter to 5–7 mm/day in spring when soil moisture is still high, before dropping to lower levels as the soil dried (Fig. 12.3). One of the Douglas fir stands approximated the radiata pine trends, but another, old, low-density stand had very low transpiration values.

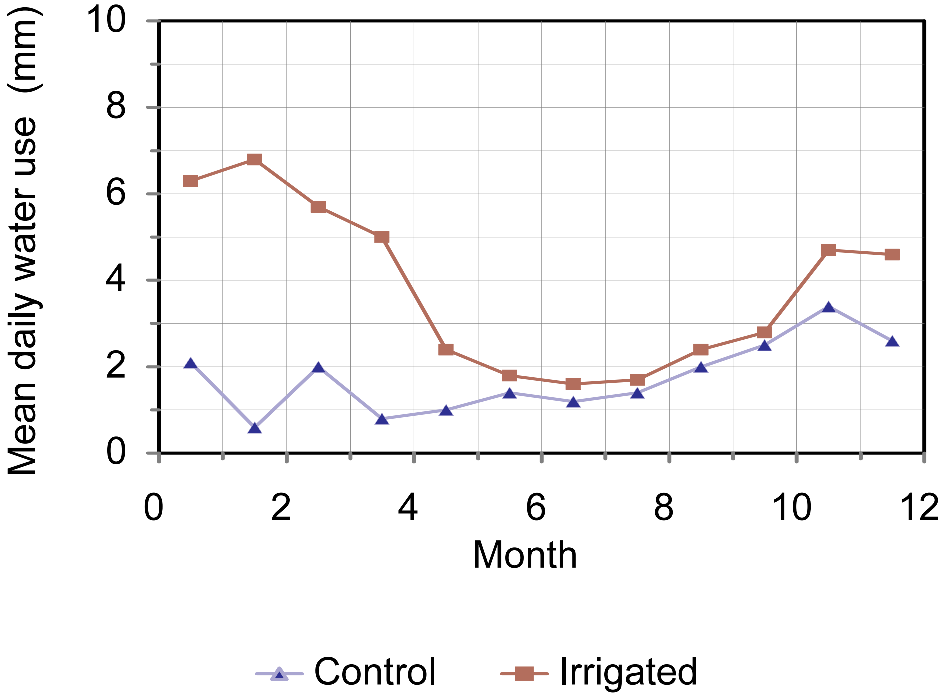

Fig. 12.2 Range in mean daily water use by irrigated and non-irrigated radiata pine stands in ACT, Australia. Data taken from a graph in Myers & Talsma (1992).

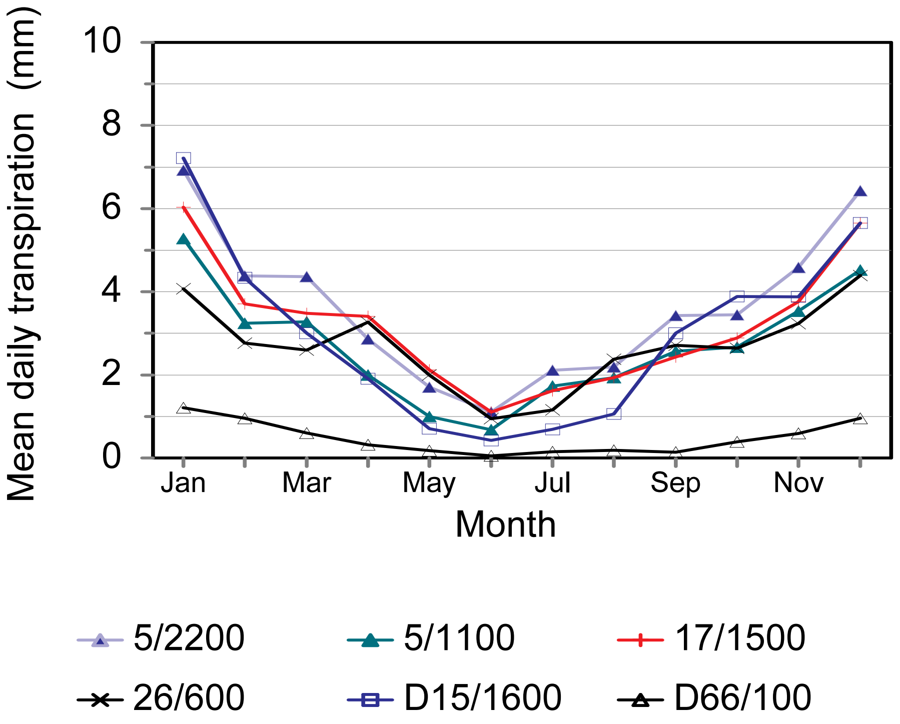

Fig 12.3 Rain-free-day transpiration at Whakarewarewa Forest, Rotorua for radiata pine and Douglas fir stands (calculated from Swanson 1981). The legend indicates age/stand densities with D representing Douglas fir.

Two other studies present trends for monthly transpiration from differing native vegetation. Benecke & Evans (1987) studied hard beech forest for 1 year at Donald Creek in Nelson and Campbell & Murray (1990) investigated native snow tussock transpiration for 10 months at Glendhu in upland East Otago. The tussock data are presented in Figure 12.4 with that for the beech forest being estimated by LKR from a figure in Benecke & Evans' paper. Transpiration trends from these two indigenous communities are of the order of half that from a dense young radiata pine stand at Rotorua, which had the highest transpiration rate of the four stands presented by Swanson (1981).

Greenwood et al. (1981) measured transpiration for 1 day in each month for 14 months. Their transpiration values were highest from July to November (November peak was 3.88 mm/day) before falling to generally less than 1 mm/day from February to May.

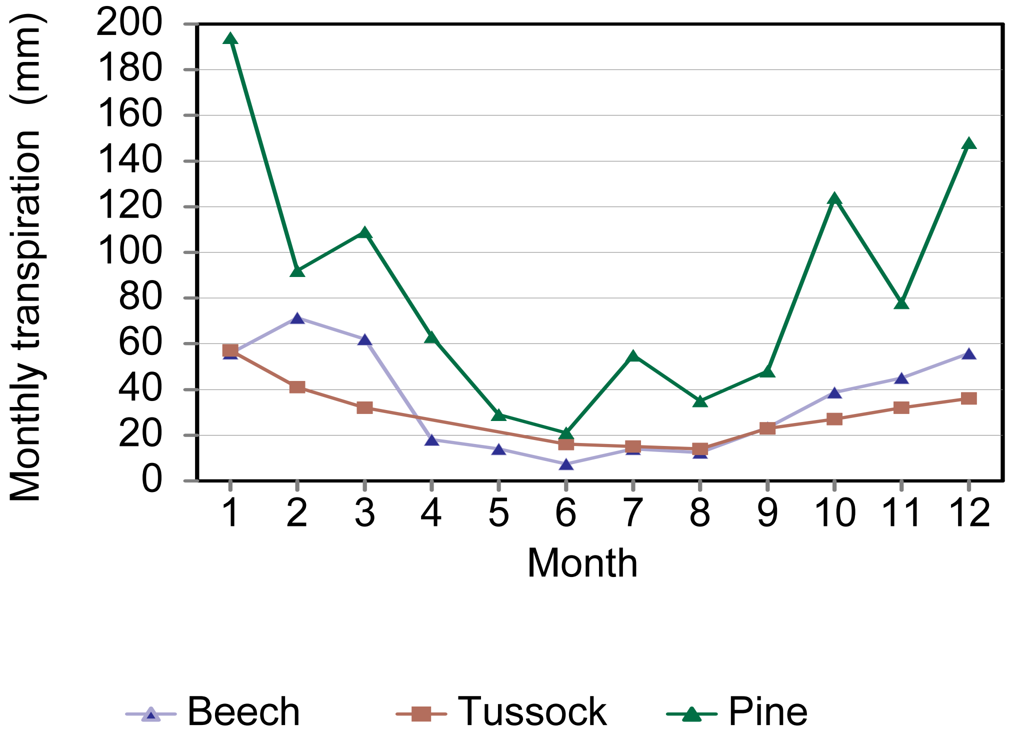

Fig 12.4 Monthly transpiration for hard beech forest in Nelson (Benecke & Evans 1987), tussock grasslands in upland East Otago (Campbell & Murray 1990), together with that from the dense 5-year-old stand of radiata pine of Swanson (1981) shown in Fig. 12.3.

A number of studies present totals for a year (Table 12.4) or given seasons, however long they are defined. (Table 12.5).

Table 12.4 Annual transpiration for a number of vegetation classes

Vegetation	Location	Age (years)	Density (SPH)	Transpiration (mm)	Precipitation (mm)	Source
Measured						
Radiata pine	Rotorua	5	2200	996	1340	Swanson 1981
Radiata pine	Rotorua	5	1100	744	1340	Swanson 1981
Radiata pine	Rotorua	17	1500	871	1340	Swanson 1981
Radiata pine	Rotorua	26	600	718	1340	Swanson 1981
Radiata pine	West Australia	16	200	910	1030	Greenwood et al. 1981
Douglas fir	Rotorua	15	1600	842	1340	Swanson 1981
Douglas fir	Rotorua	66	100	135	1340	Swanson 1981
Beech-hardwood	Nelson			423	1510	Benecke & Evans 1987
Snow tussock.	East Otago			400	1042	Campbell & Murray 1990
Calculated as soil- or catchment-water-balance residual						
Radiata pine	East Coast	23		550	1350	Pearce et al. 1987
Beech-hardwood	Nelson			340	1480	Pearce et al. 1982
Snow tussock	East Otago			210	1305	Pearce et al. 1984

Table 12.5 Total seasonal transpiration by radiata pine

Vegetation	Age	Density	Period	Transpiration	Precipitation	Source
Radiata pine	18	1350	October–May	382	816	Fahey et al. 2001
Radiata pine	54	550	October–May	406	700	Fahey et al. 2001
Radiata pine	16		November–February	346		Teskey & Sheriff 1996

Little information can be gleaned on transpiration from bracken in the overseas literature. Lockwood et al. (1986) show bracken canopy transpiration to be up to 3 mm/day, but this varies during the season as leaf area index changes; no data were given for the season. They also showed that evaporation from the litter is important. Pitman & Pitman (1986) reported mean daily evaporation and transpiration over the summer to be 2.44 mm/day with a daily maximum of 5 mm/day for a bracken stand in the open. This was about five times the transpiration from a mainly bracken forest understorey, which made up a significant proportion of the total forest transpiration (Table 12.6; Roberts et al. 1980).

Table 12.6 Transpiration from understorey bracken and forest during a northern summer

1976	Forest including understorey (mm)	Bracken (mm)	Bracken/forest (%)
Jun 9	2.1	0.51	24
Jun 11	1.8	0.38	21
Jun 14	1.8	0.41	23
Jun 15	1.8	0.35	19
Jul 6	1.9	0.97	51
Jul 9	1.1	0.72	65
Jul 13	1.1	0.66	60
Jul 15	1.3	0.7	54
Aug 4	2.6	1.57	22
Aug 6	1.3	0.56	43
Aug 9	1.5	0.45	30
Aug 11	1.6	0.58	36
Sep 16	0.9	0.19	21
Sep 22	1.3	0.41	31
Oct 12	1.1	0.21	19

Source: Roberts et al. 1980

12.4 Understorey transpiration

Greenwood et al. (1981) noted that understorey pasture added transpiration of about 1.4 mm/day in October, was zero in dry summer, but amounted to 90 mm/year or 10% of the stand transpiration. Significant understorey transpiration by bracken was noted by Roberts et al. (1980) with individual days being 20–60% of the forest total.

At Kaingaroa Forest, understorey transpiration in a 4-year-old stand of radiata pine was greater (measuring 3.1 mm) than that from the forest canopy (2.7 mm) over 2 days in March (Kelliher et al. 1990). From a 7-year-old thinned stand, Kelliher et al. measured understorey evaporation of 1.5 mm over 2 days in April which, this time, was less than for the trees themselves (1.9 mm).

Other studies, e.g., Black et al. (1980), Kelliher et al. (1992) and Arneth et al. (1998), demonstrate similar levels of evaporation from the understorey and forest floor ,but have not been included here as they include evaporation in addition to transpiration.

12.5 Conclusions

Transpiration rates vary considerably, with annual minima of the order of 0.5 mm/day in winter for radiata pine and beech forest. The timing of the annual maximum values for a given vegetation cover or site is dependent on the soil moisture status. Peaks can be attained from mid-spring to late summer as long as available soil moisture is adequate. Daily transpiration values for radiata pine may reach 7–8 mm/day if the soils are well-watered, but can be less than 1 mm/day throughout much of the summer and into autumn as soil moisture deficits occur. Available data show transpiration from beech forests can reach 3.2 mm/day, tussock grassland up to 3.2 mm/day, and bracken up to 5 mm/day.

Transpiration by understorey vegetation, where present, can also be considerable reaching levels about that of the trees themselves.

13. Evaporation

In this section we consider evaporation where no distinction has been made between interception and transpiration. These are mainly studies that have progressed for a period of a few months to a year or two, and are derived from water balances. Table 13.1 summarises many of these.

13.1 Pasture - radiata pine comparison

Holmes & Colville (1970) present evaporation data from the dry Gambier Plains region in South Australia where about 600 mm of the 700 mm annual rainfall falls between April and December. Estimates of evaporation (Table 13.1) from two radiata pine stands several kilometres apart (33 years old and planted at 2200 and 450 sph) and pasture were made using precipitation inputs, soil moisture changes and drainage from lysimeters, the drainage being low.

Table 13.1 Evaporation from radiata pine (two stands) and pasture in south Australia (Holmes & Colville 1970)

Period	Radiata pine	Pasture
8 May – 23 Sep 1963	225/272	106
2 April – 3 Dec 1964	490/614	482
29 April – 7 Sep 1965	215/270	108

13.2 Pasture and tussock grassland

In the Waipori catchment, Otago, Fahey et al. (1998) estimated evaporation from a pasture site using the Priestley-Taylor method and then compared that with water balance estimates for the tussock Glendhu catchment, GH1. Annual evaporation from pasture derived from Glendhu climate data at 590 mm was close to the 520 mm calculated for GH1 tussock. The study showed there was little difference between the annual evaporation estimates for the two vegetation types but that pasture extracted more water in summer thus delaying the recharge in autumn/winter. Low-flow periods tended to be longer and reach lower levels for pasture than tussock.

In Canterbury but on both irrigated and non-irrigated plots, Martin (1990) measured water use and pasture growth on Templeton silt loam (Table 13.2). From measurements in the top 105 cm of the profile he found that soil water extraction was mainly from the top 45–60 cm of soil at low water deficits. As the soil dried up, progressively more moisture was extracted from lower depths and evaporation rates fell.

Table 13.2 Water use by pasture at Templeton, Canterbury 1978–1981 (from Martin 1990)

Period	Rainfall (mm)	Irrigation (mm)	Penman PET (mm/day)	Water use – dry (mm/day)	Water use – irrigated (mm/day)
6/10/78 – 18/12/78	193	–	3.8	–	–
18/12/78 – 5/3/79	94	141	4.6	3.7	6.5
5/3/79 – 1/5/79	146	–	2.2	–	–
6/9/79 – 10/12/79	185	–	3.3	4.8	4.9
10/12/79 – 18/2/80	217	111	4.7	6.9	9.2
18/2/80 – 2/5/80	218	–	2.5	4.3	4.6
16/9/80 – 10/12/80	103	106	4.1	3.6	5.2
10/12/80 – 20/2/81	52	106	4.9	2	6
20/2/81 – 12/5/81	91	58	2.5	1.7	2.9

13.3 Annual evaporation trends for radiata pine

Data from Bosch & von Gadow (1990) and others reported in Dye (1996) give annual evaporation estimated as precipitation less streamflow from the three Jonkershoek catchments (and *P. patula* and *E.grandis* from other regions) (Fig. 13.1). These show that for the radiata pine data evapotranspiration reaches a maximum at about mid-rotation and is in the order of 1000–1200 mm per annum. There is no simple relationship between amount harvested and the change in evapotranspiration. A similar graph may be applicable to the New Zealand situation but here the rotation lengths are about 25 rather than 40 years. This may have the effect of shortening the period at which the change flattens out and will need to be tested in a New Zealand case study.

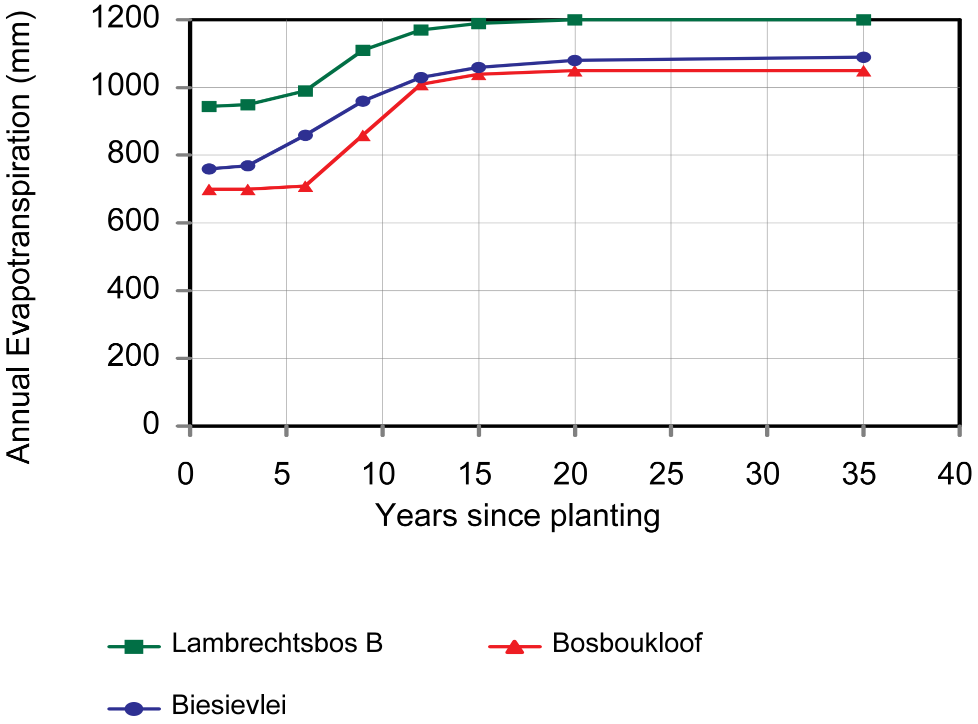

Fig. 13.1 Change in evaporation (= precipitation less streamflow) with time since planting. Bosboukloof, Biesievlei and Lambrechtsbos B were planted in 1940, 1948 and 1961, respectively.

Knight & Will (1977) used a lysimeter containing one pine tree in the midst of a pine stand to measure drainage through the soil and hence calculate evaporation as the difference from rainfall. The time trend is plotted in Fig. 13.2 and the results are listed in Table 13.3. It appears that drainage, which generally began in May and continued through to November, decreased after planting the tree, but the variability is such that it would be easy to read into the changes more than is real. In years 1967–1973 seepage averaged 210 mm less than the earlier period, but rainfall also averaged 145 mm less. Evaporation after planting averaged 1330 mm each year, but this may possibly have increased in the years after the study finished as the canopy and, hence, interception and transpiration increased. If we assume an average interception loss of 22% of rain (Section 10.1), then transpiration is calculated to be 1040 mm/year.

Table 13.3 Lysimeter drainage and evaporation under a young pine stand at Kaingaroa Forest. The stand was planted in 1962 and pruned and thinned in 1971

Year	Precipitation	Drainage	Losses
1961	1231		
1962	2150	573	1577
1963	1179	206	973
1964	1606	354	1252
1965	1444		
1966	1628		
1967	1673	118	1555
1968	1440	211	1229
1969	1370	54	1316
1970	1616	214	1402
1971	1891	385	1506
1972	1315	110	1205
1973	1195	77	1118

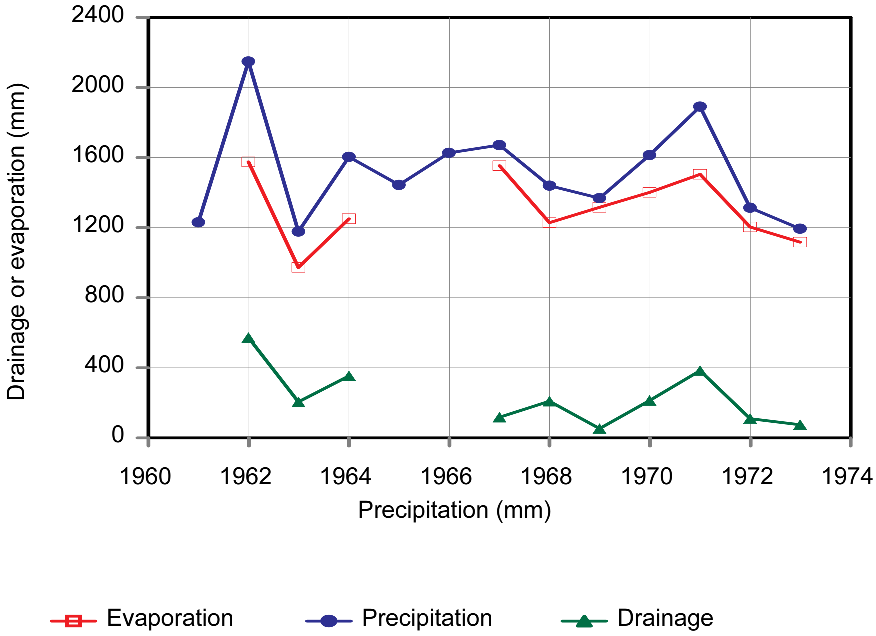

Fig. 13.2 Evaporation and drainage from a lysimeter under radiata pine stand at Kaingaroa Forest (from Knight & Will 1977)

13.4 Forest floor evaporation

Few studies present evaporation from the ground under forest even though it can be significant.

Forest floor evaporation rates under a Douglas fir stand averaged 0.23 mm/day in March to August (equivalent to September to February for New Zealand) (Schaap & Bouten 1997) and totalled 112 mm a year, about 10% of the total forest evaporation (Schaap et al. 1997). Arneth et al. (1998) found ground evaporation as a percentage of total forest evaporation was 24% in late spring, 42% in dry summer, and 12–15% in winter and early spring in a well-watered soil under a radiata pine forest. Under an undisturbed beech forest at Maruia on the West Coast, forest floor evaporation averaged 15% of the total forest evaporation during 6 days of variable weather in March (Kelliher et al. 1992a).

13.5 Evaporation models

In addition to the models mentioned in Section 11 where both interception and evaporation were included, Le Maitre & Versfeld (1997) have explored the relationship between forest evaporation and stand growth. Their work related the forest site index (SI) = fn(age, height) or stand growth (volume, SV or basal area, BA) = fn(SI, height, age, stand density) to total evaporation for the year. The models were different from region to region and are meant to project mean evaporation from a plantation, not evaporation for a particular year and its waether. There is a potential for evaluating differing plantation regimes, but note that there may be better stand variables than, for example height and BA, which will reflect the main drivers of evaporation, e.g., leaf area and water use efficiency.

Also in South Africa, Bosch & von Gadow (1990) used the Chapman–Richards equation, which is a sigmoidal function, to model the change in evaporation (E) (= rainfall − runoff) with time at Jonkershoek. The model is:

$$E = A(1-e^{-k\,t})^{m}$$

where t is time in years and A, k and m are parameters defining the relationship. A, the amplitude, will depend on the original vegetation before afforestation. Parameters are determined by curve fitting and can differ markedly as in Table 13.4.

Table 13.4 Parameters for the Chapman–Richards equation for estimating evaporation after planting at Jonkershoek.

Catchment	A	k	m
Bosboukloof	350	0.542	95.75
Lambrechtsbos-B	255	0.455	22.83
Biesievlei	238	0.276	5.52

When evaporation was plotted against years after planting, all three catchments tended to an upper limit (the asymptote) of 1200 mm, suggesting an upper limit for evapotranspiration (Fig 13.1).

13.6 Conclusions

This section has presented data from a number of varied studies. In a dryland environment in South Australia evaporation from both pasture and pine forests in winter and spring was low, with the pines the higher of the two classes. Evaporation from pasture and tussock grassland in Otago was of the order of 500–600 mm per year and that from pines in the central North Island at 1330 mm was higher that from South Africa, which was of the order of 1000–1200 mm.

Evaporation from the forest floor was a significant component of forest evaporation, ranging from 10 to 40% depending on the time of the year and soil moisture status.

14. Soil Water Extraction

Transpiration rates are controlled by the amount of water available to plants from the soil. It is generally assumed that trees extract soil moisture to a greater depth than pasture and this has been demonstrated in a number of studies. Table 14.1 lists the soil depths at which it has been observed that plants have extracted water.

Table 14.1 Extraction of soil water by pine, pasture and lucerne land covers

Location	Soil type	Vegetation	Extractable depth (cm)	Preferred depth (cm)	Source
Canterbury Eyrewell	Stony loam	Radiata pine	150	60	Jackson & Rowe 1997a
Canterbury Chaneys	Sand	Radiata pine	150		Jackson & Rowe 1997a
Canterbury	Eyrewell stony silt loam	Pasture	125	top	Hayman & Stocker 1992
Canterbury	Wakanui clay loam	Lucerne	140	140	Hayman & Stocker 1992
Canterbury	Templeton silt loam	Pasture	105+	45–60	Martin 1990
Waikato	Floodplain loamy sand	Pasture	100	30	McAneney & Judd 1983
Wellington	Judgeford silt loam	Pasture	140	60	Parfitt et al. 1985a
Southern Taranaki	Stratford silt loam	Pasture	180	75	Parfitt et al. 1985b

14.1 Soil water deficits

In their presentation of a water balance model for a soil under pasture near Palmerston North, Scotter et al. (1979) reported a maximum soil water deficit of 230 mm for Tokomaru silt loam (i.e., a gleyed yellow-grey earth). Hayman & Stocker (1992) investigated soil water extraction patterns under pasture and lucerne under irrigation in Mid-Canterbury. Their study provides information on soil water stores and extraction on Eyre and Wakanui soils (Table 14.2). From many sources, Woodward et al. (2001) have compiled field (Table 14.3) and laboratory (Table 14.4) measurements of water holding capacity for soils representing the main flatland soil orders in New Zealand.

Table 14.2 Properties (% w/w) of soil in Mid-Canterbury investigated by Hayman & Stocker (1992)

Depth	Wakanui		Eyre	
	Field capacity	Wilting point	Field capacity	Wilting point
0–30 cm	27	11.6	15.2	7.4
0–60 cm	23.4	11.3	16.1	5.9
0–105 cm	21.8	9.4	16.5	5.5

Table 14.3 Measured water holding capacity (WHC, mm) in the top 76 cm of some New Zealand soils (see Woodward et al. 2001 for sources of the data)

Soil type	WHC	Soil type	WHC
Judgeford silt loam	92	Waikiwi silt loam	128
Otokia silt loam	96	Tokomaru silt loam	91
Tokomaru silt loam	96	Ohakea silt loam	92
Lismore stony silt loam	61	Stratford silt loam	112
Horotiu sandy loam	101	Horotiu sandy loam	101
Te Kowhai clay loam	92	Te Kowhai silt loam	176

Table 14.4 Laboratory measurements of water holding capacity (WHC, mm) in the top 76 cm of some New Zealand soils (see Woodward et al. 2001 for sources of the data)

Soil type	WHC	Soil type	WHC
Tokomaru silt loam	91	Tokomaru silt loam	96
Tokomaru silt loam	114	Paraha silt loam	92
Otokia silt loam	96	Waikiwi silt loam	128
Mangapiri heavy silt loam	93	Mokotua peaty silt loam	153
Taita clay loam	72	Judgeford silt loam	92
Judgeford silt loam	114	Ohaupo silt loam	118
Horotiu sandy loam	101	Stratford silt loam	112
Tirau silt loam	131	Hamilton clay loam	88
Naike clay	70	Te Kowhai silt loam	176
Te Kowhai clay loam	92	Himatangi sand	36

14.2 Soil water deficit models

Woodward et al. (2000) also revised the two-layer soil water-balance model of Scotter et al. (1979) to predict soil water status for pastures. The Scotter et al. model required estimates of actual evapotranspiration (AET), but Woodward et al.'s modifications used available water holding capacity in place of the empirical constants need to estimate AET. In this model, AET is calculated as the lesser of potential evapotranspiration (PET) and total readily available water (RAW) on a daily basis. RAW is defined as all the water in the rapidly recharged surface zone plus a proportion of the water in the remainder of the soil profile (Woodward et al. 2000).

Mitchell & Correll (1987) investigated the change in soil moisture status and groundwater levels as a consequence of afforestation and reforestation in South Australia when radiata pine was planted into pasture and clearfelled plantation. For part of the study period, 1976–1980, mean annual precipitation was 864 mm and the equivalent period pan evaporation was 1170 mm/year. Changes in soil water content (z) were determined to be:

$$z = C_0 + C_1 \times \sin(a) + C_2 \times \cos(a) + C_3 \times \text{rain rate} + C_4 \times \text{evaporation rate}$$

where a is an angular function of time of year and months since planting. Parameters are given for the two stands.

14.3 Conclusions

While trees are considered to extract moisture from soils to greater depths than pasture, evidence does show that pasture can extract moisture over 150 cm down the profile and at similar depths to trees. Both trees and pasture prefer to extract moisture from the top 60 cm or so of a soil profile, hence 2-layer models may be best to represent changes in soil moisture.

Soil water holding capacities are variable and the top 76 cm of a profile can hold from 60 to 170 mm.

15. Groundwater

Several studies have shown the effect of afforestation on unconfined groundwater levels. In South Australia in a region with about 600–750 mm of precipitation per year, Allison & Hughes (1972) inferred from tritium measurements that there was virtually no recharge of groundwater under a radiata pine forest. Here the groundwater table is at a depth of about 5–7 m below the ground surface. In another study in the same area Colville & Holmes (1972) investigated variations in groundwater contours beneath forest and pasture and concluded that there was recharge under the forest but it was less than half that under pasture: average over 3 years (May–December) was 44 mm under forest cf. 82 mm under pasture.

In southeastern Australia, there were large differences in the depth to groundwater table between a pasture site and a recently clearfelled radiata pine site, with the latter being over 4 m lower. Recharge at the clearfelled site in the following 4 years resulted in a rise of about 4 m. Afforestation of both sites began to impact on groundwater levels about 2½ years after planting, with a 3-m fall over the next 4 years (Mitchell & Correll 1987).

In Western Australia, Bari & Schofield (1991) measured a decline in groundwater level of about 1 m relative to an adjacent pasture site over a 10-year period after planting an agroforestry regime of mixed *P. radiata* and *P. pinaster* (57% of the area, final densities 75–225 SPH) in an area subject to salinisation; rainfall was 9% lower than the mean annual rainfall of about 710 mm..

In a similar study, also in Western Australia, Bell et al. (1990) investigated the effects on groundwater levels of several types of reforestation with mixes of radiata pine and eucalypt – agroforestry, landscape, strip, etc. At one site annual minimum groundwater levels dropped up to 2.7 m compared to a pasture site over a 7-year period; changes at another site were generally not as significant.

15.1 Conclusion

In the Australian scene, afforestation was shown to decrease near-surface, unconfined groundwater tables by 1–4 m in up to 4 years.

16. Minimum flows

Many measures of low flows are used in the literature: January 2-hourly discharge as a function of temperature on rainless days (Banks 1961); mean January 2-hourly discharge on rainless days (Banks & Kromhout 1963); 7-day minimum flows (Fahey & Watson 1991; Black 1992); 50-day period of lowest flow in a year(Bosch 1979); changes in flow duration curves (Duncan 1980; Dons 1987); no flow days (Duncan (1980, 1995a; flow below the 80 percentile (Duncan 1980) or a specific value such as 0.2 mm/day (Harr et al. 1982); monthly flows below the 75 percentile (Scott & Smith 1997); days during which a precipitation index was less than 100 mm (Keppeler & Ziemer 1990). Needless to say, because of these differing measures, it is difficult to quantify and compare absolute changes with land treatment, so the information from the literature is given as a series of case studies.

16.1 Comparison of pasture with radiata pine at Moutere, Nelson

The numbers of days with zero flow were compared in a study of three pasture catchments and three forested catchments (pines aged 5–8 years) at Moutere (Table 16.1 after Duncan 1980, table 3), which seems to show an increase in the number of zero flow days over the 4 years and which was assumed to be afforestation related. Unfortunately, no data were given for the calibration or immediate post-planting period to see how much of the trends in zero-flow days are catchment or treatment related; 1978 was the second driest rainfall year in the 15 years presented and this may be an important consideration in the large number of zero-flow days in that year. Notwithstanding this, flow duration curves are presented for 1969 and 1978 that show there is a tendency in 1978 for the forested catchments to have lower flows than the pasture catchments more often than when they were in gorse or pasture.

Table 16.1 The numbers of zero-flow days at Moutere catchments (from Duncan 1980)

	Pasture				Radiata pine			
Catchment	2	5	15	Mean	8	13	14	Mean
1975	19	31	0	17	33	29	19	27
1976	115	46	0	54	120	0	16	46
1977	11	65	0	25	103	64	127	98
1978	169	160	107	145	191	151	194	179

From the extended Moutere dataset, Duncan (1995a) reported that, while under gorse, catchments 8 & 13 averaged 158 days of zero flow compared to an average of 52 days for the pasture catchments 2 & 5. After planting, the pine catchments had slightly fewer days with zero flow than the pasture catchments, but when the canopy closed (age 8–15) they had 64 days more that the 93 registered for the pasture catchments. Averaged flow duration curves also showed that flow from mature pine catchments was less than that from the pasture catchments for much of the time (Table 16.2).

Table 16.2 Approximate percentage of time that flow at the Moutere catchments was less than 5 L/s/km^2 (estimated from fig.9 in Duncan 1995a)

Period	Mean of pasture catchments	Mean of mature pine catchments
1978–1985	69	93

16.2 Afforestation of pasture with radiata pine at Purukohukohu, Central North Island

Dons (1987) shows flow duration curves for catchments at Purukohukohu 4 years before planting the Puruki catchment and when the trees were aged 9–11 years. While low flows occurred more often at the pasture catchment during the latter period, the change was more marked at the planted catchment, suggesting that planting of the pines has diminished low streamflows. Approximate percentiles for flow below 5 L/s/km^2 are given in Table 16.3.

Table 16.3 Approximate percentage of time when flow at the Purukohukohu catchments was less that 5 L/s/km^2 (estimated from fig.2 in Dons 1987).

Period	Pasture catchment	Pine catchment	Native forest
1970–1973	23	18	N.A.
1981–1984	33	55	12

16.3 Afforestation of pasture and scrub at Esk River, Hawke's Bay

Two papers (Black 1990, 1992) comment on effects of planting in the Esk River catchment, which began in the 1920s at Waikoau Forest and is now into its third rotation. Another burst of planting began in 1950 and continued through to 1970.. By 1989 about 25% of the 25 400-ha catchment above the Waipunga gauging station was in plantation forestry and according to Black (1992) "vegetation has no effect on baseflow; the afforestation of 21% of the catchment has not affected the catchment discharge".

Black (1990) gives a time line of afforestation in the Esk catchment since 1950. After 1950, 9.3% of the Esk catchment was in new plantations with 6% after 1959. Seven-day low-flow measurements at the Esk River at Waipunga during summer (December to February) 1963–64 to 1991–92 are listed in Black (1992). A Cox and Stuart test for trend (Conover 1980) by LKR compared the flows for the 1963–64 to 1976–77 period with those from 1978–79 to 1991–92 and no significant trend was found, either diminishing or decreasing. While this may seem to back Black's claim, it is only a test of the effects of planting from, say,1959, which might be having an effect by 1963–64 when streamflow measurements began. During this period only 6% of the catchment was planted up and it is quite likely that any effect would not be detectable for this magnitude of land-cover change. It is certainly not a test of the effects of planting 22% of the catchment as no flow records are available from the 1920s or so to evaluate a change from zero plantation status. Another point to note is that much of the flow from the Esk comes from high-yielding areas without plantation forestry, and this may also mask any changes.

A more valid test might have been a comparison with an unplanted control catchment for 1962–63 onwards. This may have been a more sensitive test and shown different results, but this is also unlikely in view of the small change in catchment cover. More data are also required to verify the extent of planting during this period.

16.4 Afforestation of tussock grassland in Otago

At the Glendhu tussock catchment, GH1, the minimum 7-day low flows are of the order of 0.5 to 1.0 mm/day in most years. Afforestation of 67% of GH2 appears to have had an effect about 6 years after planting, and at ages 12–15 the average decrease was 0.11 mm/day lower than predicted from GH1 (Fahey et al. 1998), or about 15% lower (Fig 16.1). Assuming a proportionate change, this flow decrease is equivalent to 0.17 mm/day for planting the whole catchment.

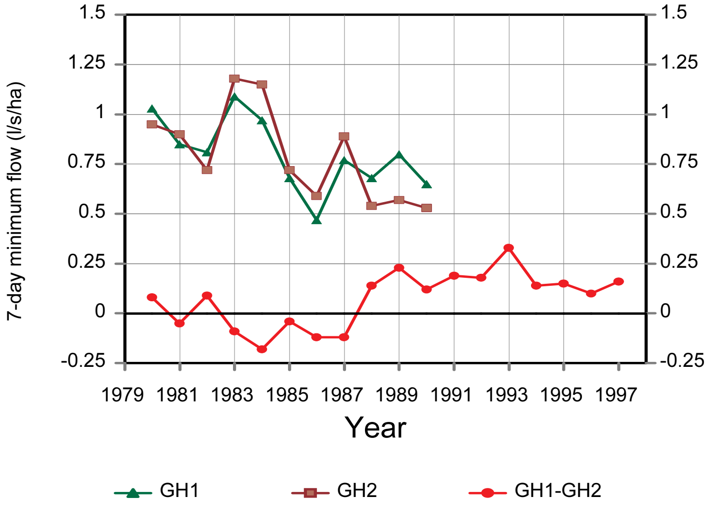

Fig. 16.1 Low-flow changes at Glendhu as a result of 67% afforestation of catchment GH2 in 1982. Data from Fahey & Watson (1991) and from fig. 9 in Fahey et al. (1998).

16.5 Afforestation after conversion of native forest, Donald Creek, Nelson

At this catchment suite, native forests were harvested in 1981 and 1982 to establish the effects of harvesting and conversion to plantations on the flow regime. Low-flow comparisons are complicated here because flow at DC2, the control catchment, dries up in most years. When this occurred, the mean flow for the 7 days prior to flow ceasing was taken as the test data. The 7-day minimum flow rose by about 0.4–0.5 mm/day compared to the native forest control catchment by the second year after harvesting (Fig. 16.2) (Fahey & Jackson 1997). Over the next 8 years or so the minimum flows fell to about native forest levels. Flow decreased after harvesting and appears to have declined further in later years. If 1984 is taken as the base year, it can be inferred from Fig 16.2 that afforestation at Donald Creek could decrease 7-day minimum low flows by about 0.4–0.5 mm/day.

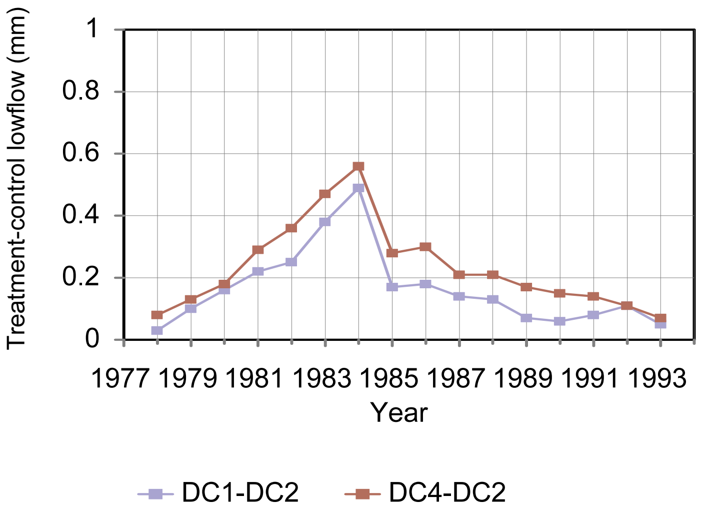

Fig. 16.2 Difference in the 7-day minimum low flow (data extracted from Fig. 5 in Fahey & Jackson 1997)

16.6 Afforestation of scrub with radiata pine at Jonkershoek, South Africa

Two early reports from the Jonkershoek catchments in the Western Cape region of South Africa reported on low-flow changes as a result of afforestation of fynbos, a dry sclerophyllic scrub. Using paired catchments, Banks (1961) determined changes from regression relationships of January 2-hourly discharge as a function of temperature on rainless days whereas Banks & Kromhout (1963) just used mean January 2-hourly discharge on rainless days. Table 16.4 indicates that the changes were of the order of 0.3 mm/day.

Table 16.4 Changes in low flow with afforestation of scrub at Jonkershoek. Data have been converted to 100% plantation by proportion and compared to control catchment(s).

Catchment	Forested (%)	Age at start (years)	Age at finish (years)	Area (ha)	Change (mm/day)	Source
Bosboukloof	57	4.5–7.5	15.5–18.5	200	-0.25	Banks 1961
Biesievlei	98	0	7.5–10.5	27	-0.37	Banks 1961
Bosboukloof	57	4.5–7.5	15.5–18.5	200	-0.33	Banks& Kromhout 1963
Biesievlei	98	0	7.5–10.5	27	-0.41	Banks& Kromhout 1963

Taking the lowest streamflow months, defined as a variable number of months each year but with flow below that expected two or three times a year, Smith & Scott (1992) reported that low flow in Lambrechtsbos B began to decline 5 years after planting. Their results are confusing as “At seven to eight years after afforestation, low flow was approximately 40% (29 mm) lower than the predicted for the catchment”. They went on to state” Low flow was further reduced over the next 8 years to almost 78%

of the predicted flow", which is difficult to reconcile with the previous statement. In neither instance was the number of months stated.

Scott & Smith (1997) presented empirical models for predicting the reductions in total and low flows resulting from afforestation. Sigmoidal or exponential sigmoidal relationships were determined of the form:

$$Y = A/(1+BX^n) \qquad \text{or} \qquad Y = A/(1+Be^{nX})$$

where Y = % flow reduction, A = asymptote = maximum Y, B intercept, X = plantation age in years, n = exponent. They found it necessary to split the results into two classes: optimal (deep soils and tropical climate) vs sub-optimal (shallow soils, less favourable climate) although at Jonkershoek the establishment of radiata pine was considered to be intermediate between the extremes as there was a short growing season but soils were deep and moderately fertile. Table 16.5 lists their model parameters.

Table 16.5 Parameters of the Scott & Smith (1997) model for estimating flow reductions.

Growth zone	Streamflow variable	Model type	Asymptote A	Intercept lnB	Coefficient n
Optimal	Annual flow	$Y = A/(1+BX^n)$	101.5	5.501	−3.251
Optimal	Low flow	$Y = A/(1+BX^n)$	101.5	4.904	−3.102
Sub-optimal	Annual flow	$Y = A/(1+Be^{nX})$	83.5	5.028	−0.382
Sub-optimal	Low flow	$Y = A/(1+Be^{nX})$	83.5	4.445	−0.383

Obviously as precipitation does not figure in these relationships, they can only be considered to give an average effect.

16.7 Harvesting Douglas fir

Harvesting of old-growth Douglas fir forest in the United States is likely to have little similarity to the harvesting of plantation stands as in New Zealand. Notwithstanding that, Harr & Krygier (1972) found there was a decrease in the annual number of low-flow days (< 1 cfs/mile^2 = 0.1093 L/s/ha = 0.94 mm/day) as minimum streamflow increased 60% over the first 5 years after a catchment was harvested in the Alsea River basin, Oregon Coast Range. At Deer Creek (25% cut) the effect was only significant in two of the 5 yr after cutting. Also in Oregon, but in the H J Andrews Experimental Watersheds on the western slopes of the Oregon Cascade Range, removal of vegetation from only 30% of a 250-acre (100 ha)catchment has caused a 12–28% increase in minimum streamflow. For a 237-acre (96 ha) catchment in which 80% of the trees were cut, the increase in low flow was 85% (Rothacher 1965). While this increase is large in percentage terms, it is quite small being equivalent to 0.02–0.1 mm/day.

From catchment studies at Caspar Creek in north-western California where 67% of the vegetation was selection cut and removed from South Fork, the number of low flow days, flow < 0.16 L/s/ha (1.38 mm/day), decreased 40% (43 days) over 5 years and returned to normal after that (Keppeler & Ziemer 1990). Summer flow change amounted to minor increases in minimum discharges averaging

0.0025 L/s/ha (0.22 mm/day) at South Fork, which was 38% higher than pretreatment levels (Keppeler 1998). Keppeler & Ziemer (1990) defined the low-flow season by an antecedent precipitation index $API_i = K \times API_{i-1} + P_i$, where P_i = precipitation on day i, K^+ is a recession constant <= 1 (used 0.97). The season was defined as the period between the API falling below and then exceeding a value of 100 mm.

Where flows are very low in summer, the increases in minimum flow after harvesting are bigger in dry years and may not be noticeable in wet years (Rothacher 1971).

16.8 Conclusions

Afforestation by radiata pine leads to:
- an increase in the number of days with zero flow
- an increase in time flow is below a given low-flow threshold
- a decrease in minimum 7-day low flow of the order of 0.17 to 0.5 mm/day.

Harvesting of Douglas fir and New Zealand native forests leads, in the short term, to:
- an increase in low flows by up to 0.125 mm/day
- a decrease in the number of days when flow is below a given low-flow threshold.

The magnitude of any given measure can be quite variable.

17. Baseflows

Baseflow is that part of the hydrograph that is generally considered to come from a groundwater store rather than as stormflow (surface runoff over the ground surface or quickflow/subsurface flow through the upper soil mantle).

Baseflow and the rate at which it recedes has been shown to be controlled to a large extent by geology. Waugh (1970a, b) and Grant (1971) have demonstrated that catchments with similar geology have similar baseflow recessions and, within a region, catchments with differing geology have different baseflow recessions. The problem as far as land-use change is concerned is to detect changes in a catchment as land-use change takes place. There can be considerable variation in low flows from year to year and this range may be more than any measureable effect. The question also to be asked is: when does the effect of a vegetation change get subsumed by the lack of rain and onset of drought?

Many methods are to be found in hydrological texts for determining total baseflow ,but all of these are arbitrary to some extent. One commonly used method of flow separation in New Zealand is that developed by Hewlett & Hibbert (1967). Here, baseflow is the residual after stormflow (often referred to as quickflow) has been separated out.

Table 17.1 Comparison of baseflow (BF) from differing vegetation covers as determined using the Hewlett & Hibbert (1967) method (all values in millimetres). The percentage figures in brackets is the proportion of total streamflow as baseflow. Data for Smith (1987) are averages of two catchments with each land use.

	Years	Pasture		Pine		Native forest		Source
		P	BF	P	BF	P	BF	
Purukohukohu	2	1480	415 (82)	1455	200 (83)	1615	315 (96)	Cooper & Thomsen 1988 (pines 10–11years)
Purukohukohu	4	1427	469 (86)	1398	223 (88)	1484	331 (98)	Dons 1987 (pines 9–11 years)
Upper Mangawhara	2	1521	586 (67)			1521	397 (74)	Petch 1984
Nelson	1	1161	335 (75)	1201	348 (70)	1151	308 (72)	McKerchar 1980 (50% 9 years; 40% 3 years)
North Canterbury	6	922	219 (48)	922	148 (41)			Jackson & Rowe 1997b (mature pines)
Otago	6	939	245 (70)	1006	185 (88)			Smith 1987 (pines17–22 years)

17.1 Baseflow comparisons between vegetation types

Annual baseflow from a number of comparative studies in New Zealand are listed in Table 17.1. The data of Cooper & Thomsen (1988) have been recalculated to meet the more usual definition, as they defined baseflow as the streamflow between storm events. Apart from the North Canterbury sites, baseflow generally makes up between 70 and 98% of total flow, with the highest amounts being at Purukohukohu in the volcanic region of the central North Island. Relative to precipitation amounts, baseflow is highest from pasture catchments ranging between 22% and 39% of precipitation. Under pine, baseflow ranges between 15 and 29% of precipitation and on average comparing sites (only using Don's Purukohukohu data as using Cooper & Thomsen's as well would introduce a bias) is 71% of that from pasture. Baseflow from native forest is also lower than for pasture as a proportion of rainfall, 20–27%, and the three comparable sites average 75% of that from pasture.

There are no consistent trends in baseflow in volume or as a percentage of streamflow when comparing vegetation types and there are only weak relationships between the baseflow for the pasture and native forest classes with precipitation (Fig. 17.1).

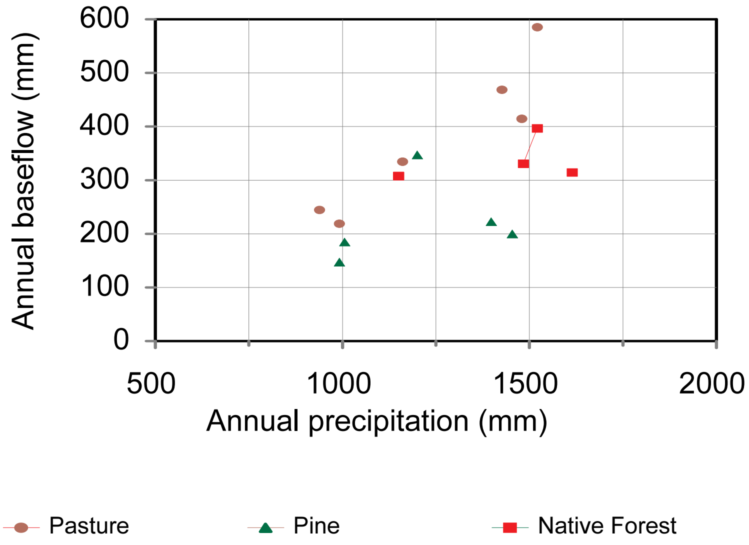

Fig. 17.1 Relationship between baseflow and precipitation for pasture, pine plantations and native forests.

17.2 Afforestation of riparian areas, Moutere

Smith (1992) has demonstrated a change in baseflow following the planting of a riparian zone in a small, previously fully pastured catchment at Moutere in Nelson (Table 17.2). The result of afforestation was a decrease in total flow, which was mainly baseflow as there was little change in the quickflow component. There appears to be inconsistent catchment numbering in this paper compared to the definitive numbering in Walter (2000) and those used by Duncan (1980, 1995a); C2 should be C5 and C4 should be C15.

Table 17.2 Precipitation and streamflow (mm), with percentages of rainfall or streamflow in brackets, at Moutere, Nelson from Smith (1992). See text for comment on catchment numbering

		Catchment C2		Catchment C4	
	Precipitation	Streamflow	Baseflow	Streamflow	Baseflow
1970–1978	1032	271 (26)	175 (65)	214 (21)	138 (65)
1979–1987	1010	266 (26)	169 (64)	161 (16)	91 (57)

17.3 Conclusions

The proportion of precipitation as baseflow ranges between:

pasture	22 and 39%
pine	15 and 29%
native forest	20 and 27%

Pine catchment baseflow from four comparable sites was 71% of that from pasture catchments.

Native forest catchment baseflow from three comparable sites was 75% of that from pasture catchments.

Afforestation of the riparian strip of one Moutere catchment reduced baseflow by about a third.

18. Storm Peaks

18.1 Afforestation of pasture and gorse in New Zealand

At Puruki in the central North Island, storms with peak flows >10 L/s (= 44 L/s/km^2) at the control pasture catchment were compared to those from a pine-planted catchment – peak flow = instantaneous peak less the baseflow at start of the storm. From shortly after planting when there was a rapid regrowth of grasses and weeds, the peak flows decreased until about year 5 when the mean peak for a year was about 80% of that predicted (Dons 1981). This estimated decrease may have been confounded by the smaller range of events after afforestation, which would tend to make the average decrease greater. There are no actual flow data given nor an analysis for different size classes.

At Moutere the greatest reduction in floods peaks (defined as peakflow less baseflow at the start of the event) since afforestation was greatest for small summer storms and got progressively smaller over time: 45% at 5–6 years, 62% at 7 yrs and 73% at 8 years (Duncan 1980). Flood peaks from the gorse catchments prior to burning were 78% less than for pasture catchments and were similar to those for 8-year-old pines. All floods were less than the mean annual flood of 38 L/s/ha. In the follow-up paper, Duncan (1995a) used a Log Pearson 3 extreme-value distribution fitted to the annual maximum series, which shows that afforestation has reduced flood peaks even in infrequent storms; the mean annual flood is reduced 35% and the 0.02 AEP peaks averages about 50% of those from pasture. The timing of large events can effect flood peaks with AEP ~ 0.05. If there is a large soil moisture deficit to be overcome at the start of a storm, then peaks can still be smaller from afforested catchments compared to pasture.

Smith (1992) demonstrated a change in a small catchment at Moutere in which the riparian strip had been planted in radiata pine. Peak flows were reduced in small events, but medium-sized storm peaks were not affected.

18.2 Afforestation of tussock grassland

Afforestation of 67% of the tussock-covered GH2 catchment at Glendhu in Otago has resulted in decreased flood peaks when compared to the GH1 control catchment (Table 18.1) (Fahey & Watson 1991; Fahey & Jackson 1997). Storms in each flow class were determined at GH1 and the comparison found with GH2. There seems to have been a small reduction in the first 3 years after planting, but this may have been a response to the pre-planting treatment where the catchment was ripped along the planting lines for better establishment. The continuing trends in later years would be a response to tree growth where all event size-classes show more than 50% reductions with over 70% in the 2–5 L/s/ha class.

Table 18.1 Mean storm peak flows for various flow classes at Glendhu, Otago before and after afforestation of tussock grassland. Sources: classes 5–10 and >10 L/s/ha from Fahey & Watson (1991); top and bottom lines taken from graphs in Fahey & Jackson (1997).

	2–5 L/s/ha		5–10 L/s/ha		> 10 L/s/ha		10–15 L/s/ha		>15 L/s/ha	
Period	GH1	GH2	GH1	GH2	GH1	GH2	GH1	GH2	GH1	GH2
1980–1982	2.8	3	6.6	6.6			13	13.9	17.3	15.2
1980–1982			7.2	6.7	14.2	13.5				
1984–1986			6.3	4.3	13.3	10.6				
1988–1990			6.3	3.3	18.6	14.7				
1991–1993	3	1.2	5.7	2.5			11.8	4.8	15.2	7

18.3 Conversion of native forest to pine plantations

Conversion of native forest to pine forest at Donald Creek in Nelson led to an increase in peak flows in the 6 years after harvesting and then planting pines in 1980 (Table 18.2; Fahey & Jackson 1997). While all catchments had similar peak flows before management, these doubled in size in the treated catchments for most flow-classes. As regrowth expanded and the pines matured there was a drop back to pretreatment levels at ages 11–14. This drop could be considered to be a halving of peak flows after afforestation. However, the trends in the higher flow-classes need to be treated with some caution as the results reflect only one storm in most size classes and the timing of that and the associated antecedent soil moisture conditions could be a factor in determining the magnitude of the change.

Table 18.2 Mean storm peak flows for various flow classes at Donald Creek, Nelson before and after conversion in 1980 of native forest to pine plantations. Source: taken from graphs in Fahey & Jackson (1997). Note that in each of the 8–15 and >15 L/s/ha classes there was usually only one storm in each sampling period, the 5–8 L/s/ha class had five storms except in the pre-harvest years when only one occurred.

	2–5 L/s/ha			5–8 L/s/ha			8–15 L/s/ha			>15 L/s/ha		
Period	DC2	DC1	DC4	DC2	DC1	DC4	DC2	DC1	DC4	DC2	DC1	DC4
1978–1980	3.5	4	4	5	5.5	5	11	10.5	11	15.5	15	14
1981–1986	3	5.5	4.5	5.5	12	9.5	12.5	14.5	12	22	33.5	28
1991–1995	2.5	2.8	3	5	5.2	5	11	10.8	12.4	25	32.5	23

A similar study was undertaken at Maimai on the West Coast where catchments M6 and M8 were unlogged, and harvesting of M7 (100% logged) and M9 (75% logged) took place (Table 18.3; Pearce et al. 1980). As at Donald Creek, peak flows increased in the 19 or so months after harvesting but this time by about 50%, which possibly reflected the wetter environment.

Table 18.3 Percentage increase in flood peaks in the period after harvesting catchments M7 and M9 at the Maimai catchments, West Coast

	M8	M7	M9
2–4.99 L/s/ha	−1	67	55
5.0–9.99 L/s/ha	1	50	41
>= 10.0 L/s/ha	−1	30	32

Leitch & Flinn (1986) present data following the felling of a native eucalypt forest and its replacement by radiata pine at Cropper Creek in Victoria, Australia. Peak flows were higher after clearing by about 40–60% in the higher storms. However, there were differences according to season in that peaks in the recharge season were substantially greater than expected because soils on the cleared catchments had higher soil moisture levels that those on the forested control catchment.

18.4 Harvesting of Douglas fir

There are many studies from the United States describing the effects of harvesting old-growth native forests but these may not be totally applicable to harvesting New Zealand Douglas fir plantations. There is some application to afforestation by Douglas fir once new crops become established. Table 18.4 summarises some of the responses.

There has been considerable debate in the literature on the change in peak flows after harvesting old-growth Douglas fir forests (Jones & Grant 1996; Thomas & Megahan 1998; Beschta et al. 2000; Jones 2000; and published comments). These studies review the literature including some of the work listed in Table 18.4, present new data, re-analyse old data, and often reach differing conclusions. Both small and large catchments are considered. The reader is referred to these references for the discussion. The work of Cheng et al. (1975) is an odd case and the results are attributed to changes in the flow mechanisms at that site.

Table 18.4 Changes in peak flows as a consequence of harvesting old-growth Douglas fir forests.

	Flows	% harvested	Increase	Source
Oregon H J Andrews		Roaded, 25% cut; burned	Nil	Rothacher 1965
Oregon Coyote Creek	> 2.2 L/s/ha	100% cut 30% cut 100% cut	47% 10% 36%	Harr et al. 1979
California Caspar Creek South Fork	Between 0.056 and 1.1 L/s/ha	100% cut over 3 years	111% (No change for peaks > 1.1 L/s/ha)	Wright et al. 1990
California Caspar Creek North Fork	> 4 L/s/ha	100% clearcut Partial cut	35% 16%	Ziemer 1998
British Columbia	No snow, and >5 mm P	19% cut over 6 years	No change in summer. Max 13.5% in winter	Golding 1987
Canada West Coast			~ 20% decrease	Cheng et al. 1975

18.5 Urbanisation

The Wairau Creek on the North Shore, Auckland, has changed from being nearly 3/4 grassland, forest, scrub and swamp in1959 to 2/3 urban in 1974 (Williams 1976). Flood levels (and therefore peaks) increased in size, and the increase in number of events was directly related to the built-up area. Time to peak and storm duration both decreased with urbanisation.

18.6 Conclusions

Afforestation leads to storm peak reductions of the order of 70–80% in small, frequent storms and lesser but still significant reductions in larger storms. The converse is true after harvesting native forests or old-growth Douglas fir forests, when peaks may double.

Timing is also important as a given storm falling on a wet catchment may have a larger change than if the same event had occurred on a dry catchment.

Urbanisation has been shown to lead to an (unquantified) increase in flood peaks.

19. Stormflow

Stormflow is that part of the stream hydrograph above assumed baseflow levels during a storm. This is sometimes referred to as quickflow especially if the Hewlett & Hibbert (1967) flow separation method is used.

19.1 Comparisons between vegetation types

Table 19.1 lists stormflows from a number of New Zealand catchments where results have been published for two or more land-use types (pasture, native forest or radiata pine forest). The tendency is for pasture to have the greater stormflow, native forest to have the smallest amount of stormflow and pine plantations to be in the middle. There is, however, no indication of the relative regimes that might have been present if the pine catchments had still been in pasture or native bush. We have to assume that they were similar and that the differences are a consequence of afforestation.

Table 19.1 Stormflow from comparative catchment studies. The data of Smith (1987) are averages of two catchments in each land use. Values in brackets are stormflow as percentages of total flow.

Location	Years	Pasture		Exotic forest		Native forest		Source
		P (mm)	Flow (mm)	P (mm)	Flow (mm)	P (mm)	Flow (mm)	
Purukohukohu	2	1480	95 (18)	1455	40 (17)	1615	11 (4)	Cooper & Thomsen 1988
Purukohukohu	4	1427	74 (14)	1398	31 (12)	1484	8 (2)	Dons 1987
Topuni (pasture)	6	1351	281					Hicks 1988
Kokopu (Forest)				1334	199			
Upper Mangawhara	2	1521	291 (33)			1521	140 (26)	Petch 1984
Nelson	1	1161	110 (25)	1218	141 (30)	1151	119 (28)	McKerchar 1980
North Canterbury	6	920	94 (52)	920	63 (59)			Jackson & Rowe 1997b (mature pines)
Otago	6	939	103 (30)	1023	25 (13)			Smith 1987 (pines 17–22 years old)

Apart from the North Canterbury sites, stormflow makes up between 2% and 30% of total flow with the lowest amounts being at Purukohukohu in the volcanic region of the central North Island. Relative to precipitation amounts, stormflow is lowest from pasture catchments, ranging between 5% and 21% of precipitation. Under pine, stormflow ranges between 2% and 15% of precipitation and on average comparing sites (only using Don's Purukohukohu data, as using Cooper & Thomsen's as well would introduce a bias) is 60% of that from pasture. Stormflow from native forest is also lower than for pasture as a percentage of rainfall, 0.5–10%, and the three comparable sites average 78% of that from pasture.

There are no consistent trends in stormflow in volume or as a percentage of streamflow when comparing vegetation types and there are only weak relationships between the baseflow for the pasture and native forest classes with precipitation.

19.2 Stormflow changes after afforestation of pasture

Table 19.2 indicates the change in streamflow regime that occurred following the planting of a riparian zone in a small, previously fully pastured catchment at Moutere in Nelson (Smith 1992). There was little change in the quickflow component as a result of afforestation in the riparian zone with the decrease in total flow being mainly baseflow. There appears to be inconsistent catchment numbering in this paper compared to the definitive numbering in Walter (2000) and used by Duncan (1980, 1995a); C2 should be C5 and C4 should be C15.

Table 19.2 Stormflow (millimetres – with percentages of rainfall or streamflow in brackets) at Moutere, Nelson, from Smith (1992). See text for comment on catchment numbering.

		Catchment C2		Catchment C4	
	Precipitation	Streamflow	Stormflow	Streamflow	Stormflow
1970–1978	1032	271 (26)	97 (35)	214 (21)	76 (35)
1979–1987	1010	266 (26)	97 (36)	161 (16)	70 (43)

19.3 Stormflow changes after afforestation of tussock grassland

At Glendhu, 67% of catchment GH2 was planted with radiata pine by 1982. The differences in annual stormflows for one pre-treatment year with that when the trees were age 7 are shown in Table 19.3 and a comparison of mean event stormflows for pretreatment and post-canopy closure periods is given in Table 19.4. Compared to GH1, the amount of stormflow at GH2 has decreased since planting (Fahey & Watson 1991). The events in the smallest size class have had the biggest decline in percentage terms (57%) with a 43% decline in the largest events (Fahey & Jackson 1997).

Table 19.3 Stormflow changes (millimetres – with percentages of rainfall or streamflow in brackets) at Glendhu, Otago (Fahey & Watson 1991).

		Catchment GH1		Catchment GH2	
Year	Precipitation	Streamflow	Quickflow	Streamflow	Quickflow
1981	1265	723 (57)	175 (25)	707 (56)	178 (25)
1989	1222	705 (58)	224 (32)	574 (47)	143 (25)

Table 19.4 Mean stormflow (mm) for events at catchments with tussock grassland and pines 9–11 years old at Glendhu, Otago (from a graph in Fahey & Jackson 1997).

	1980–1982			1991–1993		
Size class	Pairs	GH1	GH2	Pairs	GH1	GH2
5–10 mm	21	6.5	7	37	7	3.5
10–20 mm	6	13	15	23	14	8
20–40 mm	4	24	30	6	28	16
> 40 mm	3	43	46	3	52	30

19.4 Changes in stormflow after converting native forest to plantations

A comparison of event stormflows between two catchments in native forest that were harvested at Donald Creek in Nelson and an unlogged catchment showed increases of about 30% in the 5 years following harvest for storms in the 20–40 mm size class. There were indications of smaller percentage increases in higher flow-classes but the sample sizes were very small. After 10–14 years of growth the patterns were similar to the pre-harvest period (Fahey & Jackson 1997).

In small catchments at Maimai on the West Coast, stormflow yields increased in the 19 months following harvesting of the native forest. Table 19.5 shows that mean stormflow yields in six flow classes were similar for two untouched catchments, M6 and M8, but the two harvested catchments, M7 and M9, had considerably higher yields. The increases were largest in small events although for events greater that 60 mm at M6, M7 quickflow was still 20% greater.

Table 19.5 Stormflow yields in the 19 months after harvesting catchments M7 and M9 at Maimai (from Pearce et al. 1980). M7 and M9 events are paired with native forest catchment M6; M6 and M8 comparisons are for the native forest.

Size class	M6	M8	M6	M7	M6	M9
0.25–0.99	0.46	0.68	0.45	1.3	0.46	1.34
1.00–4.99	3.27	3.98	2.89	6.79	2.89	5.74
5.00–14.99	8.6	9.7	8.8	18.0	8.8	16.3
15.00–29.99	18.3	17.7	19.2	29.7	19.2	29.3
32.0–59.99	39.7	41.9	39.4	57.2	39.6	51.4
>= 60.0	102.4	107.7	94.6	120.1	94.6	120.7

Harvesting a eucalypt forest in Victoria and planting with radiata pine led to an increase in stormflow, as shown by mass curve analysis for the 7 years after harvesting. The biggest increase was in the year after harvesting, but the next 6 years still produced more stormflow than would have been expected from the control catchment for unlogged conditions and another unlogged catchment (Bren & Papworth 1991).

19.5 Conclusions

The proportion of precipitation as stormflow ranges between:

pasture	5% and 21%
pine	2% and 15%
native forest	0.5% and 10%.

Pine stormflow from four comparable sites was 60% of that from pasture.
Native forest stormflow from three comparable sites was 78% of that from pasture.
Afforestation of the riparian strip of one Moutere catchment did not affect stormflow.

20. Annual Water Yields

20.1 Comparisons between vegetation types

Table 20.1 lists annual water yields from a number of New Zealand catchments where results have been published for two or more land-use types: pasture, native forest or radiata pine forest.

Table 20.1 Water yields from comparative catchment studies. All values in millimetres.

	Period	Pasture		Exotic forest		Native forest		Source
	Years	P	RO	P	RO	P	RO	
Purukohukohu	2	1480	510	1455	240	1615	328	Cooper & Thomsen 1988
Purukohukohu	4	1427	543	1398	254	1484	339	Dons 1987 [1]
Mamaku Plateau	3			1960	430	2350	1210	Dell 1982 [1]
Upper Mangawhara	2	1521	877			1521	537	Petch 1984
Taita	3	1130	290			1130	235	Jackson 1973 [2]
Taita	1.9		188				138	McColl et al. 1977 [2]
Moutere	6	1004	217	1004	64			Duncan 1995a [3]
Kikiwa, Nelson	1	1161	447	1201 1218	497 512	1151	427	McKerchar 1980
Westland–Maimai M5	1			2668	1818	2668	1554	Rowe & Pearce 1994
Westland – Maimai M13	1			2461	1731	2461	1446	Rowe & Pearce 1994
North Canterbury	6	922	180	922	107			Jackson & Rowe 1997b (mature pines)
Otago	6	1010	385	1010	213			Smith 1987 [4]
Lidsdale, NSW Pine catchment 2	2.6			855	70	880	125	Smith et al 1974; pines 33 years old [5]
Lidsdale, NSW Pine catchment 1	3			842	190	870	269	Pilgrim et al. 1982 [5]

Notes:

[1] Catchments may not be watertight or geomorphic areas may not reflect the hydrologic boundary. See text for further comment

[2] Pasture catchment has 1/3 scrub

[3] Data for Moutere are means of two pasture catchments and three pine catchments

[4] Otago data from Smith (1987) are the averages from two catchments in each land use.

[5] Australian (NSW) native forest = eucalypt

There is some doubt as to the true area of the pasture catchment at Purukohukohu as the hydrologic and geomorphic boundaries may not coincide because of the volcanic geology of the region. Hence, yields given here by (Dons 1987) could be in error. The Mamaku Plateau might present similar problems. Although the Mamaku data presented by Dell (1982) for 3 years were consistent at each site as a percentage of rainfall, there were major concerns about the watertightness of the catchments. For example, annual water yields from a native forest catchment and a mixed native/exotic forested catchment were 51% and 17% of annual precipitation, respectively. It would be anticipated that these should be similar, which brings into question the watertightness of the catchments.

Notwithstanding the reservations above, from Table 20.1 streamflow from pasture averaged 34% of precipitation (range 20–57%); from pine forest it averaged 33% of precipitation (range 12–70%); and from native forest it averaged 41% of precipitation (range 20–58%). There is, however, no indication of the relative regimes that might have been present if the pine catchments had still been in pasture or native bush. We have to assume that they were the same and that the differences are a consequence of afforestation. For comparable catchments, streamflow from pine forest was 63% of pasture and 96% of native forest, and streamflow from native forest was 73% of that from pasture catchments.

Linear regression analyses on that streamflow and precipitation data (Fig. 20.1) provided statistically significant relationships (Eqns 20.1 to 20.3). In practice, these relationships become unuseable because the confidence limits on the parameters are so large. A second factor to consider is size of the regression coefficient, which in all cases could be greater that 1.0 when the confidence limits are taken into account – which would imply that once the limit of the intercept was reached, streamflow generated could be greater than the incident precipitation without even considering catchment evaporation in the water balance equation. This problem is likely to be an artefact of the low sample numbers.

Pasture streamflow = −710 ± 580 + 0.97 ± 0.49 × PTTN   n = 7, r^2 = 0.838, SE = 105   (20.1)
Pine streamflow = −810 ± 400 + 0.93 ± 0.36 × PTTN   n = 9, r^2 = 0.843, SE = 285   (20.2)
Native forest streamflow = −720 ± 390 + 0.84 ± 0.20 × PTTN   n = 7, r^2 = 0.958, SE = 125   (20.3)

The overall dataset can be increased by including data from a number of single-catchment studies of pasture and native forest streamflow (Table 20.2). The average streamflows from pasture and native forest were 37% and 44%, respectively, and the new equations that still have wide confidence limits and high regression coefficients which affect their use as prediction equations are:

Pasture streamflow = −800 ± 485 + 1.04 ± 0.41 × PTTN   n = 13, r^2 = 0.742, SE = 114   (20.4)
Native forest streamflow = −790 ± 240 + 0.89 ± 0.13 × PTTN   n = 11, r^2 = 0.965, SE = 122   (20.5)

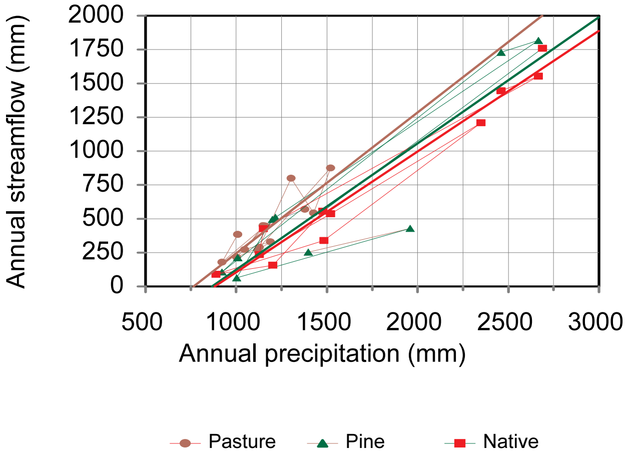

Fig 20.1 Water yields from New Zealand catchments. See text for comment on the precision of the lines.

Table 20.2 Water yields from individual catchments studies. All values in millimetres.

	Years	Precipitation	Streamflow	Source
Pasture				
Northland – Pukewaenga	11	1380	570	Pearce & McKerchar 1979
Auckland – Manukau	7	1150	450	Pearce & McKerchar 1979
Tararua – Tuapeka	1	1048	273	Bargh 1978
Wellington – Makara 11	8	1190	330	Pearce & McKerchar 1979
Nelson – Moutere 5	15	1120	270	Pearce & McKerchar 1979
Otago – Glendhu	11	1355	800	Fahey & Watson 1991 [1]
Native forest				
Hawkes Bay - Ngahere	9	2690	1760	Pearce & McKerchar 1979
Tararua - Ballance	1	1202	158	Bargh 1977
Wellington – Taita No 4	0.75	890	90	Claridge 1970 [2]
Nelson – Donald Creek	2	1480	555	Pearce et al. 1982 [3]
Westland – Maimai	1	2652	1556	Pearce et al. 1976 [4]
Westland – Maimai M15	11	2304	1256	Rowe & Pearce 1994
Westland – Maimai M6	11	2435	1324	Rowe & Pearce 1994

Notes: [1] Tussock grassland

[2] Data converted to 1 year by proportion
[3] Mean of three catchments

[4] Mean of six small catchments

An estimate of annual water yields from forest and pasture catchments was made by Riddell & Martin (1982). They used annual water yield data from 38 pasture, 32 native forest and 20 pine forest catchments throughout New Zealand to make the prediction equations 20.6 to 20.9 that are shown in Fig. 20.2.

For pasture catchments
Streamflow = 0.60 × PTTN − 267 PTTN < 1400 mm; n = 28, r = 0.758, SE = 106 (20.6)
Streamflow = 1.4 × PTTN − 1477 PTTN ≥1400 mm; n = 20, r = 0.938, SE = 134 (20.7)

For forested catchments
Streamflow = 0.68 × PTTN − 605 PTTN < 1600 mm; n = 12, r = 0.797, SE = 119 (20.8)
Streamflow = 1.24 × PTTN − 1537 PTTN ≥ 1600 mm; n = 40, r = 0.985, SE = 145 (20.9)

Riddell & Martin (1982) concluded from mean streamflow versus mean precipitation plots that:

- pasture catchments have a greater runoff than forested catchments, and
- in the rainfall range where native forest and pine plantation catchments overlap, relationships between runoff and rainfall were indistinguishable.

While the results seem plausible they need to be treated with caution as very few of the catchments used could be considered paired catchments for comparison purposes and the study covers a wide range of precipitation regimes. The regression coefficients for the high precipitation regimes being greater than 1.0 are also cause for concern. The standard errors would translate to 95% confidence limits on the estimated mean Y values of about ± 250–300 mm.

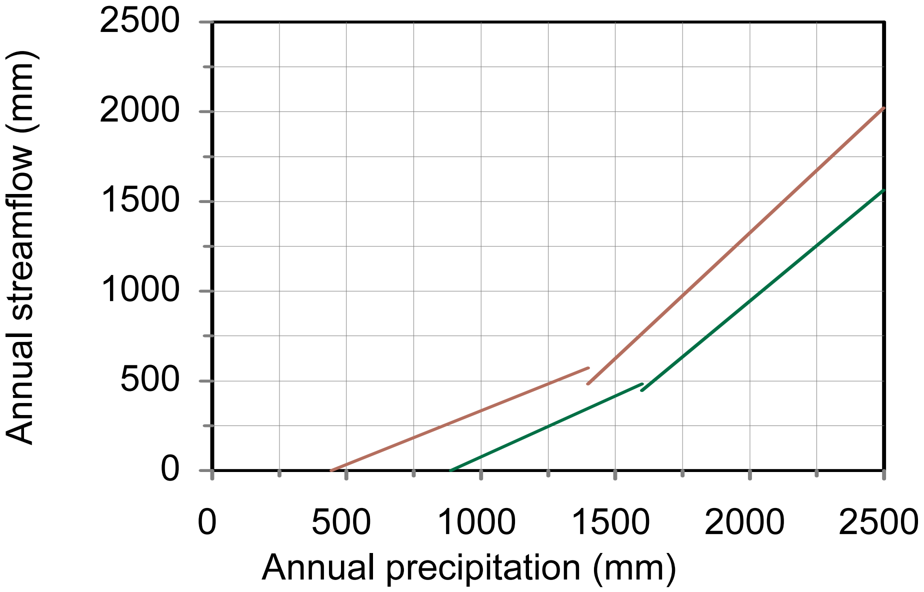

Fig 20.2 Streamflow prediction equation from Riddell & Martin (1982)

A contrasting study by McKerchar & Waugh (1976) had earlier come to different conclusions. They carried out a regionalisation study of annual streamflow using regression analysis on data from 57 catchments throughout New Zealand. The best predictors were mean annual precipitation and average altitude. Catchment area and percentage of forest cover had regression coefficients not significantly different from zero. They also showed examples of flow duration curves and concluded that annual rainfall had a dominant influence on the patterns observed. Baseflow recessions were presented for 13 catchments and the importance of geology on these flows was stressed.

20.2 Afforestation of pasture/scrub

Northland – Waiwhiu

In 1975, 47% of the 803-ha Waiwhiu River catchment in Northland (130 ha in scrub and 220 ha in improved pasture) was planted in radiata pine; the remaining 53% was retained in native forest. The native forested Ngunguru River catchment 80 km to the north was used as the base for comparisons. The Waiwhiu catchment is in one of the wetter regions of New Zealand and the annual rainfall averages about 1840 mm (Waugh 1980). The farm was destocked, and the scrub crushed and burned before planting. In the 3 years after land preparation for planting started there was an average decrease in streamflow of 530 mm/year and this was attributed to increased interception of precipitation as the grass became rank (Waugh 1980).

A later analysis by Rowe & Jackson (1997) determined the annual streamflow–precipitation relationship for the period before treatment until 5 years after planting. This was used to estimate the streamflow regime that would have occurred if there had not been planting and compared it with that recorded from the planted catchment. It was estimated that planting 47% of the catchment would contribute to a reduction in streamflow of 220 mm for 1500 mm precipitation and 310 mm for 2000 mm precipitation; these equate to reductions of 470 and 660 mm for a 100% conversion from pasture/scrub to mature pine plantation.

Central North Island – Puruki

A snapshot of the changes to the streamflow regime with afforestation at Puruki has been given earlier (Table 20.1; Dons 1987; Cooper & Thomsen 1988). A water-balance modelling approach using a daily time step has provided further information for the mature pine plantation (Table 20.3; Rowe & Jackson 1997). The pasture (1970–1974, A–B) and forest (1980–1996, A–C) models predicted annual streamflow well for Puruki in those covers. This suggests that the predicted differences between the pasture and pine-forest states of about 320 mm/year will be close to reality. Differences given by Cooper & Thomsen (1988) at 270 mm and by Dons (1987) at 290 mm were for trees in the first few years of the 1980–1996 dataset used by Rowe & Jackson (1997) and may be smaller because there was lower average rainfall during their sampling periods or as a consequence of the trees being younger although the canopy was closed.

Table 20.3 Mean annual precipitation and streamflow at Puruki and the changes resulting from afforestation of pasture in 1973.

	Calibration period 1970–1974	Treatment period 1980–1996
Precipitation (mm)	1625	1543
A: Puruki streamflow (mm)	794	404
B: Predictions from pasture model (mm)	793	404
C: Predictions from forest model (mm)	458	707
Difference A–B (with standard deviation)	0 (44)	−304 (91)
Difference A–C (with standard deviation)	340 (55)	1 (94)

Nelson – Kikiwa

Hewitt & Robinson (1983) and McKerchar (1980) present data from a suite of catchments located near Kikawa in Nelson (Table 20.4). The longer dataset (Hewitt & Robinson 1983) began 3 years after Graham Creek was planted. Therefore there is no effective calibration period. Changes in the flow regime at Graham Creek appear to be present as there was more streamflow than from the pasture catchment in 1978, 3 years after planting, and less from 1980. In the drier years (1981 and 1982) there is little difference between any of the vegetation types. There is no certain reference point to indicate the comparative situation when planting occurred, nor are any rainfall data given for each catchment to indicate whether there are differences between catchments that might allow a fuller explanation of the trends seen. Rainfall data plotted in Fig 20.3 were extracted from a graph in Hewett & Robinson (1983) by LKR so there may be some error in the numbers; they are also a regional average. One year of data in McKerchar (1980) indicates there could be differences of up to 60 mm in rainfall between catchments, which will be significant if changes are considered in terms of evaporation as a function of precipitation-less-streamflow.

Table 20.4 Kikiwa catchments

Catchment	Area	Vegetation and Management
Graham Creek	474 ha	Reverting pasture, 82% planted in exotics during 1974–1976
Hunters Creek	502 ha	Untouched beech forest
Kikiwa Creek	285 ha	Rough pasture with bracken and pockets of scrub

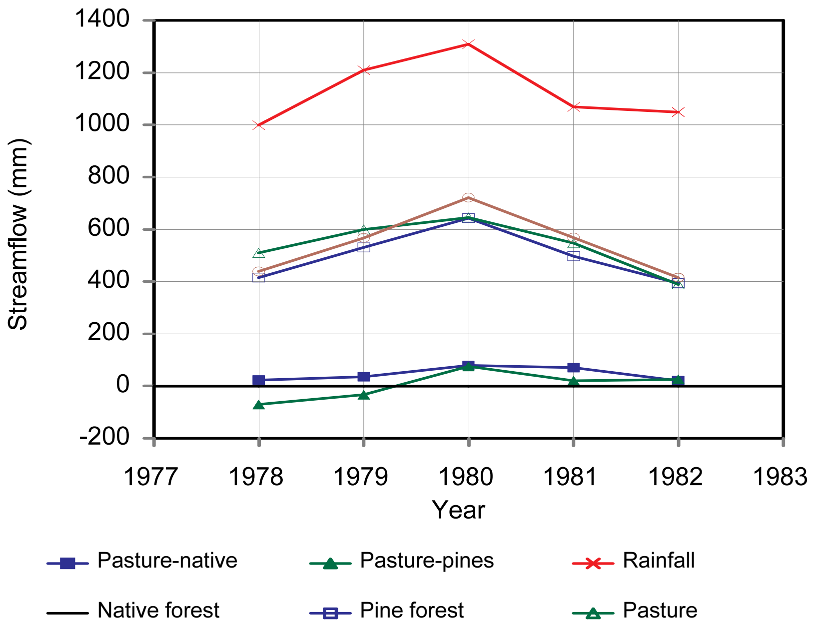

Fig. 20.3 Rainfall and streamflow for the Kikiwa catchments, Nelson. Graham Creek was planted in 1974–1975.

Nelson – Moutere

The Moutere catchments were established as part of the International Hydrological Decade (IHD) programme in the late 1960s. The small catchments, 2.71 to 7.65 ha, were located on Moutere gravels about 20 km south-west of Nelson where the average precipitation is about 1100 mm/year; more detailed information can be found in Duncan (1980). Table 20.5 lists catchment data derived from a number of papers. The earliest published work from Moutere was presented by Duncan (1980).

Table 20.5 Moutere catchments information (Duncan 1995a, 1980)**.** Records were not taken between 1988 and July 1991 and ceased in July 1993.

Catchment No.	2	5	15	8	13	14
Area	3.96	6.95	2.71	4.41	7.65	4.33
Flow records began	1963	1963	1963	1963	1963	
Initial vegetation	Pasture	Pasture	Pasture	Gorse	Gorse	Gorse
Intermediate treatment	Gorse in gullies sprayed out by 1968	Gorse in gullies sprayed out by 1968		Burnt 1970 and line-dozed	Burnt 1970 Misc. land treatment to 1971	To pasture in 1964 Disced 1970
Planted			1978 20%	1970	1971	1970
Thinned			1984	1978, 1981	1978, 1981	1975, 1981
Felled				1991	1991	1991

Duncan (1980) presents data up until 8 years after planting. Burning gorse and line-dozing catchment 8 increased streamflow from that predicted using calibration period regression relationships by about 175 mm; similarly clearing catchment 13 resulted in a 290-mm increase. Streamflow increases persisted for 4 years at catchment 8 and then dropped back to levels about 75 mm lower than predicted in the next 4 years, but catchment 13 showed little change from pretreatment levels. At catchment 14 there was an increase in streamflow after converting scrub to pasture, and again after pre-planting ground preparation. From the third year after planting there has been a steady decrease in the expected streamflow to about 195 mm in 1978. On a season basis, in the 5–8 years after planting, streamflow was reduced by more than 50% in most seasons with the greatest reductions in absolute terms occurring in winter. Duncan (1983) showed that streamflow had leveled out at catchment 14. A later report covers the effects of the full forest rotation (Duncan 1995a). At catchment 14 (Fig. 20.4) the predicted departure from pasture was 170 mm from age 8 to age 16.

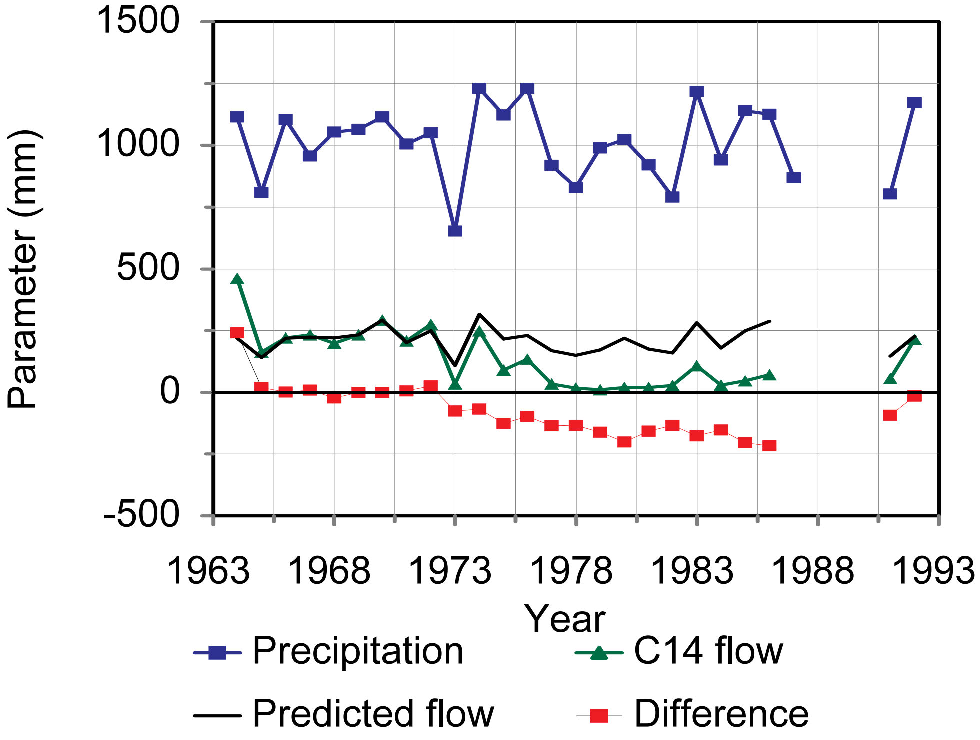

Fig.20.4 Moutere catchment 14 streamflow and the change in annual streamflow as a consequence of afforestation of pasture.

Harvesting in mid-1991 led to an increase in streamflow, as can be seen in Fig. 20.4 for catchment 14. The largest effect was in the second year as soil moisture levels had taken some time to recharge. At this time, yields from catchments 5 and 8 were similar to the initial years after burning and planting, and at catchment 14 was similar to that expected if it had still been in pasture.

West Australia

One Australian study (Borg et al. 1988) presents data on the change in streamflow with afforestation of farmland in an effort to reduce salinity problems. Unfortunately, flow records did not begin until a significant part of the catchment, 37% in addition to the 25% of forest present, had been afforested in either radiata pine or eucalypts. The rainfall in the region averaged 770 mm and, in the first 3 years of data collection when the establishment of the trees would still have had little effect on decreasing yields, streamflow was 140 mm or 18% of rainfall. Over the next 6 years there was a decreased yield of about 100 mm, but putting this into context is not straightforward as planting was still continuing and the percentage of the catchment stocked applied to the whole catchment, not the area above the gauging station.

20.3 Afforestation of tussock grassland

A series of papers outline progressive changes at Glendhu as a consequence of the afforestation of the tussock grassland; e.g., Pearce et al. (1984), Fahey (1990), Fahey & Watson (1991); Fahey & Jackson (1997), Fahey et al. (1998). About 6 years after planting 67% of catchment GH2 annual streamflow yields began to decline and flows averaged about 270 mm lower than predicted from tree ages 9–16 years (Table 20.6; Fig. 20.5). This equates to about 400 mm per annum for completely planting the catchment.

Table 20.6 Water yield changes at Glendhu for 67% afforestation of GH2. 1980-1990 data from Fahey & Watson (1991); 1991–1997 data extracted from a figure in Fahey et al. (1998).

Year	Precipitation (mm)	GH1 (mm)	GH2 (mm)	Difference (GH1-GH2)	Reduction (%)	Management
1980	1555	911	907	4	1	Tussock
1981	1265	728	707	21	3	Ripping
1982	1482	837	825	12	1	Planting
1983	1572	1115	1145	-30	-3	
1984	1388	946	883	63	7	
1985	958	488	476	12	2	
1986	1487	799	810	-11	-1	
1987	1591	1008	959	49	5	
1988	1321	718	681	37	5	
1989	1222	705	574	131	19	Part thinned
1990	1063	533	428	105	20	
1991	1352	890	632	270	29	
1992	1466	1054	800	265	24	
1993	1368	918	689	230	25	
1994	1338	959	686	285	28	
1995	1398	928	656	280	29	
1996	1301	839	588	265	30	
1997	1446	953	677	290	29	

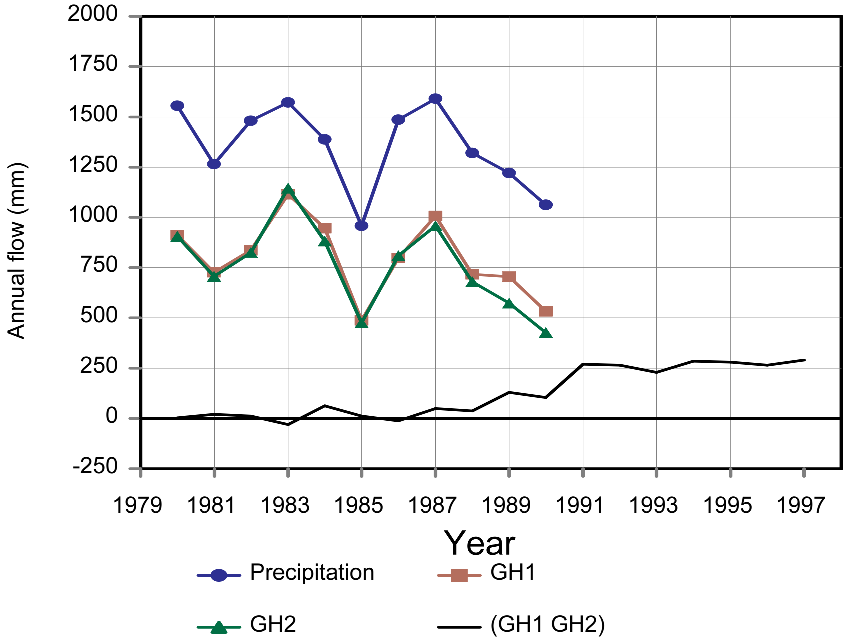

Fig 20.5 Streamflow at Glendhu catchments GH1 (tussock) and GH2 (67% radiata pine) and the difference in flow with time.

20.4 Afforestation from scrub

South Auckland – Moumoukai catchments, Hunua Range

An experimental programme was established in the Hunua Ranges near Auckland in 1969 when monitoring began on three catchments in native scrub (Table 20.7) (Barton 1972; Herald 1978, 1979; Barton & Card 1979). In 1968, the vegetation was a mixture of ferns and native scrub but in that year all large vegetation was felled, reducing the cover to bracken and low scrub. In March 1970, the vegetation in the Central and South catchments was burnt and the catchments were planted in *Cryptomeria japonica* or *P. radiata* during August. There are small wetlands in the lower part of the catchment, which were not planted.

Table 20.7 Catchment parameters for Moumoukai catchments

Catchment	Vegetation	Area (ha)	Wetland (ha)
North	Control scrub	8.84	0.17
Central	*C. japonica*	11.42	0.40
South	*P. radiata*	14.98	0.81

Release cutting was carried out in both catchments in 1971 and 1972 (also in 1973, 1974 and 1975 in Central) and pruning of South took place in December 1975, January 1978, and December–January 1978–1979; thinning to 300 SPH also took place at the latter date. By 1978 the understorey under dense radiata pine canopy was thin or non-existent; *Cryptomeria* growth in Central was not as good as expected and groundcover was dense, and dense scrub had also regenerated in North.

Herald (1978, 1979) presented the first longer-term streamflow data for the North and South catchments. His data are for a shorter period and are slightly different from the annual streamflows calculated from data in Barton & Card (1979) (Table 20.8), possibly having been adjusted for climatic variations. Accumulated totals derived from Barton & Card's (1979) data and plotted in Fig 20.5 show that, compared to the control scrub catchment, there has been a decrease in streamflow after planting cedar (600 mm over the 10 years) and radiata pine, a total of 2050 mm over the 10 years—equivalent to 290 mm/year over the last 7 years. One complicating factor in these analyses, which will effect the magnitude of any change, is the possibility that there has been some change at the control catchment in the first few years of the study as the scrub recovered from the 1968 clearing – and yields will decrease while this is happening. There is a suggestion that the flows in the radiata pine catchment may have stabilised, but an extension of the record is necessary to verify that (Fig. 20.6).

Table 20.8 Water yield at Hunua after Barton & Card (1979)

	Control (North)		*P radiata* (South)		*C. japonica* (Central)	
	Precipitation (mm)	Streamflow (mm)	Precipitation (mm)	Streamflow (mm)	Precipitation (mm)	Streamflow (mm)
1969	1580	756	1515	646	1536	660
1970	1786	989	1712	978	1736	1028
1971	2046	1154	1961	1048	1989	1102
1972	1698	829	1627	743	1650	800
1973	1382	500	1325	386	1344	446
1974	1563	600	1498	414	1519	596
1975	1922	907	1842	614	1868	836
1976	2014	919	1930	591	1958	830
1977	1794	868	1720	458	1744	765
1978	1661	766	1592	357	1615	611

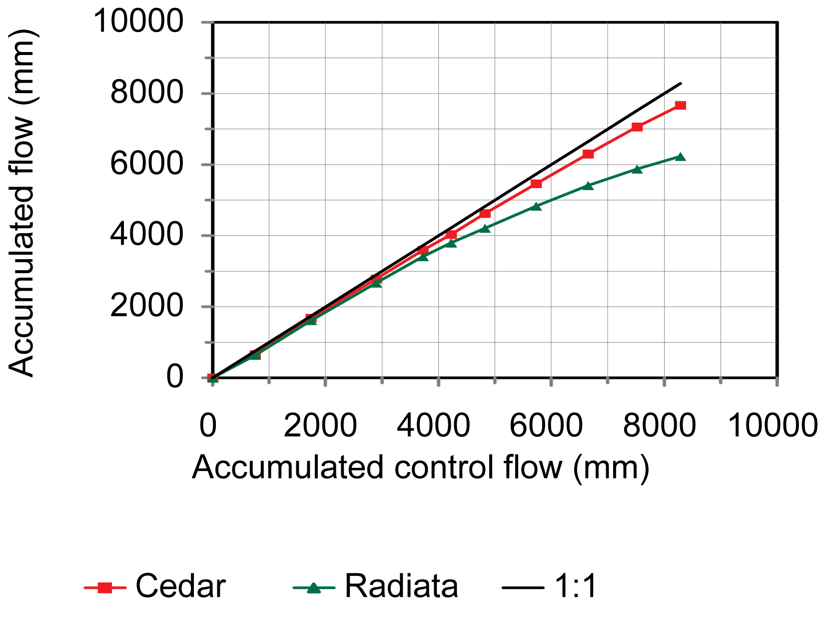

Fig 20.5 Accumulated flow for Moumoukai catchments 1969–1978.

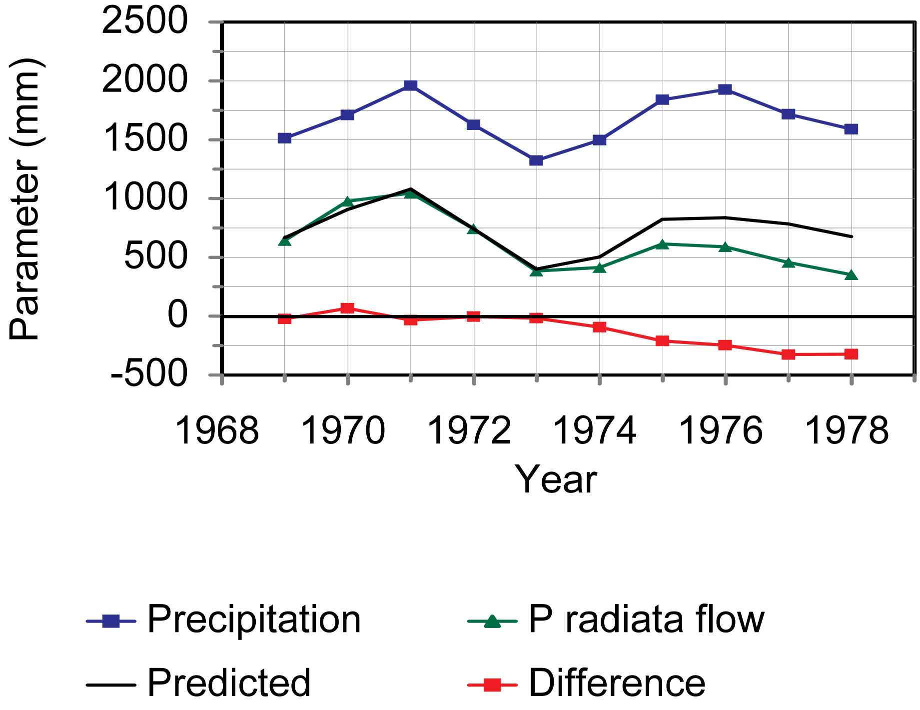

Fig 20.6 Difference between flow at the control catchment and the radiata pine catchment at Moumoukai, Hunua Range

Nelson – Moutere

Catchments 8 and 13 at Moutere were planted on land that had previously been in gorse (Table 20.5). Annual streamflows from these catchments are shown in Figs 20.7 and 20.8 (data from Duncan 1980). The immediate effects of clearing the gorse was an increase in annual streamflow of about 375 mm in catchment 8 and 200 mm in catchment 13. The response differences are considered slope related as catchment 8 faces southeast and catchment 13 north. Over the course of the next 6 years, streamflow decreased to pre-treatment levels as the pasture grasses and trees grew. At catchment 8 from age 6 to 15, streamflow was 100 mm less than when it was in gorse while at catchment 13 it was 26 mm less.

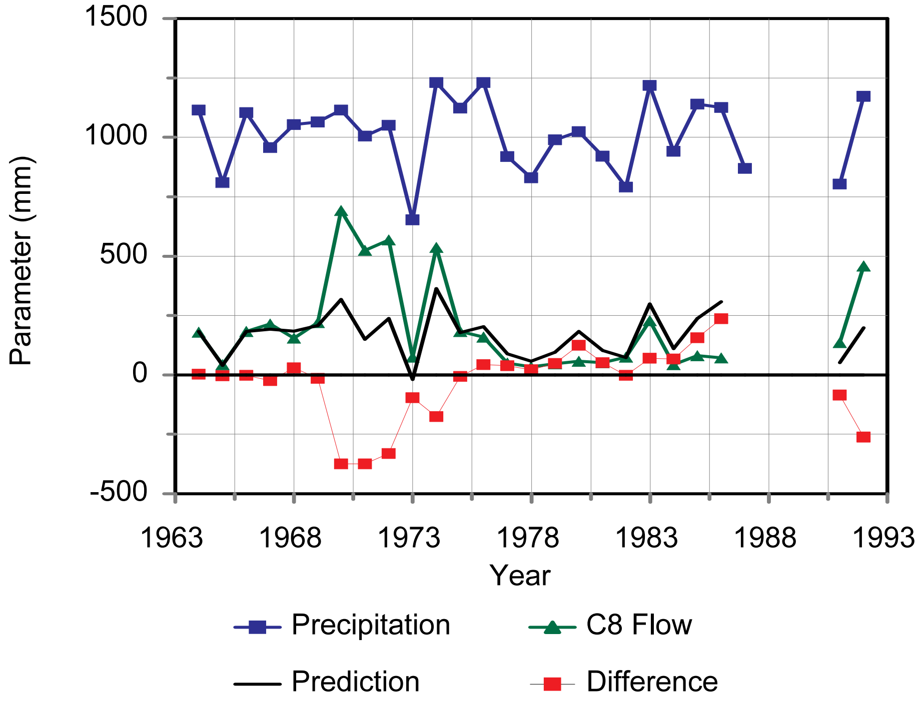

Fig. 20.7 Streamflow from Moutere catchment 8 in which gorse was burned and planted in radiata pine. Difference is predicted streamflow for the gorse covered catchment less the measured streamflow.

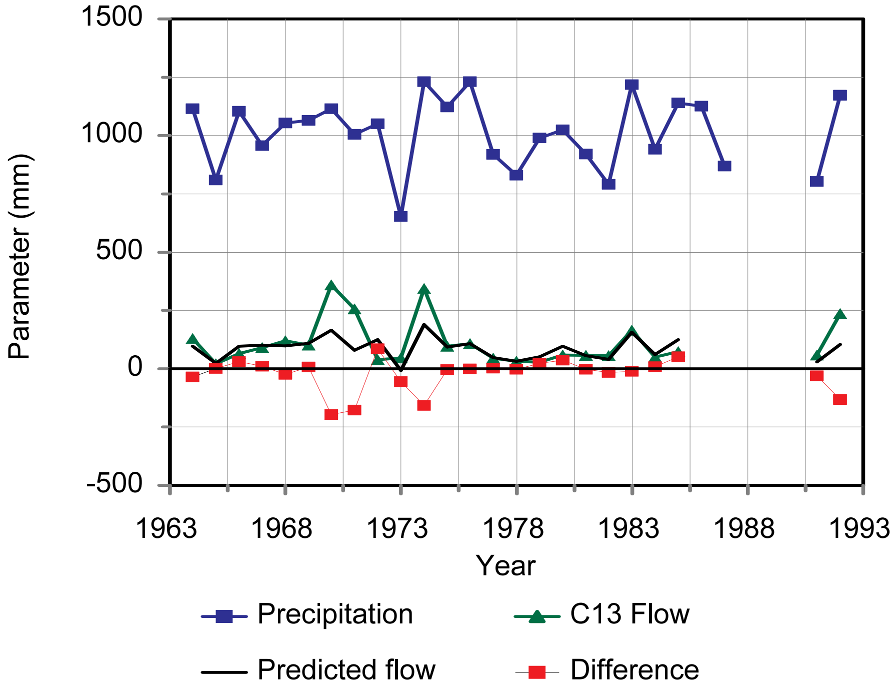

Fig 20.8 Streamflow from Moutere catchment 13 in which gorse was burned and planted in pine. Difference is predicted streamflow for the gorse covered catchment less the measured streamflow.

Jonkershoek, South Africa

The Jonkershoek catchments in the Western Cape of South Africa have been studied since the 1940s when the first catchment was converted from the sclerophyllic fynbos scrub to radiata pine. Table 20.9 gives the treatments and catchment parameters gleaned from a number of sources (Banks 1961; van Wyk 1987; Bands et al. 1989; Le Maitre & Versfeld 1997; Scott 1997).

Table 20.9 Jonkershoek catchment treatments. Biesievlei has afforestation to the river edge; other catchments have a 20-m (1-chain) riparian reserve.

Catchment	Rainfall (mm)	Natural runoff (mm)	Year Planted	Forest (%)	Years felled	Wildfire	Area (ha)
Bosboukloof	1300	600	1940	57	1979–1982	1986	200
Biesievlei	1430	660	1948	98			27
Tierkloof	1800	1000	1956	36			157
Lambrechtsbos B	1500	530	1964	84			65
Lambrechtsbos A	1410	640	1972	89			31
Langrivier	2260	1600	Not	0		1942	246

No paper obtained contained a continuous set of precipitation or streamflow data from the start of the experiments. Fig 20.9 shows that streamflows were steadily decreasing at Bosboukloof from the time the Lambrechtsbos B station was established (the difference Lambrechtsbos B less Bosboukloof was getting larger) (data from Banks & Kromhout 1963). When available data resumes (from Scott 1997) Lambrechtsbos B had been planted and the trees were now 15 years old and those at Bosboukloof were approaching harvesting (age 37 years). From these data we could only speculate that the higher degree of planting at Lambrechtsbos B (84% of the catchment cf. 57%) led to a greater change in flow through afforestation (hence the L-B line falling below the 0 line – Fig. 20.9). As Bosboukloof was felled between 1979 and 1982 streamflow increased and the change may have been leveling out in 1986 when it was burned by wildfire. The analysis by Scott (1997) indicated there was a smaller increase in streamflow as a result of the wildfire than there had been as a consequence of harvesting.

The summary from van Wyk (1987) with the long-term changes in streamflow following afforestation for all the Jonkershoek catchments is given in Table 20.10. Annual reductions can be variable in an individual year, and the reduction can be over 500 mm in wetter years (about 3000 mm rainfall).

Table 20.10 Streamflow reduction at Jonkershoek (van Wyk 1987)

Catchment	Area (ha)	Forest (%)	Rainfall (mm)	Age at start of reduction	Age at peak reduction	Streamflow reduction (mm/year)
Bosboukloof	200	57	1300	7	19	197 (33%) between ages 16 and 40
Biesievlei	27	98	1430	3	14	313 (47%) between ages 16 and 32
Tierkloof	157	36	1800	3		171 = mean between ages 16 and 24
Lambrechtsbos B	65	84	1470	4		185 after age 16
Lambrechtsbos A	31	89	1410	3		168 after age 8

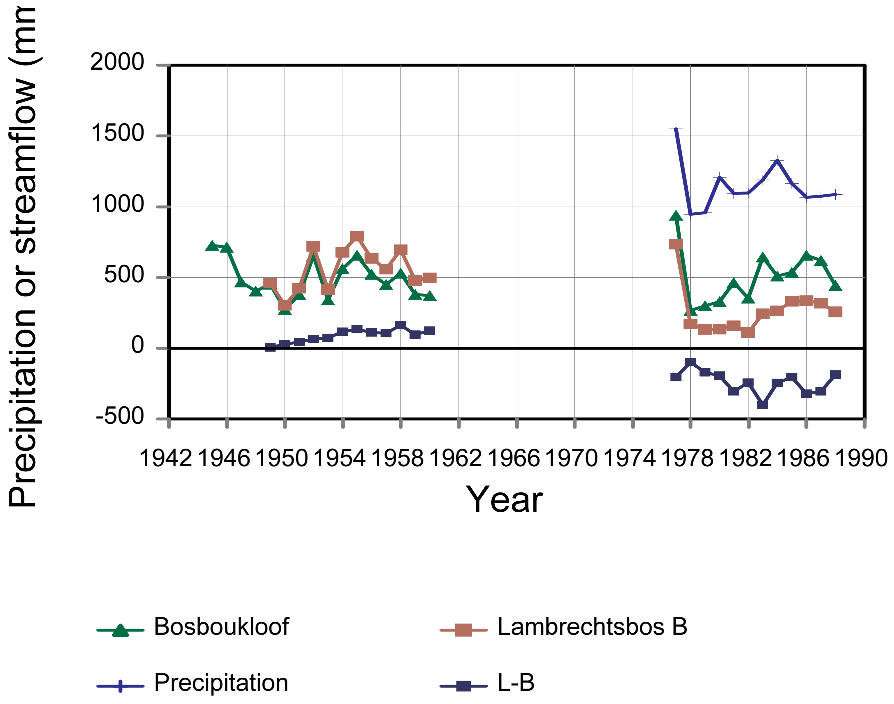

Fig 20.9 Streamflow from Lambrechtsbos B and Bosboukloof at Jonkershoek. Early data calculated from Banks & Kromhoult (1963), later data from (Scott 1997)

20.5 Conversion of native forest

Nelson – Donald Creek

At Donald Creek in Nelson, native forested catchments were cleared and planted in radiata pine in 1981; the treatments are given in Table 20.11

Table 20.11 Treatments applied to the Donald Creek catchments, Nelson (from Fahey & Jackson 1997)
.

	DC1	DC2	DC3	DC4
Area	8.57	4.74	7.48	20.19
Harvested	1980: 83% using tractor based methods	None – control	Selection harvest	1980–1981: 94% using cable systems
Before plant preparation	Part burned Rootraked			None
Planted	Sept 1981 1250 SPH			Sept 1981 1250 SPH
Thinned	1986/87 600 SPH			1986/87 600 SPH

Water yield differences extracted from a figure in Fahey & Jackson (1997) are shown in Table 20.12 and Fig. 20.10. In the 4 years after 83% clearfelling of DC1 streamflow increased 312 mm/year (61%) and at the 94%-cleared DC4 catchment the yield was 344 mm/year higher (90%). These are proportionally equivalent to 375 and 365 mm on a 100% clearfelling basis (LKR). After this, there was a decline in flows to pre-harvest levels after about 8 years.

Table 20.12. Differences in annual water yield (mm) between control catchment DC2 and treated catchments DC1 and DC4.
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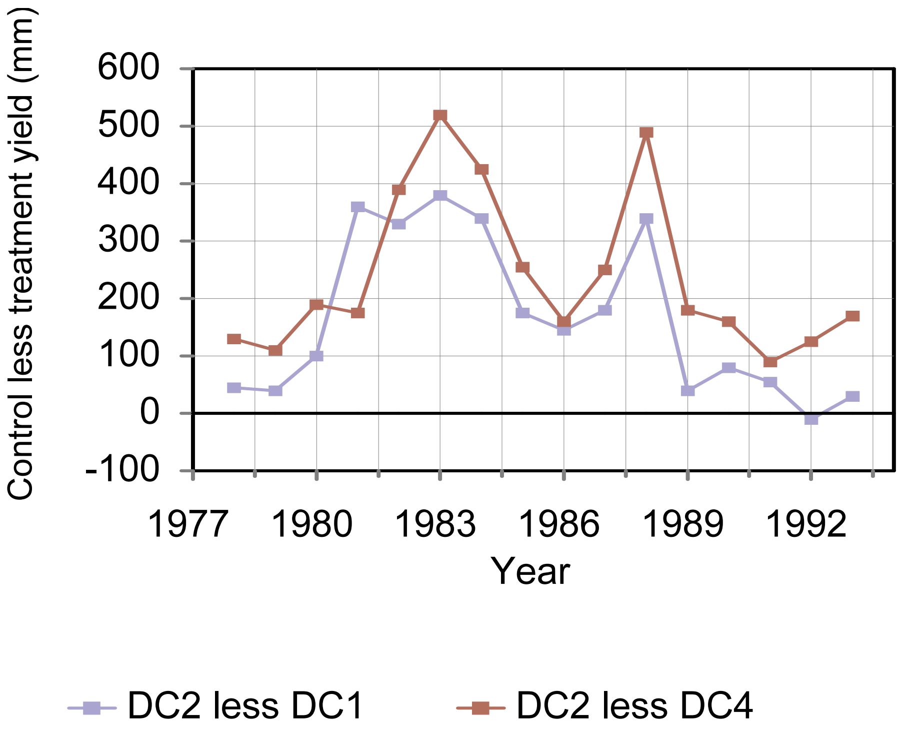
Year	DC2 less DC1	DC2 less DC4
1978	45	130
1979	40	110
1980	100	190
1981	360	175
1982	330	390
1983	380	520
1984	340	425
1985	175	255
1986	145	160
1987	180	250
1988	340	490
1989	40	180
1990	80	160
1991	55	90
1992	−10	125
1993	30	170



Fig, 20.10 Difference in streamflow between the Donald Creek control catchment (DC2) and treated catchments DC1 (83% harvested) and DC4 (94% harvested).

West Coast – Maimai

A similar study was begun a few years earlier than the Donald Creek study, at Maimai on the West Coast (Rowe et al. 1994). Early results were reported by Pearce (1980), Pearce et al. (1982), Rowe & Fahey (1988; 1991) with the main analysis of annual yields being reported by Rowe & Pearce (1994). The eight small, steep, south-west-facing catchments (1.63–8.26 ha) were monitored from 1974. Two catchments were retained as native mixed evergreen forest and the rest were subjected to various harvesting and land preparation techniques (clearfelling, slash burning, herbicide treatment, riparian protection) before being planted with *P. radiata* between 1977 and 1980 (Table 20.13). Annual rainfall is of the order of 2450 mm.

Table 20.13 Maimai catchments, Reefton, December 1974 to November 1975

	M5	M6	M7	M8	M9	M13	M14	M15
Area (ha)	2.31	1.63	4.14	3.84	8.26	4.25	4.62	2.64
Pretreatment runoff 12/74 to 11/75 (mm)	1578	1532	N/A	1213	N/A	1775	1948	1355
Year of harvest	1978	N/A	1976	1978–9	1976–7	1978	1977–8	N/A
Extraction method	Cable		Cable	Cable	Tractor	Cable	Cable	
Burning	No		1977	1980	1978	None	1978	
Planting	1978		1978	1980	1978	1979	1978	
Riparian reserve (%)	No		0	5	25	0	0	

An early estimate of the effects of harvesting M7 and M9 was made by comparison with M6 and M8 (Pearce 1980; Pearce et al. 1982). Estimates of the pre-harvest flows were made by regression analysis using M6 and M8 data as none were available for M7 and M9. These were used to find the treatment effects, which were 650 mm/year for M7 and 540 mm/year for M9, the smaller increase for M9 being a result of it only being 75% harvested. Actual streamflow data for a period of 19 months post-harvest is in Table 20.14.

Table 20.14 Streamflows for the 19 months after harvesting Maimai catchments M7 and M9
.

	M6 unlogged	M7 100% logged	M8 unlogged	M9 75% logged
Rainfall	3055	3055	3055	3055
Streamflow	1500	2635	1605	2460

In the main catchment experiment, increases in streamflow following harvesting were variable, but in the year after treatment there was an increase usually between 200–250 mm, except for one treatment (M5, clearfelling, herbicide application, no riparian reserve) where the increase was 550 mm. The catchments were planted with *P. radiata*, but rapid colonisation by bracken (*Pteridium esculentum*) and Himalayan honeysuckle (*Leycesteria formosa*) led to a rapid decline in stream flow, which returned to pretreatment levels after an average of about 5 years. Streamflow yields then continued to decline for another 2–3 years before stabilising at a level about 250 mm/year lower than pretreatment levels, at which time the catchments had a dense bracken/honeysuckle understorey beneath 5-m-tall *P. radiata*. Annual rainfall and streamflow for the catchments are listed in Table 20.15 and the differences between streamflow from the treated and control catchments showing the trends after harvesting are shown in Fig. 20.11. Significant regression relationships were developed for determining the expected diminishing yields as the catchments recovered after treatment, but these were variable and inconsistent with the perceived severity of treatment.

Table 20.15 Rainfall (UM & LM) and streamflow for Maimai catchments (mm)

Year	M5	M6	M8	M13	M14	M15	LM	UM
1977	1306	913				806	1888	1840
1978		1075				1069	2138	2087
1979	2441	1419		2040		1297	2625	2462
1980	2624	1775	2029	2216		1538	2827	2711
1981	2058	1363	1687	1779	1615	1323	2482	2356
1982	1745	1070	1414	1522	1335	1119	2253	2144
1983	2322	1688	1991	2082	1863	1633	1996	2735
1984	1919	1324	1597	1636	1417	1261	2468	2303
1985	1374	1130	1229	1324	1325	1160	2193	2107
1986	1418	1250	1250	1396	1334	1167	2247	2133
1987	1818	1554	1654	1731	1674	1446	2668	2461
Mean		1324				1256	2435	2304

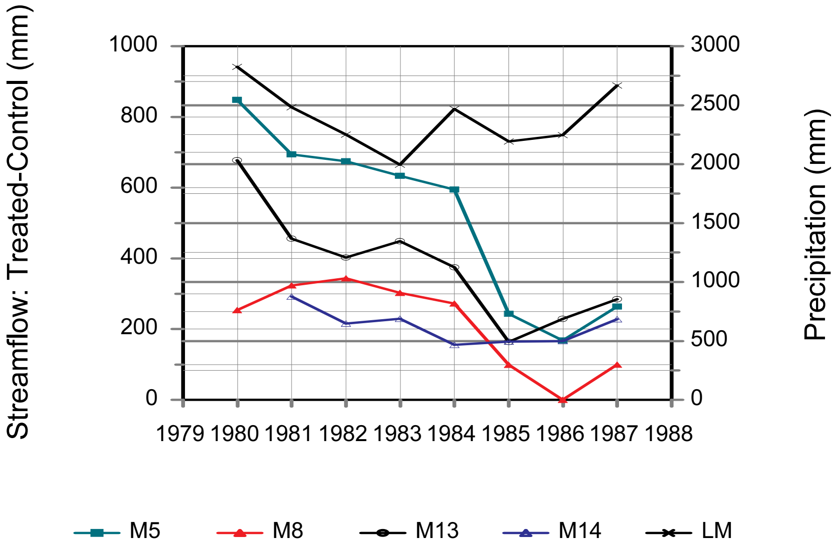


Fig 20.11 Difference between streamflow measured at Maimai control catchments (M6 for M5 and M8; M15 for M13 and M14) and the treated catchments.

Australia – Cropper Creek, Victoria

Hopmans et al. (1987), Leitch & Flinn (1986), and Bren & Papworth (1991, 1993) present data following the felling of a native eucalypt forest and its replacement by radiata pine plantation. Annual rainfall is about 1400 mm and streamflow from a eucalypt catchment is about 375 mm. Streamflow was available for 4 years prior to harvest and 7 years after planting radiata pine. Bren & Papworth (1993) give the increase in streamflow for the years after planting relative to the pre-harvest conditions. The increase in flow the first year after harvesting was estimated to be 350 mm (Table 20.16). By year 8 this had diminished to about 100 mm more that the native forest, which implies a decrease in flow through afforestation of 250 mm. No annual rainfall data are given.

Table 20.16 Estimated annual flow increase after harvesting eucalypt forest at Cropper Creek, Victoria, Australia.

Year	Flow increase (mm)
1	350
2	230
3	30
4	310
5	170
6	160
7	120
8	80

Australia – Lidsdale, New South Wales

A number of papers describe changes that have taken place at Lidsdale in New South Wales as a number of catchments were converted into radiata pine plantations (Smith et al. 1974; Pilgrim et al. 1982; Putahena

& Cordery 2000). Lidsdale has the longest published dataset of the Australia studies and, of the papers published, Putuhena & Cordery (2000) provide the most extensive information, with catchment L6 (9.4 ha) having been monitored for 27 years – 11 years before and 16 years after the conversion of a eucalypt forest to radiata pine. Rainfall in the region averaged 775 mm/year and ranged between 416 mm and 1124 mm (Fig. 20.12). As a consequence of harvesting, streamflow is estimated to have increased by about 200 mm/year. This increase diminished over the next 6 years so that yields were similar to those expected from a eucalypt catchment and decreased further thereafter, so that for the last 8 years flows averaged 35 mm less than the eucalypt and afforestation could be said to cause a drop in streamflow of about 225 mm per year in that environment.

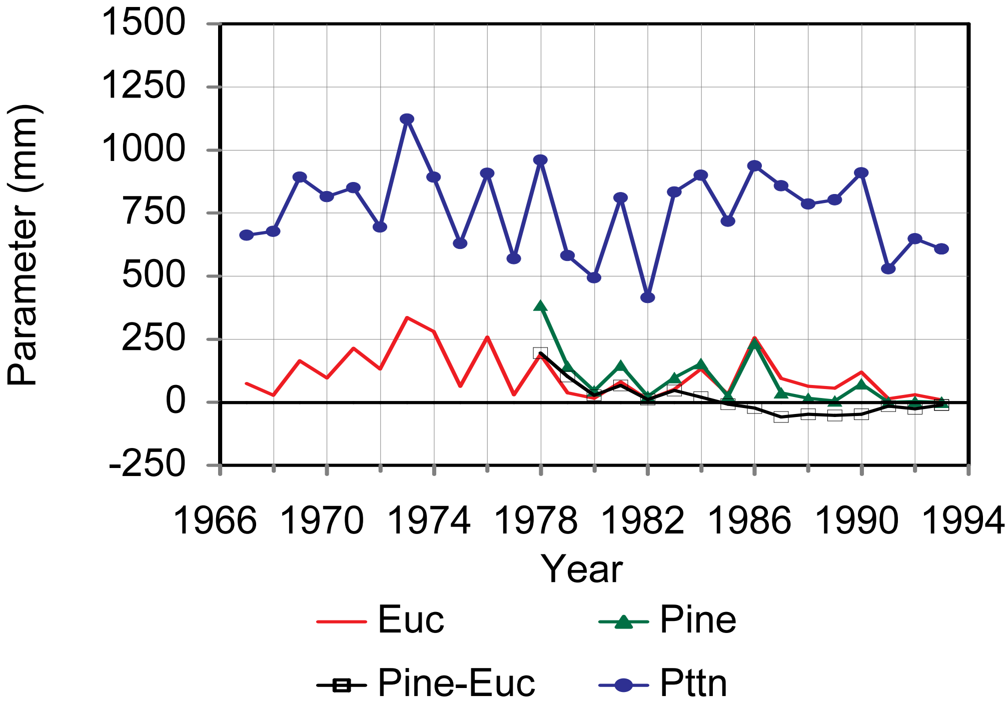


Fig. 20.12 Precipitation, streamflow and evaporation for Lidsdale catchment L6. The eucalypt- forested catchment was harvested in 1977 and planted in radiata pine.

Australia – Stewarts Creek, Victoria

Nandakumar et al. (1991) report on the conversion of a eucalypt forest to radiata pine plantation at Stewarts Creek in Victoria. Catchment 5 was cleared of native forest in May 1969 and planted in April 1970. A comparison with Catchment 4 in native eucalypt forest shows an increase in streamflow averaging 255 mm/year in the 5 years after clearing, which diminished over time (Table 20.17).

A subsequent paper (Nandakumar & Mein 1993) gives more detailed data (Fig. 20.13) showing an increase in runoff of about 360 mm the year after harvesting. This increased runoff slowly fell over the next 20 years back to the levels of the eucalypt forest (Fig 20.13). A generalised, fitted equation for the increase in flow after t years after the maximum increase observed was

$$\Delta = I_{max}*\{ - (1/L_t)*Log(t)\}$$

where I_{max} is the maximum increase in flow (used 296 mm) and L_t is the log of time in years from the year of maximum increase to the year of zero increase (1.30) and t = time in years after the maximum increase (20 years).

Table 20.17 Streamflow from Stewarts Creek Catchments 4 (native forest) and 5 (pine plantation)

			Catchment 4		Catchment 5	
Period	Catchment 5 vegetation	Precipitation (mm)	Runoff (mm)	P–R (mm)	Runoff (mm)	P–R (mm)
1960–1969	Native forest	1129	201	928	178	951
1970–1975	Regenerating scrub with pine seedlings	1254	275	979	530	724
1976–1980	Pine	1030	173	857	258	772
1981–1985	Pine	1080	167	913	207	873
1986–1989	Pine	1230	310	920	291	939

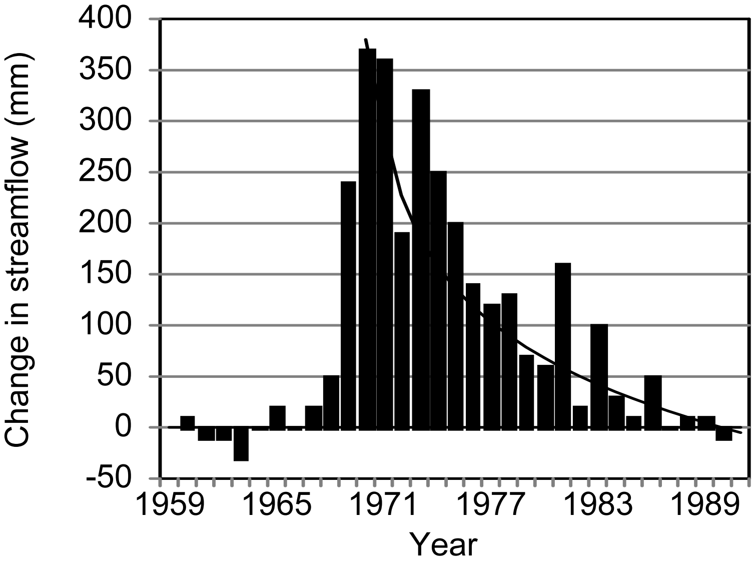


Fig. 20.13 Change in streamflow at Stewarts Creek, Victoria, after harvesting in 1969. Data extracted off a graph in Nandakumar & Mein (1993).

20.6 Scrub to pasture

Northland – Puketurua

At Puketurua in Northland 250 ha of manuka scrubland was burned in February 1971, disc-cultivated for about a year and planted in pasture between March and May 1972. Grazing began in July 1972. By winter 1973 the vegetation cover was 83% pasture, 4% native bush, 12% gorse/bracken/manuka regeneration. Early streamflow data presented by Schouten (1976) are listed in Table 20.18.

Table 20.18 Precipitation and runoff at Puketurua before and after scrub clearance in 1971–1972. (Schouten 1976).

Year	Precipitation (mm)	Runoff (mm)
1966	1685	824
1967	1433	565
1968	1849	985
1969	1352	612
1970	1238	507
1971	1570	929
1972	1297	743
1973	1017	480
1974	1219	709

Regression analyses by LKR on the annual precipitation–streamflow data for before treatment and the next 4 years produced highly significant relationships, but they could not be considered different because the confidence limits on the intercept and regression coefficients overlapped, an artefact of the small sample size. The two regression lines are offset by about 200 mm (Fig. 20.14), which is a bit higher than the 150 mm change for the same period predicted by regression from streamflow at the Opahi, a similar catchment 43 km away (Waugh 1980). When the treatment/post-treatment was extended to 7 years, Waugh (1980) suggested that streamflow had fallen to about pretreatment levels.

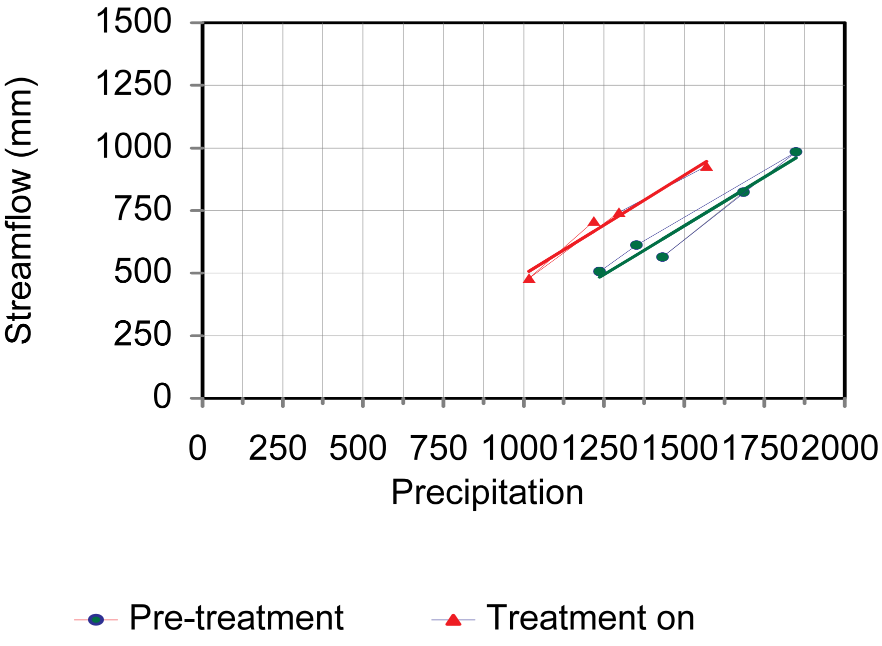


Fig. 20.14 Relationship between precipitation and streamflow at Puketurua before and after conversion of scrub to pasture

Nelson – Moutere

Duncan (1995a) presents annual streamflow data for catchment 14 (see Table 20.5 for catchment parameters), which was converted to pasture from gorse and later planted in radiata pine. From his prediction equation to estimate catchment 14 streamflow from control catchment 5 streamflow, there is a difference of about +250 mm in the first year after clearing of the gorse (Fig. 20.4) that can be attributed to the clearance.

20.7 Scrub to cropping

Also from Moutere is the only published example of the effects of crop establishment on water yield (Scarf 1970). Catchments 2 (4 ha) and 5 (7.6 ha) were maintained in pasture and were mob-stocked while catchment 10 (4.5 ha) was converted from gorse to cultivation and cropping in 1965.

From the annual streamflows in Table 20.19, the trend in streamflow before and after cultivation is shown in Fig 20.15. The differences between the two periods indicates that streamflow from cropping is about 130 mm more than from the gorse covered catchment. After treatment at C10, there was a decrease in the number of days of flow, 19% vs 25%, while the reverse occurred at control catchment 5, 76% vs 66%. Flood peaks increased at C10 after cultivation, but for peaks in excess of 15 mm/hour(= 42 L/s/ha) there was little or no change, which was interpreted as "indicating that vegetation cover is relatively ineffective in reducing peak discharges during severe storms" (Scarf 1970).

Table 20.19 Precipitation and runoff (mm) at Moutere

Year	Catchment 2		Catchment 5		Catchment 10	
	Precipitation	Runoff	Precipitation	Runoff	Precipitation	Runoff
1962 [1]	1099	530	1099	724	1099	323
1963	1038	205	1038	272	1038	88
1964	1191	247	1191	270	1189	56
1965	822	132	824	130	825	62
1966	1105	109	1083	288	1124	153
1967	1016	332	1052	299	1076	215
1968	1129	326	1119	288	1150	177

[1] 1962 data, May to December only.

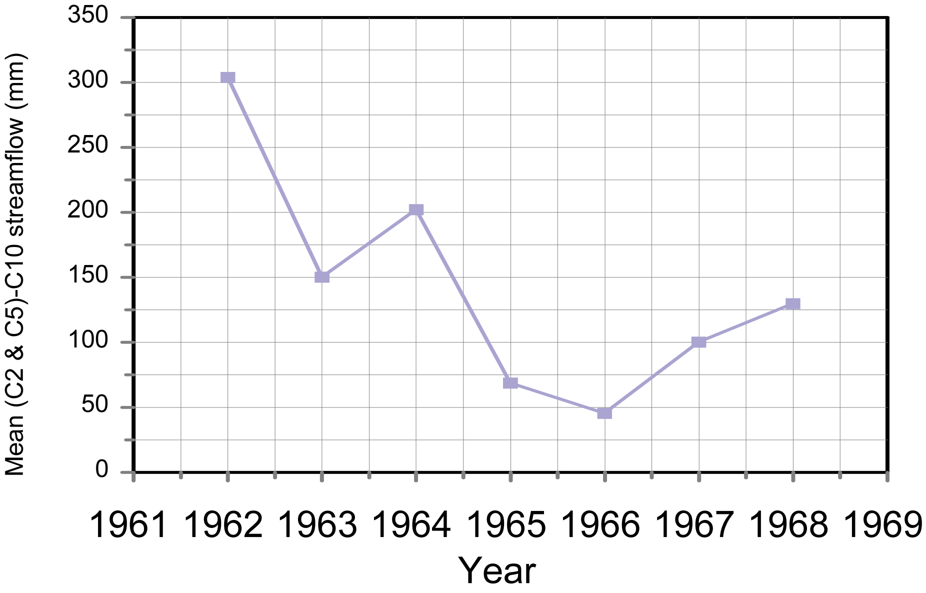


Fig 20.15 Difference between the mean of the annual streamflow at catchments C2 and C5 and streamflow from C10 at Moutere. Conversion from gorse to cropping took place in 1965.

20.8 Pasture management

The suite of small experimental catchments established at Makara near Wellington is one of only two studies investigating the effects of grazing practices on streamflow from pasture catchments in New Zealand (Table 20.20).

Table 20.20 Makara catchment treatments and annual water yields (mm)

Catchments	Grazing level	Pasture status	Mean annual runoff (calibration period)	Mean annual runoff (evaluation period)
2 & 8	Hard	Unimproved	167	149
1 & 5	Hard	Improved	178	105
3 & 4	Lax	Unimproved	191	147
6 & 7	Lax	Improved	184	99

Conclusions from papers by Toebes et al. (1968), Yates (1964, 1971), Wilkie et al. (1965) were that the reductions in flow with treatment as predicted from a control catchment (catchments 2 or 8) were as follows: improved pasture/lax-grazed 22.5%; improved pasture/hard-grazed 9.8%, unimproved pasture/hard-grazed 5.2%; unimproved pasture/lax-grazed 1.9%. In storms of less than 25 mm, the effect was more significant with reductions in runoff of the following: improved pasture/lax-grazed 92%; improved pasture/hard-grazed 71%, unimproved pasture/hard-grazed 47%; unimproved pasture/lax-grazed 43%. In storms greater that 25 mm, the picture was not as clear with some treatments having an increase in flow, and one a decrease.

20.9 Forest management

New Zealand

Thinning of radiata pine catchments has been demonstrated to provide a temporary respite to the trend of diminishing yields as plantations become established. This is illustrated well in examples shown earlier where the Donald Creek catchments in Nelson were thinned 4–5 years after planting and streamflow rose about 200 mm more than expected (Fig. 20.10; Fahey & Jackson 1997). Duncan (1995a) suspected that thinning of catchments at Moutere also had an effect but the severe drought that occurred at the same time complicated the issue.

South Africa

A paired-catchment method was used to test for the effects of thinning on the water yield in three afforested catchments in South Africa: Biesievlei, Jonkershoek, 98% afforested with *P. radiata* (3 thinnings). During and after two separate thinnings, each of which removed roughly one-third of the stems in a maturing *P. radiata* plantation in the Biesievlei catchment, annual streamflow increased by between 10% and 71% (19–99 mm). These increases persisted for 3 and 2 years after the thinning, respectively (Lesch & Scott 1997). A final thinning in the same catchment removed only 22% of stems at an age of 28 years. The following years (1977 and 1978) were wetter than average, and reductions in annual streamflow of 26% and 55% were recorded in these 2 years.

20.10 Douglas Fir

Water yields – natural forests

Changes in water yields as a consequence of harvesting old-growth Douglas fir forests in North America are presented in this section for completeness. Although not directly comparable to harvesting New Zealand plantations, the results could provide an indication of water use by Douglas fir. Table 20.21 presents annual runoff data from a number of studies from Douglas fir and mixed Douglas fir forests.

Table 20.21 Annual flows from predominantly Douglas fir watersheds in Canada and the United States

Catchment	PTTN (mm)	RO (mm)	ET=PTTN − RO (mm)	Source
British Columbia	2670	1700	970	Feller & Kimmins 1979
Haney A	1820	1010	810	
British Columbia				Feller & Kimmins 1979
Haney C	2040	1040	1000	
Oregon	2520	1700	820	Fredriksen 1972
HJ Andrews 10	2150	1350	800	
Oregon	2190	1280	910	Harr et al. 1982:
HJ Andrews 8				16-year means
Oregon Alsea: Flynn	2520	1970	550	Harris 1973, 1977
Oregon Alsea: Needle	2480	1890	590	
Oregon Alsea: Deer	2480	1910	570	

Many harvesting studies have been done in the United States and Stednick (1996) has reviewed the annual water yield changes found. Table 20.22 has the Douglas fir studies listed in his paper. The maximum streamflow increase usually was in the first year after harvest but this sometimes happened later as a reflection of the rainfall regime over that time period. The data in Stednick's table sometimes differ from other author's interpretations as shown in some of the more detailed descriptions later in this report.

Table 20.22 Maximum increase in streamflow in the first five years after harvesting Douglas fir and Douglas fir/mixed forest (Stednick 1996)

Catchment	Area	MAP (mm)	Streamflow (mm)	% Cut	Streamflow increase (mm)
Coyote Creek #1	69	1230	630	50	60
Coyote Creek #2	68	1230	630	30	119
Coyote Creek #3	50	1230	630	100	360
Fox Creek #1	59	2730	1750	25	0
Fox Creek #3	71	2730	1750	25	0
Deer Creek	303	2480	1910	25	150
NeedleBranch	71	2480	1885	82	615
HJ Andrews #1	96	2390	1380	100	462
HJ Andrews #3	101	2390	1380	30	297
HJ Andrews #6	13	2150	1290	100	425
HJ Andrews #7	21	2150	1290	60	240
HJ Andrews #10	96	2330	1650	100	400

Harr et al. (1982) reported increases in streamflow after logging 130-year-old Douglas fir in two small watersheds at the H J Andrews Experimental Forest watersheds in western Oregon. Increases in annual water yield were up to 420 mm in the first years after harvest. Average yield increases of the first 4 years were 380 mm in a 13-ha clearfelled catchment (HJA6) and 200 mm in a 15.4-ha catchment (HJA7) where a shelterwood felling removed 60% of basal area. Both catchments were harvested in 1974 and then burned in 1975. The annual streamflow totals are shown in Fig 20.23.

Also from HJ Andrews, Hicks et al. (1991) reported that clearfelling HJA-1 over 5 years followed by burning resulted in increased water yield by up to 520 mm/year averaging 370 mm for the first 8 years. Over the next 8 years the average increase was about 285 mm and was continuing to stay at about that level. This was in contrast to the 25% patch-cut and burning operation in HJA-3 where streamflow yield increased up to 200 mm/year and steadily fell towards preharvest levels over the next 20 years. Rothacher (1965, 1970) had previously reported early post-harvest changes.

Table 20.23 Streamflow (mm) at HJ Andrews experimental watersheds (Harr et al. 1982). HJA-6 was 100% clearfelled the burned ; HJA-7 had 60% BA removed and then burned; HJA-8 was not treated.

Year	PTTN (mm)	HJA-6	HJA-7	HJA-8
1964	2040	1320	950	1150
1965	2730	1700	1280	1570
1966	1720	1040	680	880
1967	1880	1170	820	1070
1968	2160	1100	720	1000
1969	2310	1740	1210	1540
1970	1990	1250	890	1150
1971	2820	1940	1300	1750
1972	2810	2310	1620	1900
1973	1600	720	550	680
1974	2900	2530	1710	2140
1975	2160	1960*	1260**	1350
1976	2570	2090*	1420**	1480
1977	1250	730*	470**	420
1978	2440	1920*	1280**	1350
1979	1750	1560*	970**	1120
Mean	2190			1280

Notes: * = clearcut; ** = shelterwood cut.

Coyote Creek experimental watersheds, Oregon, have a vegetation cover of mixed conifers with Douglas fir, pines and cedar, a mean annual precipitation of 1145 mm, and mean annual runoff from control catchment CC-4 of 627 mm. When harvested, increases in streamflow up to 360 mm were measured in the first 5 years with the magnitude depending on annual precipitation and degree of harvest (Table 20.24) (Harr et al. 1979).

Table 20.24 Changes in streamflow at Coyote Creek after harvesting Douglas fir (Harr et al. 1979)

	CC-1	CC-2	CC-3
Area (ha)	69.2	68.4	49.8
Area harvested (%)	100	30	100
Type of cut	Shelterwood cut (50% of BA removed)	Patchcut	Clear-cut
Increase in flow years 1–5	10–90 mm	70–120 mm	230–360 mm

In another Oregon study at Alsea, Harris (1973, 1977) indicated a 480 mm average increase in streamflow in the first 7 years after clearcutting the Needle Branch catchment and for the same period only a 28 mm increase in the 29% cut Deer Creek. Flows were still elevated 7 years after harvest.

20.11 Models for predicting reductions in flow

South Africa – Jonkershoek

Scott & Smith (1997) presented a number of empirical models to predict reductions in total and low flows resulting from afforestation. These equations were determined from paired catchment studies in South Africa, some from the afforestation experiments at Jonkershoek. Curves were also developed to predict the effects of afforestation under optimal and sub-optimal growing conditions.

The curves were sigmoidal relationships for the percent reduction in flow (and low flow) with time since planting:

$$Y = A/(1+Be^{nX}) , \qquad 20(10)$$

where Y = % flow reduction, A = asymptote = maximum Y, B intercept, X = plantation age in years, n = exponent. The optimal land classes had deep soils and a tropical climate compared to the sub-optimal classes with shallow soils and less favourable climate.

There was an obvious precipitation influence but no data were given to isolate this as these predictions were for average conditions. The low-flow period is those months below the 75th percentile of monthly flows – none in some years.

An alternative method for the same region had been presented earlier by van Wyk (1987). He presented a simpler linear model:

$$Qadj = Qt - b \times [(PTTN - PTTN_{mean}) \text{ or } (Qc - Qc_{mean}] \qquad 20(11)$$

where		
	Qadj	adjusted streamflow
	Q	annual streamflow of treated catchment
	b	regression constant
	PTTN	annual weighted catchment precipitation
	$PTTN_{mean}$	annual mean weighted catchment precipitation
	Qc	annual streamflow from the control
	Qc_{mean}	annual mean streamflow from the control.

New Zealand – West Coast, Maimai

For the four harvested native-forest catchments that were replanted in radiata pine at Maimai on the West Coast, Rowe & Pearce (1994) fitted relationships between measured streamflow with time since planting and precipitation of the form

$$Q = a + b \text{ x } \log Y + c \text{ x } PTTN \qquad 20(12)$$

where Q = the predicted annual streamflow
a, b and c were coefficients
logY = $\log_{10}$ of the years since planting, and
PTTN = is a precipitation estimate.

There was a wide range in the coefficients determined (a: −160 to −640; b: −53 to −770; c: 0.89 to 1.06) that reflected the inherent differences in streamflow from the small catchments and the range of treatments that were applied. There was, however, no correspondence between the size of the coefficients and the perceived degree of severity of the treatments.

20.12 Conclusions

The annual water yield data presented in Section 20.1 provide a cautionary note to interpretation of non-paired information. Average annual yield from a number of pasture catchments throughout New Zealand averaged about 35% of associated annual precipitation, from pine forests streamflow was a similar percentage, and native forest catchments averaged about 42% of precipitation. This is an unlikely scenario as streamflow from pasture catchments is generally higher than for equivalent forested catchments. When paired catchments are considered, annual streamflows from pine-forested catchments and native forests were similar, and were 63% and 73%, respectively, of that from pasture catchments.

Relationships between annual streamflow and precipitation for catchments from the three vegetation classes, although statistically significant, had very wide confidence limits making them unreliable in practice and, in one case, implied that more streamflow could be generated than an increase in precipitation input could provide.

Streamflow changes immediately after a land-use change at one or more of a set of paired catchments are presented in Table 20.25. The increases following harvesting native forest were the largest but these were generally for wetter areas than for scrub manipulation. Two decreases in flow were noted, one being scrub clearance, and both could be attributed to improved pasture establishment and increased interception processes, especially at Waiwhiu in Northland.

Table 20.25 Early annual streamflow yield changes as a result of vegetation change, excluding afforestation.

Catchment	Vegetation change	MAP (mm)	Years	Change in streamflow (mm)	Equivalent for 100% change (mm)
Northland – Waiwhiu	18% scrub burned 29% grazing ceased	2110	3	−530	−1100
Northland – Puketurua	100% scrub to pasture	1270	5	+200	+200
Nelson – Moutere C14	100% gorse to pasture	1100	1	+250	+250
Nelson – Moutere C8	100% gorse clearance	1100	2	+375	+375
Nelson – Moutere C13	100% gorse clearance	1100	2	+200	+200
Nelson – Moutere: mean of C2 & C5	100% gorse to cropping	1100	3	+130	+130
Nelson – Donald Creek DC1	83% native forest harvesting	1480	4	+310	+370
Nelson – Donald Creek DC4	94% native forest harvesting	1480	4	+340	+370
West Coast – Maimai (4 catchments)	80–100% harvesting native forest	2450	2	+250–550	+250–550
Wellington – Makara	pasture improvement			decrease	

A number of paired catchment studies in which one had pine plantations established are summarised in Table 20.26. Conversion of native forest to pine plantation resulted in a decrease of 250 mm/year at Maimai but no real changes at Donald Creek where the environment is 1000 mm drier. Where scrub has been converted to pine plantations in South Africa and New Zealand, there have been highly varied responses with decreases in yield of between 600 and 26 mm/year. Annual yield changes when pines were planted into pasture were 170 mm at Moutere, 320 mm at Puruki, and at Glendhu where tussock grassland was planted the yield change was 400 mm/year.

Table 20.26 Annual streamflow yield changes as a result of planting pines.

Site	Cover change	Precipitation (mm)	Change in flow (mm)	Equivalent for 100% change (mm)
Central North Island – Puruki	100% pasture to pines	1600	−320	−320
Nelson – Moutere C14	100% pasture to 8–16-year-old pines	1100	−170	−170
Otago – Glendhu	67% tussock grassland to pines	1360	−270	−400
Northland – Waiwhiu	18% scrub to pines 29% pasture to pines	1840	−280	−600
Auckland – Moumoukai	100% scrub to 3–10-year-old pines	1700	−290	−290
Nelson – Moutere C8	100% gorse to 6–15-year-old pines	1100	−100	−100
Nelson – Moutere C13	100% gorse to 6–16-year-old pines	1100	−26	−26
South Africa – Bosboukloof	57% fynbos to 16–40-year-old pines	1300	−200	−350
South Africa – Biesievlei	98% fynbos to 16–32-year-old pines	1430	−310	−320
South Africa – Tierkloof	36% fynbos to 16–24-year-old pines	1800	−170	−470
South Africa – Lambrechtsbos A	84% fynbos to 16+ year-old pines	1470	−185	−280
South Africa – Lambrechtsbos B	89% fynbos to 8+ year-old pines	1410	−170	−190
Nelson – Donald Creek DC1	83% native forest to 10+ -year-old pines	1480	0	0
Nelson – Donald Creek DC4	94% native forest to 10+ -year-old pines	1480	0	0
West Coast – Maimai (4 catchments)	80–100% native forest to 7+ -year-old pine	2450		−250

Thinning a plantation has been shown to increase streamflow yields by perhaps 200 mm at Donald Creek in Nelson, and by up to 100 mm in South Africa. These effects lasted between 2 and 3 years.

There are no studies where Douglas fir plantations have been harvested, nor established in pasture. Several United States studies on the effects of harvesting old-growth Douglas fir forests have indicated flow increases generally up to 400 mm/year for 100% harvesting but increases over 600 mm have been recorded.

21. Riparian Zones Management

The importance of forest management in the riparian zone was clearly demonstrated by Scott & Lesch (1995). The water yield gains obtained from clearfelling riparian zone vegetation in the Biesievlei catchment at Jonkershoek amounted to 1150 mm/ha cleared, which equated to a 44% increase in streamflow for clearing 10% of the catchment. This compared to a gain of only 343 mm/ha when the non-riparian zone was cleared, a 14% increase in catchment runoff for 10% of the catchment harvested.

Smith (1992) has demonstrated a change in streamflow following the planting of a riparian zone in a small, previously fully pastured catchment at Moutere in Nelson (Table 17.2). The result of afforestation was a decrease in total flow by about 5%, which was mainly in baseflow (about 45 mm/year) as there was little change in the quickflow component.

21.1 Conclusion

Planting trees in the riparian zone can result in decrease in streamflows and the decrease can be much larger than for equivalent planting on the catchment hillsides.

22. Annual Water Yields at a Large Scale

For this section a threshhold of 200 km^2 (20 000ha) has been set for consideration as a large catchment.

22.1 Tarawera River, New Zealand

Over 250 km^2 of the Tarawera catchment above Awakaponga (906 km^2) in the central North island, New Zealand, was planted in pine forest between 1964 and 1981 (Dons 1985, 1986). Between 1964 and 1981 annual, summer and winter Tarawera flows showed significant reductions of 10.9 m^3/s, 11.4 m^3/s and 9.6 m^3/s respectively. This streamflow decrease is equivalent to 380 mm and is greater than a decrease in rainfall over the period of 300 mm.

Simple flow models for the Tarawera, and two neighbouring catchments that had undergone little land-use change (Kaituna at Te Matai of 948 km^2 and Rangataiki at Te Teko of 2893 km^2), showed that about 4.5 m^3/s of the reduction, 13% of the mean flow over the calibration period, could be attributed to afforestation, while the remainder was due to decreased rainfall. A flow reduction of 4.5 m^3/s flow is nearly 160 mm/year and 560 mm over the area which has changed. The reduction attributed to afforestation was in accord with the results of small catchment studies.

22.2 Massachusetts, USA

Patric & Gould (1976) presented a discussion on how changing land-use patterns in several large watersheds in Massachusetts from the mid-to-late 1800s to the 1970s have affected streamflow. There are non-statistically significant decreases apparent in mass curves of annual flows that coincide with significant changes in land-use practices as farms were abandoned and allowed to revert to forest until the 1950s. The trend reversed in the 1950s and is attributed to urbanisation. The flow changes that occurred as reversion from agriculture to forest took place totalled 1500 mm over the 46-year period (an average 32 mm loss each year) but the decreases were not apparent until at least 50% of the watersheds had been altered. There is no indication of the amount of reversion that has occurred except to indicate that on a state-wide basis, 20% of the land might have been in forest at the beginning of the century and 65% was forested by the 1970s, nor is there an indication of the flow reduction at the end of the period.

22.3 South-eastern USA

Ten watersheds ranging in area from 2820 km^2 to 19 450 km^2 in the south-eastern USA had undergone transformation from cultivation to pasture and forest in the 1900s (Trimble & Weirich 1987; Trimble et al. 1987). They used annual streamflow–rainfall regression analysis for early and late periods (generally within 1900–1940 and 1955–1975) and double-mass analysis to determine changes in streamflow that could be attributed to afforestation. The results are show in Fig. 22.1 together with a trend-line calculated by LKR. Although this line has no statistical significance (the analysis only explained 3% of the variation in the data) it does indicate the order of magnitude of change that could be expected from a 100% change to forestry, an unlikely scenario considering that pasture farming and urbanisation must be significant land uses in catchments this size.

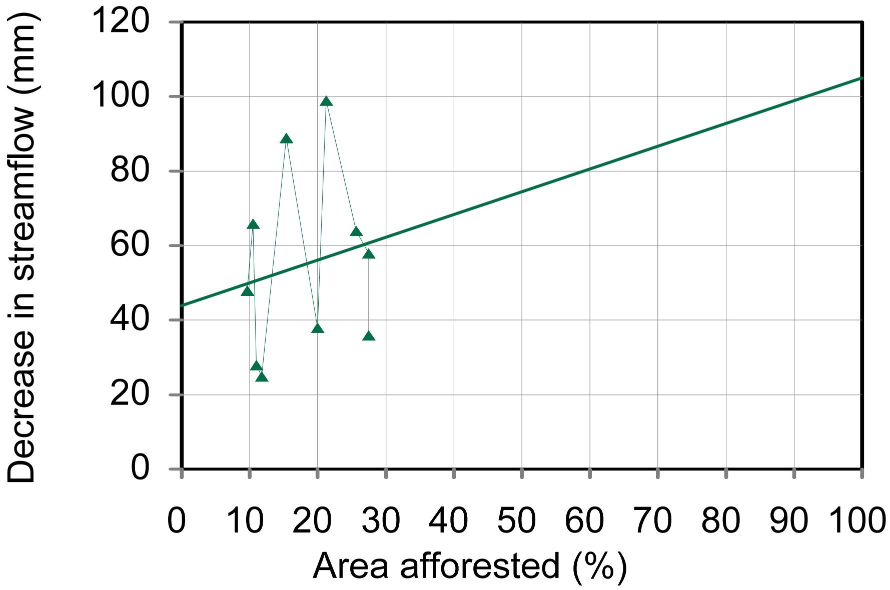


Fig 22.1 Decreases in streamflow with afforestation in large catchments in the south-eastern USA (data from Table 1 in Trimble& Weirich 1987). The trend line has no statistical significance but was added to indicate the change that might be expected for 100% afforestation.

22.4 South Africa

In the 20 000-ha Queens River catchment, forestry expanded from 12% to 55% over the period 1948–1971 (Pitman 1978). A decline in catchment streamflow of about 4.3 mm/year accompanied the rate of afforestation of 360 ha/year. At year 24, the catchment stream yield decrease was 103 mm/year for a 43% increase in afforestation, which is equivalent to 240 mm over the area afforested. No indication of the annual precipitation regime was given nor the pre-afforestation vegetation cover.

22.5 Conclusion

Changes in streamflow in large catchments as a consequence of afforestation have been observed at a number of locations throughout the world. There are difficulties with cover changes over the long-term as these are gradual and effects can be difficult to detect, both in landcover and in streamflow and precipitation trends— decrease might not be detectable until 50% of a catchment cover has changed. Trends of 240 to 560 mm/year have been observed.

23. Low Flows at a Large Scale

Duncan (1995b) has presented mean annual low-flows for the Mangakahia above Titoki. This 80 900-ha catchment has undergone afforestation of 24% between 1980 and 1995. The changes given are in Table 23.1. The paper does not give rainfall data but states that "rainfall differences between the periods are unlikely to be the cause of the this reduction in minima". If this is true, the implication is a decrease in annual minimum flow of 149 L/s, or 0.016 mm/day which equates to 0.066 mm for 100% planting.

Table 23.1 Minimum low flows (L/s) for the Mangakahia River above Titoki

	1961–1982	1983–1995
Measured mean annual low flow L/s	1447	1298 (10.8% less)

24. Peak Flows at a Large Scale

In the Deschutes River catchment in the Cascades Mountains, Washington State, 44% of the 23 200 ha of mainly Douglas fir, western hemlock and Pacific silver fir headwaters were continuously harvested over 30 years (Duncan 1986). At the end of the study 44% of the catchment was < 15 years old and all clearcuts had regenerated with Douglas fir. Similar tests were made with another catchment that was not harvested.

Duncan regressed peak flow against total storm rainfall for 67 storm events and plotted residuals against time to examine the relationship between increasing clearcut area and peak flow magnitude. A linear relationship gave a better r^2 than a power relationship, but less than half the variance could be explained by the relationships. No trends could be seen in the residuals, nor in that of the untreated catchment. This indicated that at this catchment scale and the distributed progressive harvesting regime, no effects could be detected.

Between 1940 and 1980 about 15% of the 66 800-ha Willamette River catchment in Oregon was harvested (Lyons & Beschta 1983). For 46 major storms over the last 22 years, they regressed peak flow (flows >100 m3/s = 1.5 L/s/ha) against total storm rainfall (= rainfall on the day of the peak and the two previous days) to get:

$$\text{Peak flow (cumecs)} = 7.08 \times \text{Precipitation (mm)}^{0.7784} \tag{24.1}$$

Only 38% of the variation in the data was explained by the regression, but an analysis on the residuals from the regression showed a time trend that indicated increasing peak flows. The magnitude of the increase was not given.

As referred to earlier (Section 18) there has been considerable debate in the literature on the change in peak flows after harvesting old-growth Douglas fir forests (Beschta et al. 2000; Jones 2000; Jones & Grant 1996; Thomas & Megahan 1998; and published comments). Some large catchments were included in those studies, which presented new data, re-analysed old data, and often reached differing conclusions. The reader is referred to these references for the discussion.

25. Summary and Discussion

25.1 Summary

Research into the hydrologic regime of catchments and the changes that follow as a consequence of land-cover change have been observed since at least the 1940s. The magnitude of change that occurs for a specific land-cover transition and climate, and the effects on specific parts of the hydrologic regime, have been the subject of considerable debate. Considerable folklore and myths abound concerning land use and water. We have endeavoured in this report to bring together information from the New Zealand and international literature (for radiata pine and Douglas fir only) facts relating to vegetation and water use, and the effects on streamflow of land-cover changes.

It is highly unlikely in the New Zealand context that forests will influence the rainfall regime (Section 4), or that fog (Section 5) and dew (Section 6) will be significant factors in catchment water balances.

The interception process (Section 7) is the major factor in the water balance that influences total water yields from a catchment. The New Zealand data, a subset of the worldwide data set, shows that annual throughfall under a forest canopy is larger for radiata pine (67% of rainfall) than for Douglas fir (57%) or native forest (57%) (Section 8). Throughfall under scrub cover is smallest at 48% of precipitation. Stemflow is generally a minor component of the interception process, with that from radiata pine and Douglas fir plantations being about 5% of precipitation. The few New Zealand studies have stemflow averaging higher than this for native forests (18%) and scrub cover (11%) (Section 9).

Interception loss, or wet canopy evaporation, (Section 10) rounds out the interception balance, being the difference between incident precipitation and throughfall+stemflow. Again, the average of New Zealand data is similar to that found worldwide for radiata pine and Douglas fir. Interception loss for radiata pine plantations averages 22% of precipitation whereas for Douglas fir plantations the loss is 28%, and for New Zealand native forests and scrub the loss is about 35%. For tussock grassland interception loss has been measured at 21% of precipitation, and that by pasture grasses is very rarely measured and considered negligible.

Throughfall, stemflow, and hence, interception loss data were highly variable, which probably reflects the precipitation regime of the study locations, measurement techniques, and the characteristics of the vegetation being studied. Thus, there is a potential for considerable error in making estimates for a given stand. Estimates of precision for interception loss indicate potential error of the order of 100 mm or 30%. A range of interception models of varying complexity has been developed (Section 11).

Transpiration (dry canopy evaporation) for any given land cover varies widely from season to season with annual minima for radiata pine and native forest being of the order of 0.5 mm/day in winter (Section 12). Soil moisture status is a major controlling factor on peak rates. Depending on the available soil moisture supply, peak rates in the annual cycle can occur anytime between mid-spring to late summer. It has been shown that under a well-watered situation such as when irrigation is applied, evaporation from a radiata pine stand can be as much as 7–8 mm/day in summer, but when soil moisture is limited it may be much less than 1 mm/day. Beech forest and tussock grassland can transpire up to 3.2 mm/day, and bracken up to 5 mm/day. Understorey vegetation can play a significant part in the total forest evaporation (Section 13).

There is an assumption that forests use water from much greater depths than pasture. There is evidence from New Zealand studies that pasture will extract moisture from over 150 mm down the soil profile although there is preferential extraction from the top 60 cm or so. One study under radiata pine in Canterbury showed similar water use preferences to that from pasture at a location with similar soil features. Soil water holding capacities are variable and for New Zealand soils can range between 60 and 170 mm (Section 14).

Few studies present the effects of vegetation change on low flows and measures used are diverse (Section 16). Afforestation by radiata pine has been shown to increase the number of zero flow days in regions where streams are ephemeral, increase the time flow below a given low-flow threshold, and decrease the minimum 7-day low flow of the order of 0.17 to 0.5 mm/day. Conversely, harvesting of Douglas fir and New Zealand native forests leads, in the short term, to an increase in low flows by up to 0.125 mm/day and a decrease in the number of days when flow is below a given low-flow threshold .

Annual baseflow from New Zealand catchments determined using the Hewlett & Hibbert (1967) method ranges between 15% and 39% of precipitation (Section 17). For comparable catchments, baseflow from pine catchments was 71% of that from pasture catchments. Similarly, native forest catchments had baseflow 75% of that from pasture catchments. One study showed that planting the riparian strip in a pasture catchment reduced baseflow by about a third. Seasonal baseflow has not been reported.

Storm peak reductions attributed to afforestation are of the order of 70–80% in small, frequent storms and lesser but still significant reductions in larger storms. The converse is true after harvesting native forests or old-growth Douglas fir forests, when peaks may double. Timing is also important as a given storm falling on a wet catchment may have a larger change than if the same event had occurred on a dry catchment. Urbanisation has been shown to lead to an (unquantified) increase in flood peaks (Section 18).

Stormflow, also called quickflow, is the difference between total streamflow and baseflow, and ranges between 0.5% and 21% of precipitation (Section 19). Pine stormflow from four comparable sites was 60% of that from pasture while native forest stormflow from three comparable sites averaged 78% of that from pasture. Afforestation of the riparian strip of one Moutere catchment did not affect stormflow.

Published annual streamflow yields are available for individual and paired catchments with differing land covers throughout New Zealand. These are generally short-term snapshots of up to 4 years duration. Simple averaging of non-paired data can result in misleading conclusions. For example, annual streamflow yield from a number of pasture catchments throughout New Zealand averaged about 35% of associated annual precipitation. Streamflow from pine forests was a similar percentage, and that from native forest catchments averaged about 42% of precipitation. This is an unlikely scenario as streamflow from pasture catchments is generally higher than for equivalent forested catchments. Relationships between streamflow and precipitation for a given land cover using average data from catchments throughout New Zealand were also suspect, as the regression coefficients were often greater than 1.0 implying that above the intercept threshold, more streamflow was being generated than was available from precipitation.

When paired catchments are considered, annual streamflow yields from pine-forested catchments and native forests were similar, and were 63% and 73% respectively, of that from pasture catchments.

Paired catchment studies where streamflow data are available before and after one catchment undergoes a cover change provide the most useful information. Changes are variable, but where scrub has been cleared, initial streamflow increases of up to 375 mm/year have been recorded, which is similar to that reported when native forests have been harvested. That the initial changes following scrub clearance and forest harvesting can be similar is not surprising, as interception losses and transpiration rates have been shown to be of the same order of magnitude. Most of the scrub clearance studies, mainly from gorse at Moutere, however, do show smaller increases generally between 150 and 250 mm/year. Harvesting old-growth Douglas fir forest in North America generally indicated increases up to 400 mm/year.

The converse occurs after afforestation and, again, the results are variable. Compared to scrub, mid-rotation-aged pines tend to have streamflow yields from about 100 mm to over 400 mm lower which may not be the result of interception changes alone. Conversion of native forest to pine at Donald Creek in Nelson showed no difference in yield, but at Maimai on the West Coast, where there was a dense understorey of bracken and honeysuckle, streamflow from the plantation was about 250 mm lower. Two studies of afforestation of pasture showed reduced yields of 170 and 320 mm/year and afforestation of tussock grassland a reduced yield of 400 mm/year.

Thinning operations in plantations have been shown to cause temporary (1–2 years) increases in streamflow of perhaps 100-200 mm/year. Planting riparian areas can also cause substantial streamflow reductions (Section 21).

Few studies have been reported on the effects of land cover change at large catchment scales (Section 22). Changes in streamflow in large catchments as a consequence of afforestation have been observed. However, there are difficulties with changes over the long term as these are often gradual and effects can be difficult to detect, both in land-cover and in streamflow and precipitation trends— changes might not be detectable until 50% of a catchment cover has been altered. Trends of 240–560 mm/year have been observed. At the low-flow end of the scale (Section 23), planting 24% of a large catchment in Northland decreased flow by 0.016 mm/day, or 0.066 mm/day for the whole catchmen. At the peak-flow scale Section 240 , the only information available is for harvesting old-growth Douglas fir forests, where conclusions have been equivocal.

25.2 Discussion on annual water yields

In the literature there are substantive reviews only for work on annual water yields. In the first of these, Hibbert (1967) reviewed 39 catchment experiments from worldwide sources. He concluded:
- Reduction of forest cover increases water yield.
- Establishment of forest cover on sparsely vegetated land decreases water yield.
- Response to treatment is highly variable, and, for the most part, unpredictable.

A later review by Bosch & Hewlett (1982), in which 94 catchment experiments were summarised, accepted the first two of these conclusions. They did not accept the “unpredicability” part of Hibbert’s third conclusion and made the following points relevant here:
- Coniferous and eucalypt cover type cause ~ 40 -mm changes in annual water yield per 10% change in forest cover change.
- 10% changes in brush or grasslands seem to result in ~10 -mm change in annual yield.
- Error limits cannot be set on these coefficients.
- Reductions in forest cover of less than 20% apparently cannot be detected by measuring streamflow.
- Streamflow responses to deforestation or afforestation depend both on the region’s MAP and on the precipitation for the year under treatment.
- Yield changes are greatest in high rainfall areas.

Data presented in this report for change of forest generally fit these conclusions, although that for scrub (~10 mm change in streamflow for 10% cover change) is low. Part of the reason for this is that New Zealand scrublands tend to have dense cover unlike much North American scrubland studied, and the rate of change may be closer to ~30 mm or more for a 10% cover change such as clearance.

Most New Zealand data reported are for relatively short periods following a major change in catchment cover. Therefore, effects are related to the disturbance rather than to long-term changes. Work in South Africa reported by Cornish (1989) has shown that mature plantations have a smaller effect on catchment water yields than young forests. In one example, water yield decreased after afforestation of fynbos by radiata pine peaked at 400 mm in mid-rotation and decreased to less than 300 mm approaching harvest. Reported New Zealand work (Fig. 20.4, Duncan 1995; Fig. 20.5,Fahey & Watson 1991, Fahey et al. 1998) show yield changes levelling out near mid-rotation but the data were not available to see if a reduction would be apparent in the late-rotation period.

One additional point worth noting is that variations in annual runoff associated with variations of rainfall can be considerably greater that the reductions in water yield that might occur when grassland is afforested, especially in lower rainfall regions. Constraints on land use, such as the prohibition of afforestation in important water-supply areas, offer resource managers only a limited opportunity to influence water yield; management of water storage is required to better utilise winter runoff (Jackson & Rowe 1997b).

26. Acknowledgements

Christine Bezar and Wendy Weller have had the unenviable tasks of editing and typing this report and we extend our sincere thanks to them.

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