Land Use and Water Resources: A Comparison of Streamflow from New Zealand Catchments with Different Vegetation Covers SMF2167: Report No. 6

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1. Introduction

Project 2167: Land Cover Effects on Water Availability is jointly funded by a grant from the Ministry for the Environment's Sustainable Management Fund and a number of territorial authorities and forestry companies throughout New Zealand. The purpose of the project is to provide information and tools to assist managers of water and land to make the best allocations of water resources for all end-users.

Within the project, a series of bibliographies have been prepared providing information on hydrological data for radiata pine (*Pinus radiata)* plantations, Douglas fir (*Pseudotsuga menziesii)* forests and plantations, and New Zealand land-use studies (Rowe et al. 2001a, 2001b, 2001c) and from these a summary of the effects of land-use change on the hydrology of catchments has been produced (Rowe et al. 2002).

Rowe (2003) produced a listing of catchments in New Zealand that have gauged streamflows and contain a substantial proportion of exotic plantations, either *P. radiata* or Douglas fir. In order to have a basis for assessing changes to the streamflow regime, control catchments with stable land use, either a single land use or a mix of, say, native forest and pasture, were included as were a number of raingauges. This report is an analysis of data sourced as a result of that screening process.

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. Attention has focussed 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 forests are planted, 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 often less damaging than other land uses (e.g., Phillips et al. 1990; McLaren 1996)
- 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 lead to improvements in the hydrological properties of the soil (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' rainwater to meet the biological needs of trees for growth, and downstream-users, who require water for municipal, stock-water and irrigation supplies; sustaining minimum levels in rivers for recreation; and maintaining stream habitats, especially at times of seasonally low flows. Water managers then have the unenviable task of allocating scarce resources to all users. Conflicts in the allocation process can lead to litigation.

The draft National Agenda for Sustainable Management Action Plan (Ministry for the Environment (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 be used in the preparation of such a guideline.

2.1 SMF Project 2167: Land Cover Effects on Water Availability

Two workshops in 1999, one in Nelson in March sponsored by Tasman District Council, Landcare Research, and the New Zealand Hydrological Society (Rowe 1999), and one in Rotorua in May sponsored by the 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 develop a decision support resource to enable managers of water and land 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 New Zealand plantation forests

At 1 April 2001, the New Zealand exotic forest estate covered 1.80 m ha, 6% of New Zealand's land area. *Pinus radiata* D. Don is the most common plantation species grown, comprising more than 1.61 m ha, or over 89% of the total plantation area (NZFI undated). *Pinus radiata* is commercially grown mainly in rainfall regimes between 600 mm and 2500 mm/year, and below about 1000 m altitude. Douglas fir (*Pseudotsuga menziesii*) is the next most significant species planted (103 000 ha) and is found mainly in the lower South Island or at higher altitudes, often above 1000 m. About 88 000 ha of other species are grown, including eucalypts (NZFI undated).

Between 1992 and 1999, new 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 estimate for 2001 was about 34 000 ha (NZFI undated). Most of the new plantings are on pasture land both improved (about 44%) and unimproved (about 44%), with the balance in scrubland (12%) (MAF 2000).

2.3 Sources of data

Small experimental-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 published information on the hydrology of New Zealand forests, but for *Pinus radiata* plantations or native forests, not Douglas fir plantations. Apart from Moutere and Ashley, these are in higher-rainfall areas where concerns about water yields are not high. This is in contrast to Nelson and the east coast 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. Reviews by Fahey & Rowe (1992), McLaren (1996) and Rowe et al. (1997) summarise some of these studies while books published by the New Zealand Hydrological Society (Mosley 1992; Mosley & Pearson 1997; M.P. Mosley, C.P. Pearson, J. Harding,B. Sorrell *eds* for the NZ Hydrological Society in prep.) provide good summaries of the wider aspects of New Zealand hydrology.

Sites with data related to forest and other land-use impacts have been listed in Rowe (2003). The following sections report the analysis of the more important data sets found. The data are summarised by region and include catchments operated by the territorial authorities, the National Institute of Water and Atmospheric Research (NIWA), Landcare Research (LCR) and Watercare Services. In each of the groupings, there are summaries of a particular area focussing on one or more catchments with exotic plantation. Site details have generally been sourced from Walter (2000) although other information has been provided by the recording authorities.

Land-cover information will be used to help explain observed trends in flow changes, if any. The dominant land cover in each of the catchments is shown in the tables. This has been derived mainly from 1:50 000 maps of which two editions are available for some areas. Where required, earlier 1:63 360 topographic maps were also used. TUMONZ, The Ultimate Map of New Zealand (Vision Software 2002), which contains the New Zealand Topographic database from Land Information New Zealand, has been used to provide the latest published information. In some cases the territorial authorities have provided more-accurate distributions of the various land-use categories. Where it was thought that there could be benefit from more detailed information, forest owners have been approached to provide areal coverage of their holdings and dates of planting.

2.4 Statistical tests

Statistical tests used to look for trends in the streamflow records have usually been simple non-parametric tests as hydrological data often do not meet the assumptions of normality required for standard parametric tests. The Mann–Whitney test has been used to test differences in mean values between samples, and trends have been examined using the Cox & Stuart test for trend and the Kendall's Tau rank correlation test (Conover 1980).

Regression analyses have used routines found in the statistical packages within the Corel Quattro Pro and Microsoft Excel spreadsheet programs. They have been used without regard to normality requirements as in most hydrological studies. The procedure for comparison of regression tests is that of Freese (1967).

In all cases, the significance level used is 95%.

2.5 Hydrological analyses

Annual streamflow has been reported on a calendar year basis and all results are presented in millimetres depth for direct comparison with precipitation, and with other sites. Note: to convert to flow rates, 1 mm of streamflow is equivalent to 0.1157 L/s/ha of catchment area for one day.

Annual 7-day low flow (LF7) is the average daily flow for the lowest consecutive 7-day period within any water year beginning 1 July. Mean annual 7-day low flow (MALF7) is the mean LF7 for any given period.

Mass curves are accumulated values over time for two variables plotted against each other. A straight line indicates the two variables have consistent records, whereas a change from a straight line is an indicator of an inconsistency, which may be caused by a change in land use, a shift in position of a raingauge, etc.

Precipitation normals have been taken from New Zealand Meteorolical Service (1973) for the period 1941–1970 and from Tomlinson & Sansom (1994) for 1961–1990. With the changes to Government organisations in the 1980s–1990s, site numbers for precipitation and meteorological stations have been duplicated within two databases. Stations originally operated for and the database of the New Zealand Meteorological Service (NZMetS) were taken over by NIWA and incorporated into the National Climate Database (CLIDB) in the early 1990s. Normals taken from NZMetS (1973) reference the NZMetS site numbers and ownership while those from Tomlinson & Sansom (1994) will reference the NIWA site number and ownership. Where daily and annual data have been retrieved from CLIDB, NIWA will be referenced as the source although data may have been collected for the NZMetS network.

2.6 Abbreviations

Territorial and recording authorities

ARC	Auckland Regional Council
NRC	Northland Regional Council
EBOP	Environment Bay of Plenty
ECAN	Environment Canterbury
ESTH	Environment Southland
EW	Environment Waikato
GDC	Gisborne District Council
HBRC	Hawke's Bay Regional Council
HMW	horizons.mw
LCR	Landcare Research
MDC	Marlborough District Council
NIWA	National Institute for Water and Atmospheric Research
NZMetS	New Zealand Meteorological Service
ORC	Otago Regional Council
TDC	Tasman District Council
TRC	Taranaki Regional Council
WRC	Wellington Regional Council
WCRC	West Coast Regional Council

Others

LF7	mean daily flow for the lowest consecutive 7-day period within the year beginning 1 July
MALF7	mean LF7 for any given period
NZMS	New Zealand Map Series
NZMOW	New Zealand Ministry of Works
PTTN	Precipitation

3. Northland Region

3.1 Mangakahia Suite

This suite of gauged catchments, some with a high percentage of exotic plantations, in the Northland Region is located south of Kaikohe and west of Whangarei being centred on the Mangakahia River and the Kaihu River to its east. Table 3.1 lists the catchments in this suite and their approximate land cover. Most of these catchments have a mix of exotic plantations, native forests, and pasture. The hydrological nature of this part of Northland is varied as indicated by a complex delineation of hydrological regions (Toebes & Palmer 1969).

Table 3.1 Northland Region: Mangakahia Suite catchments with land cover at 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Kaihu @ Gorge	Mar 1970		116	Native + exotic + pasture
Kaihu @ Maropiu	Oct 1958	Feb 1971	162	Native + exotic + pasture
Opouteke @ Suspension Bridge	Dec 1984		105	Exotic + native
Hikurangi @ Moengawahine	Apr 1960		189	Pasture + native + exotic
Puketurua @ Puketitoi	Jan 1964	Aug 1986	2.48	Pasture
Mangakahia @ Titoki	Feb 1983		798	Pasture + native + exotic
Mangakahia @ Gorge	Dec 1960		246	Pasture + native + exotic
Opahi @ Pond	Feb 1966	Jan 1994	10.6	Pasture + native + scrub

Kaihu River

The western-most of the catchments in this suite is the upper reach of the Kaihu River from about 25 km north of Dargaville and predominantly in the Waipoua hydrological region (Toebes & Palmer 1969). Streamflow has been recorded at two sites, the Gorge and 4.5 km downstream from there at Maropiu. Based on interpolation of 1961–1990 annual rainfall normals (Waipoua Forest 1585 mm; Waimatenui No. 2 1951 mm; Parakao 1424 mm; Mamaranui 1285 mm; Tomlinson & Sansom 1994), and NRC data for Brookvale (1970–1989 average 1780 mm) rainfall over the Kaihu River catchment would range from about 1400 mm at the Gorge gauging station to about 1700 mm at the top of the catchment with an average in the order of 1600 mm.

Maps of the NZMS-1 series (N18 2nd Edn 1967; N19 2nd Edn 1969; N23 1st Edn 1964) do not show areas of plantation forest in the Kaihu River catchment. By the late 1980s, about 14 km^2 (11%) of the catchment above the Kaihu River Gorge flow recording station was in plantation forest, the balance being predominantly native forest but including some pasture (NZMS-260: O06 1st Edn 1987; O07 1st Edn 1987; P06 1st Edn 1989; P07 1st Edn 1989). Viewing TUMONZ (Vision Software 2002) indicates little further change after the late 1980s. The vegetation change was mainly conversion of scrub and native forest.

Before closure of the Maropiu site in 1971, there was an overlapping record of about 11 months with the Gorge recorder. The result of the regression analysis of daily streamflow (in mm) from these two gauging sites is:

$$\text{Gorge} = 0.15 \pm 0.05 + 1.09 \pm 0.01 \times \text{Maropiu} \qquad SE = 0.40;\ r^2 = 0.99;\ n = 348 \text{ days} \quad (3.1)$$

This is equivalent to

$$\text{Gorge} = 54 \pm 19 + 1.09 \pm 0.01 \times \text{Maropiu} \quad (3.2)$$

for streamflow on an annual basis, which can be used to make up a synthetic annual record for the Kaihu River @ Gorge site prior to 1971.

While we now have a streamflow record of substantial length for the Kaihu River, there is no gauged catchment nearby with more or less stable land cover over the same period; the adjacent Opouteke River catchment has a record from 1987 on, the Mangakahia River catchment has undergone partial afforestation as has the Hikurangi River catchment. Puketurua, a pasture catchment, had flow measured in the early years but this was discontinued in 1986. Perhaps the best catchment to be used for comparative purposes is the Opahi Stream, 40 km north, which spans most of the Kaihu River record.

A daily rainfall record from Waimatenui No. 2 (NIWA site A53672), 19 km north of the Kaihu Gorge site, has a record that spans that of the Kaihu River. A mass-curve comparison between Waimatenui No. 2 and Dargaville (NIWA site A53982) indicates the records are reasonably consistent up until 1980. After that, there is a slight change either as a reduction in annual rainfall at Waimatenui No. 2 of 5%, which amounts to about 100 mm/year, or as an increase in annual rainfall at Dargaville of 5%. Notwithstanding this variance, Waimatenui No. 2 can provide an index against which to evaluate change; it is **not** the catchment rainfall.

Of the 40 years record at Kaihu River, 33 years were considered to be suitable for analysis of annual yields, the other years having significant missing records for which no simple and reliable estimate could be made. Standard tests (Cox & Stuart test for trend; Kendall's rank correlation test; linear regression) could not detect any trends with time in the records from Kaihu River or Waimatenui No. 2. However, the difference between the two (rainfall less streamflow) does show an increasing difference with time which would indicate increased evaporation as shown using Waimatenui as a rainfall index (Table 3.2; Fig. 3.1).

Table 3.2 Average annual streamflow (mm) at Kaihu River (Gorge) and Opahi Stream, and rainfall (mm) for Waimatenui No. 2.

Period	Kaihu River	Opahi Stream	Kaihu/Opahi	Waimatenui	Kaihu/Waimatenui
To 1980	1205	790	1.52	1900	0.65
After 1980	1090	745	1.46	2010	0.54

The reason for the change in flow regime is unclear. The shift in the mass curve of accumulated Waimatenui No. 2 rain and Kaihu River streamflow values occurred about 1980 and coincided with the change in recording authority from the former New Zealand Ministry of Works(NZMOW) Water & Soil Division, Auckland, to the (then) Northland Catchment Commission, and also the possible change in Waimatenui No. 2 rainfall. The slope change in the Kaihu River streamflow/Waimatenui precipitation ratio (Table 3.2) is equivalent to about 200 mm/year for the whole catchment, about 5 times that expected to accompany a 10% change in catchment land cover from pasture to forest (Bosch & Hewlett 1982; Rowe et al. 2002). If the catchment rainfall had not decreased as inferred from the rainfall index, Waimatenui No. 2, then the flow decrease would be even larger, possibly 250 mm/year. Furthermore, as much of the cover change has been from native forest to pine plantation, any change would be expected to be much smaller than 40 mm/year.

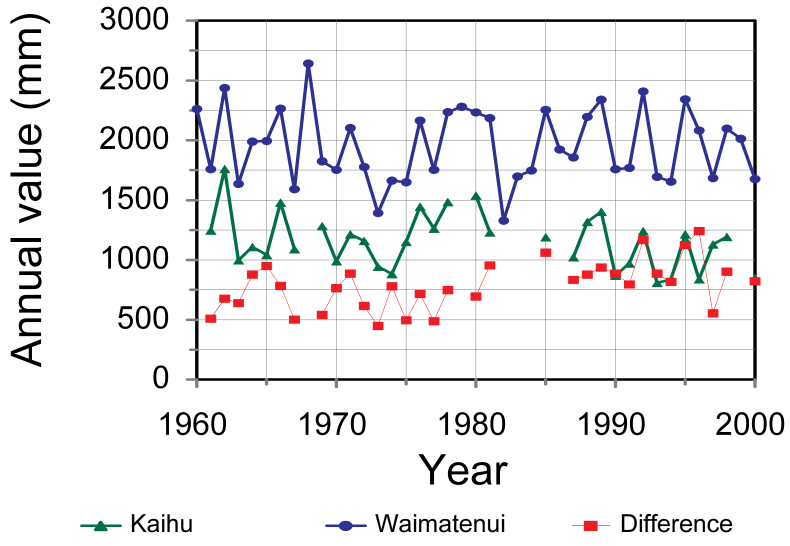

Fig. 3.1 Annual streamflow from Kaihu River at the Gorge together with annual rainfall at Waimatenui No. 2, and catchment evaporation determined as the difference between precipitation and streamflow.

An analysis between comparable streamflow from the Opahi Stream and the Kaihu Gorge (Fig. 3.2) indicated that there was no trend in either record nor in the difference between them. The inference from this is that the break in the mass curve and the difference between Waimatenui No. 2 precipitation and Kaihu River Gorge streamflow is, in fact, a rainfall aberration but different to that suggested by a comparison with Dargaville. However, the Opahi is 40 km away, has a different rainfall regime, is in a different hydrological region (the Hokianga region (Toebes & Palmer 1969)), and the mass-curve plot did show some variance about the overall trend line.

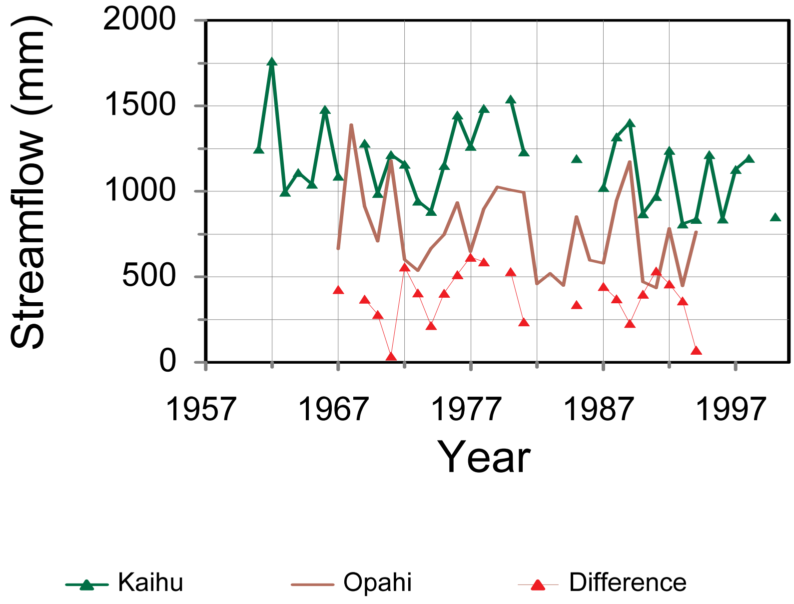

Fig. 3.2 Annual streamflow from Kaihu River Gorge together with that from the Opahi River and the difference between them.

No attempt was made to synthesise a low-flow record for Kaihu River @ Gorge prior to 1971 as the potential for errors could introduce false results. Therefore, from 1971 on, except when records were missing in some summers, the minimum mean 7-day low flow was extracted from the data. No trends were found (Fig. 3.3) although for comparable periods, the mean annual 7-day low flows (MALF7) were 0.57 and 0.03 mm/day for Kaihu and Opahi, respectively, which reflects the different hydrological regions of these catchments

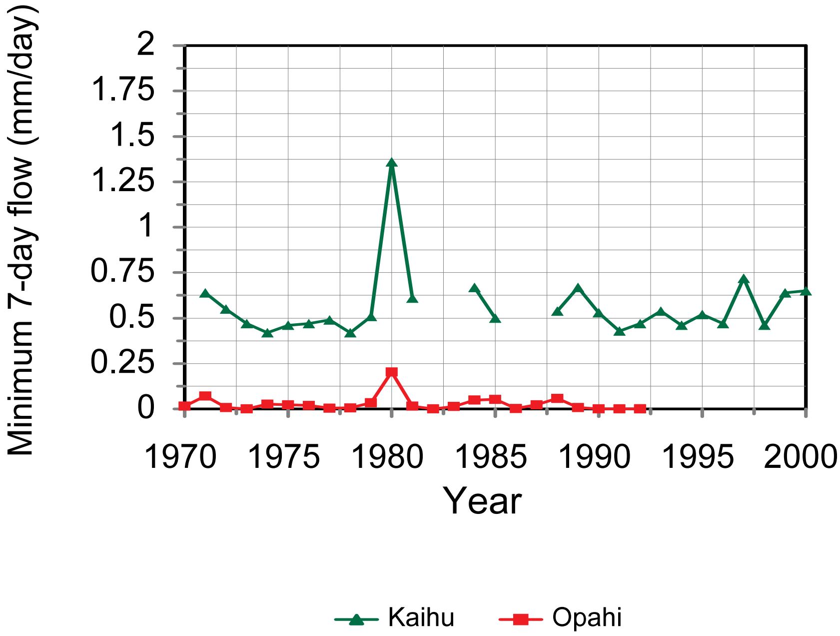

Fig. 3.3 Annual 7-day low-flow (mm/day) measured for the Kaihu River at the Gorge and the Opahi River.

Opouteke River

The Opouteke River abuts the eastern edge of the Kaihu River catchment and drains into the Mangakahia River between the Gorge and Titoki gauging stations. As for the Kaihu River, the Opouteke River is located in the Waipoua hydrological region. Interpolating the same rainfall stations used for the Kaihu River catchment indicated an approximate rainfall gradient from 1600 mm in the south-west to 1850 mm in the north-west with a catchment average of about 1750 mm.

Of the gauged catchments in this area, the Opouteke River catchment now has the most extensive area of forest, over 95%, with about 60% in exotic plantations in 1986 (NZMS-260: P06 1st Edn 1989; P07 1st Edn 1989) and limited scope for expansion thereafter as a consequence of changes in government policy. A scan of TUMONZ (Vision Software 2002) confirms there has been little, if any, change. The plantations established by 1986 were a significant change in land use as at 1969 there were no plantations present (NZMS-1 N19 2nd Edn 1969). The majority of the plantation estate was established in pasture with about 20% having been originally in scrub and native forest.

The streamflow record began at about 1986 and the vegetation cover could be considered stable over the period of record, subject to forest management operations. Unfortunately, the number of missing values in this streamflow record does not allow an analysis of trends in annual yields to be made (Fig. 3.4). However, the 10 years of records available had an average streamflow yield of 1200 mm, 69% of the assumed catchment average rainfall of 1750 mm. As a comparison, for the same years, the Kaihu River at Gorge yield was 1100 mm, 69% of the assumed 1600 mm annual rainfall, this catchment having some 55–60% pasture.

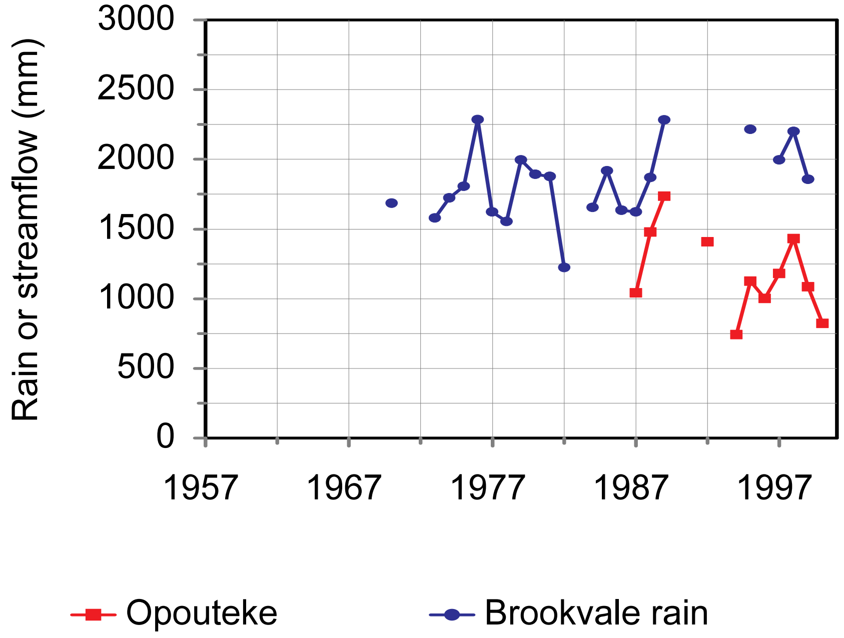

Fig. 3.4 Annual streamflow from the Opouteke River catchment and rainfall for Brookvale located near the stream gauging station.

A more complete record of low flows at Opouteke River enabled a comparison with the Kaihu River to be made, there being no detectable trend over time at the latter site. The 16-year record at Opouteke River does not show any trend with time (Fig. 3.5) and mean values were Opouteke 0.55 ± 0.09 mm/day and Kaihu 0.54 ± 0.04 mm/day.

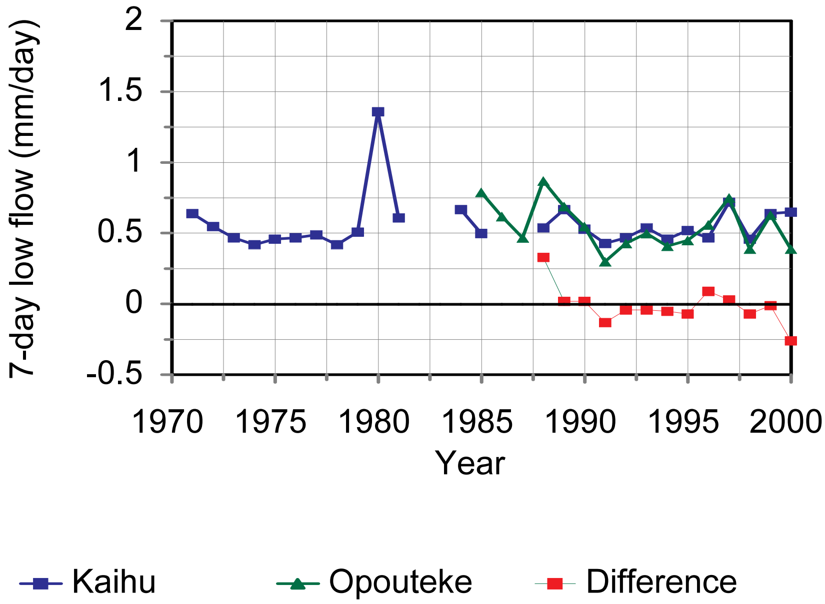

Fig. 3.5 Annual mean 7-day low flow (mm/day) measured for the Opouteke and Kaihu rivers and the difference between them.

Hikurangi River

Like the Opouteke River, the Hikurangi River enters the Mangakahia River between the two gauging stations, but is located in the Hokianga hydrological region. The streamflow record is, unfortunately, in two phases: 1961–1968 measured by NZMOW and beginning again after reinstallation by the (then) Northland Catchment Commission in1985. Rainfall at Pipiwai (NIWA site A53691) in the middle of the catchment is about 1500 mm (1941–1970 normal from NZMetS (1973) reduced by about 100 mm to bring it in line with other local 1961–1990 normals from Tomlinson & Sansom (1994)). No other streamflow record from a catchment with unchanged land cover is available for comparison over this whole period, but there is a rainfall record from Ruatangata No. 2 (NIWA site A54623; 1961–1990 normal 1670 mm), 16 km east of the Hikurangi gauging station.

The plantations established by 1986 were a significant change in land use because there were no plantations present in 1969 (NZMS-1 N19 2nd Edn 1969). Land cover in 1986 (NZMS-260: P06 1st Edn 1989; P07 1st Edn 1989) was about 43 km^2 (24% of the catchment) in plantation with pasture (c. 48%) and native forest and scrub (c. 28%) making up the balance. The majority of the plantation estate was established in scrubland (perhaps of the order of 60%) with the balance more or less evenly split between pasture and native forest. From the hydrological standpoint, the land-use change is equivalent to planting only about 5% of the total catchment from pasture.

When annual streamflow from the Hikurangi River was plotted against annual rainfall from Ruatangata (Fig. 3.6) there were no obvious differences for the two periods 1964–67 and 1989–97. This was confirmed using a Mann-Whitney test, not unexpectedly considering the small change in land cover from the hydrological standpoint. Rainfall in the catchment is likely to be higher than the Pipiwai normal would suggest, this being located in the main valley. As Ruatangata No. 2 has a normal of about 1670 mm, the Hikurangi River catchment rainfall may be closer to 1600 mm. At Ruatangata No. 2, rainfall averaged 95% and 89% of normal for 1964–67 and 1989–97, respectively. Assuming these percentages applied to the Hikurangi River catchment rainfall estimate, the average streamflow yields for the same periods at 880 and 770 mm were 59 and 54% of rainfall. This difference could not be attributed to the landuse change as there is some doubt over the rainfall base used for comparisons.

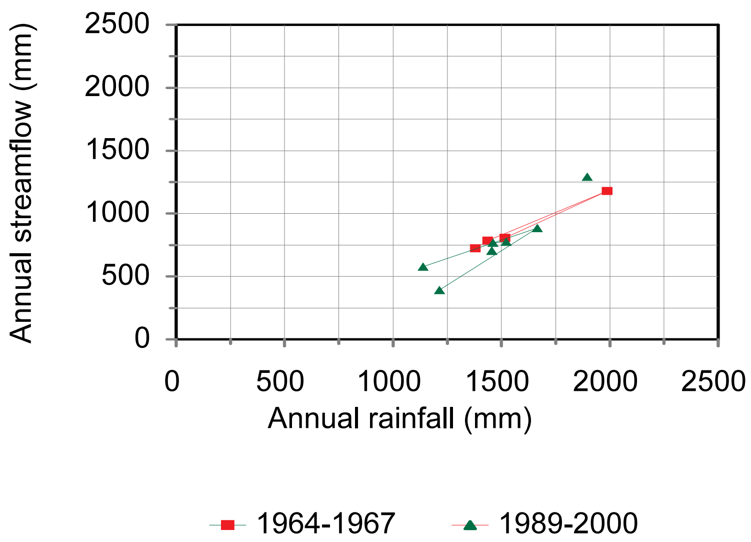

Fig. 3.6 Relationship between annual streamflow from the Hikurangi River catchment compared to rainfall at Ruatangata No. 2.

The annual mean 7-day low flows for the Hikurangi River are shown in Fig. 3.7. There is a significant difference (Mann–Whitney test) in the levels for the two periods with the mean for 1961–68 being 0.28

mm/day and that for the 1985–1998 period 0.16 mm/day. Annual streamflow totals were similar for the two periods. Because of the break in the record, it is difficult to assign the difference in MALF7 values for the two periods to a land-use change as it may be a consequence of the reinstallation of the equipment or stream channel changes.

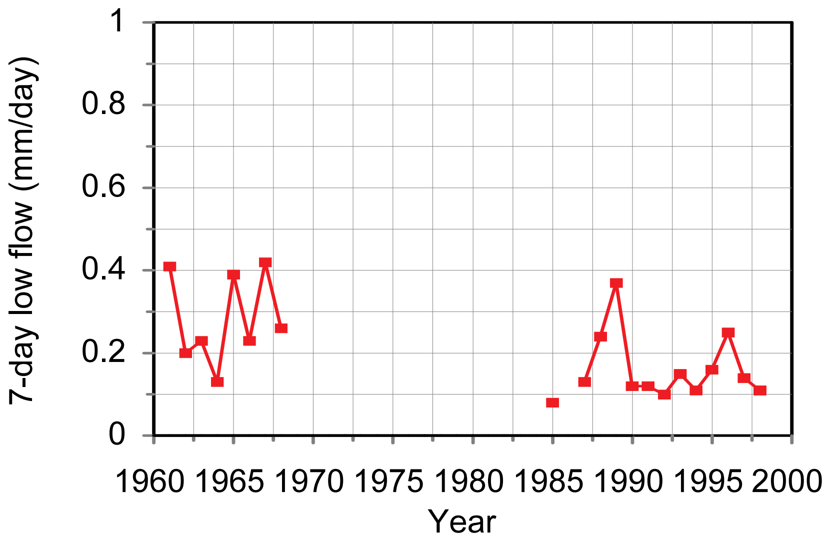

Fig. 3.7 Annual minimum mean 7-day low flows measured at the Hikurangi River.

Puketurua

The Puketurua catchments were established as part of the International Hydrological Decade programme in the mid-1960s with the purpose of investigating the effects of scrub clearance and the establishment of improved pasture on water yield and quality. They are part of the Hokianga hydrological region, and drain into the Aponga Stream, which enters the Mangakahia River just below the Hikurangi River and above the Titoki gauging station. Puketitoi Stream is the largest of the catchments monitored, has the longest streamflow record and, hence, is the only one considered here. Rainfall measured at the Pukewaenga raingauge (NIWA Site A54601; 1941–1970 normal 1538 mm; NRC site 543030) in the middle of the catchment is able to provide an index of catchment rainfall.

Prior to the study, the catchment was covered with mixed-age manuka scrub (NZMS-1 N19, 2nd Edn 1969), which had regenerated after burning. Some patches of scrub were up to 40 years old. The manuka scrubland was burned in February 1971 and the catchment disc-cultivated for about a year before being planted in pasture between March and May 1972. Grazing began July 1972 (Schouten 1976; Waugh 1980). By winter 1973, the vegetation cover was 83% pasture, 4% native bush, 12% gorse/bracken/manuka regeneration. Before 1976, a start had been made on large-scale forestry planting, mainly in areas unsuitable for pasture (Schouten 1976). Schouten implied that more afforestation would be taking place but the 1989 topographic map (NZMS-260 P06 1st Edn 1989) shows scrub in the gullies with no plantation establishment.

Changes in annual streamflow reflect these land-use changes. Prior to the land treatment phase, streamflow averaged 690 (47%) of 1480 mm rainfall at the Pukewaenga gauge and a regression analysis resulted in:

$$\text{Streamflow} = -410 \pm 330 + 0.76 \pm 0.22 \times \text{Rainfall} \qquad SE = 44;\ r^2 = 0.96;\ n = 8 \qquad 3.3$$

This equation has been used to predict the streamflow that would have been measured if there had been no change in land use and, thus, to estimate the change in streamflow that could be attributed to the change (Fig. 3.8). After burning there was an increase of 200 mm in the first year with a steady decline over the next 9 years so that by 1980 streamflow was about the pre-treatment level or below. Table 3.3 summarises the changes which, in the absence of additional information, can only be attributed to the initial clearance of the scrub followed by reversion back into scrubland.

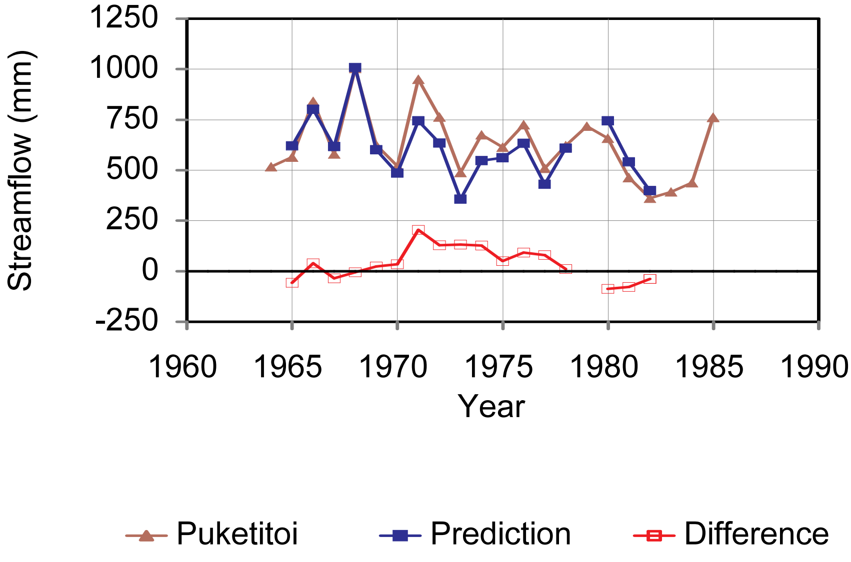

Fig. 3.8 Annual streamflow measured at Puketitoi Stream and that predicted for no landuse change using Equation 3.3. The difference is the effect of land-use change. No estimate could be made for 1979 as rainfall data were missing.

Table 3.3 Average annual streamflow at Puketitoi Stream and changes as a consequence of land cover. No estimate could be made for 1979 as rainfall data were missing.

	Rainfall (mm)	Streamflow (mm)	Streamflow/ rainfall (%)	Average change from prediction (mm)
1964–1970 Manuka scrub	1480	690	47	0
1971–1978 Pasture & reversion	1310	670	51	105
1980–1983 Reversion	1310	495	38	−70

The Puketurua and Hikurangi river catchments both fall into the Hokianga hydrological region (Toebes & Palmer 1969). Three years of concurrent data are available for the catchments, with Puketitoi Stream under scrub and Hikurangi River under mixed cover. Differences in streamflow yields from the catchments are apparent with the 100% scrub-covered Puketitoi Stream catchment yielding less streamflow than the mixed-cover Hikurangi River catchment (Table 3.4), which has a significant area, mainly the Moengawahine Stream catchment, in pasture. The differences are opposite to the trend normally expected where a catchment with a significantly larger pasture component and similar rainfall would be expected to have the greater water yield. Thus, the comparison should be treated with caution as there is a large disparity in catchment area, and the catchment rainfall estimates may also contain unknown, but significant, differences from true values.

Table 3.4 Annual streamflow at Puketitoi Stream and Hikurangi River for 1965–1967. The Ruatangata No. 2 rainfall has been reduced 5% to approximate a closer estimate of catchment rainfall (see previous discussion under Hikurangi).

	Streamflow (mm)		Rainfall (mm)	
Year	Hikurangi	Puketitoi	95% of Ruatangata No. 2	Pukewaenga
1965	790	570	1360	1390
1966	1180	840	1890	1630
1967	810	580	1440	1380
Average	930	660	1570	1470
Streamflow/rainfall (%)	59	45		

The annual series of 7-day low flows for Puketitoi Stream (Fig. 3.9) show that low flows tend to be very low, generally less than 0.1 mm/day and a consequence of the geologic makeup of the region. The Puketitoi Stream has run dry in 11 of the 21 years of record. There was only one occurrence in the pre-burning period, but the catchment has run dry up to 125 days a year in most years after treatment. While it would be tempting to attribute this increased frequency to regeneration of scrub, one factor may be a drier rainfall regime as average rainfall between1971 and 1983 was 170 mm lower than in the pre-burning phase.

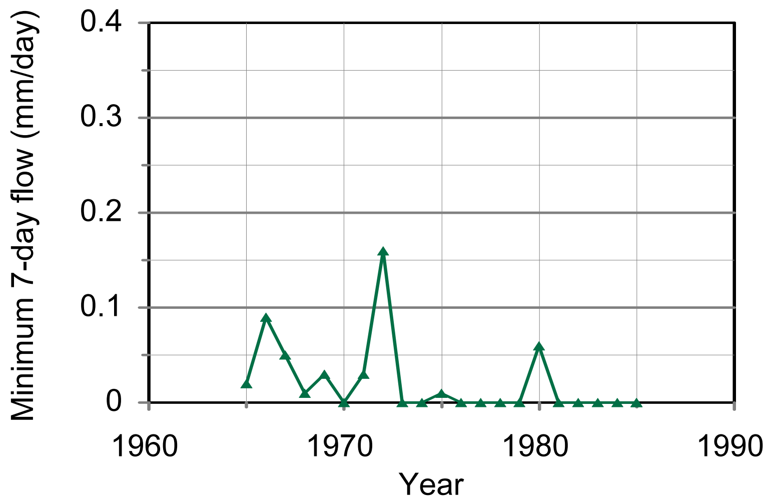

Fig. 3.9 Annual minimum mean 7-day low flows at Puketitoi Stream.

Mangakahia River

This large catchment is to the north and east of the Kaihu River catchment and west of the Hikurangi River catchment and has been gauged at two sites. The upper site at the Gorge has been gauged since 1960 and a recording site at Titoki was instrumented in 1983. Above the Gorge site, the majority of the catchment falls into the Waipoua hydrological region of which the Mangakahia River was selected as the representative basin (NZMOW 1970) while a substantial proportion of the area joining the catchment between the Gorge and Titoki sites is typical of the Hokianga region. The records from the Titoki site are not considered here because it only began in 1983 and there are a large number of missing periods.

In the catchment above the Gorge site, rainfall varies considerably, with Waimatenui No. 2 in the south-west receiving about 1950 mm/year, Kauana Downs in the north-east about 1700 mm (NIWA Site A53591; 1941–1970 normal 1766 mm). Outside this catchment are a number of rainfall sites indicating lower values: Kaikohe aerodrome (NIWA site A53481; 1941–1970 normal 1570 mm) to the north; Pipiwai (NIWA site A53691; 1941–1970 normal 1590 mm) to the east; Waipoua Forest (NIWA site A53651; 1941–1970 normal 1696 mm) to the west; and south at Pakotai (NIWA site A53781; 1941–1970 normal 1712 mm), Parakao (NIWA site A53791; 1941–1970 normal 1530 mm; 1961–1990 normal 1424 mm) and Titoki (NIWA site A54702; 1941–1970 normal 1418 mm; 1961–1990 normal 1302 mm). Making an adjustment for the difference between the two sets of normals, average catchment precipitation above the Gorge will be of the order of 1700–1800 mm, the top end of this range being the average given in NZMOW (1970).

Land cover has changed over the 40 years of the streamflow record. NZMOW (1970) gives the land cover as 30% native forest with the remainder in rough pasture and land reverting to fern and scrub. However, there was 250 ha of plantation (1% of the catchment) present north-west of Awarua in the mid-1960s (NZMS-1 N19 2nd Edn 1969). Information from Carter Holt Harvey (quoted in Rowe 1996) indicated that by 1980 about 1150 ha (5%) of the catchment had been planted and this had risen to some 5100 ha (20%) in 1986 (NZMS-260 P06 1st Edn 1989, compiled 1986) and 5900 ha (24%) by 1989. Little additional planting had taken place by 1993 (Rowe 1996) and this is confirmed in plots from TUMONZ (Vision Software 2002). Most of the cover change was from undeveloped pasture and scrub.

When accumulated annual streamflow at Mangakahia River @ Gorge is plotted against rainfall from Waimatenui No. 2 as a surrogate catchment rainfall index, there is a change in slope that occurs at about 1989 (Fig. 3.10). The planting of 9% of the catchment between 1972 and 1983 had no obvious effect on streamflow yields probably because planting was spread throughout this period, which makes yield changes very difficult to detect. The observed change after 1989, 15% of the catchment had been planted in the previous 6 years, is equivalent to 150 mm/year for the whole catchment and is a reduction in streamflow from 66% of precipitation to 58%.

When annual streamflow is plotted against annual rainfall there is a tendency for separate clusters prior to 1988 and after1988 (Fig. 3.11), the annual mean yields being 1290 and 1150 mm for respective mean rainfalls of 1945 and 1960 mm. A Mann–Whitney test on Mangakahia River annual yields to 1988 and for 1989 onwards indicated the difference between the means would be significant.

Separate regression equations were calculated for each of these periods. Notwithstanding the fact that Equations 3.4 and 3.5 are not statistically different because the confidence limits overlap greatly, they do produce a difference of 150 mm for mean Waimatenui rainfall, which is similar to the differences above.

To 1988	Mangakahia = −150±300 + 0.73±0.15 × Waimatenui	SE = 120; r^2 = 0.82; n = 25	(3.4)
1989 on	Mangakahia = −470±570 + 0.82±0.28 × Waimatenui	SE = 120; r^2 = 0.81; n = 10	(3.5)

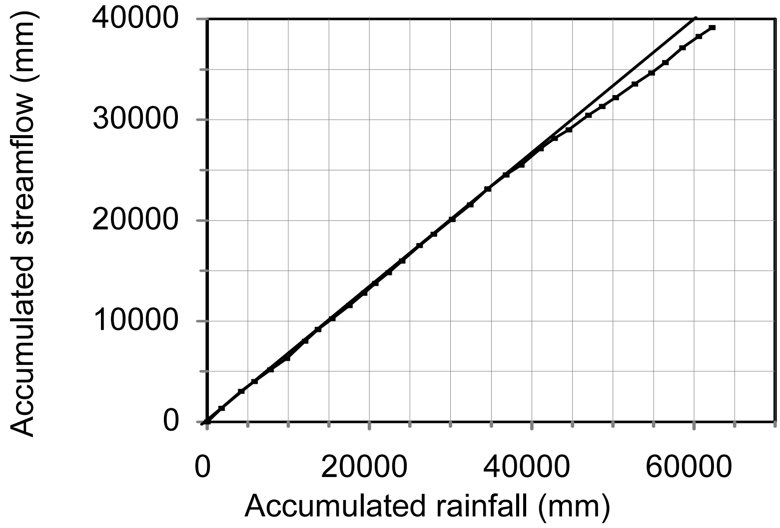

Fig. 3.10 Accumulated streamflow at Mangakahia River @ Gorge plotted against accumulated rainfall at Waimatenui No. 2 shows a change in slope about 1989 when accumulated rainfall is about 40 000 mm.

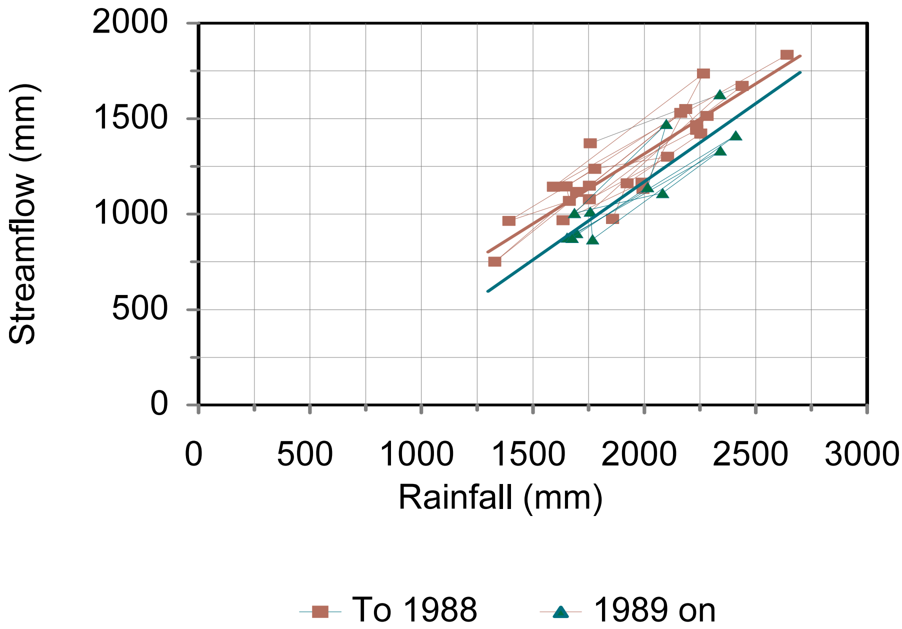

Fig. 3.11 Annual streamflow at Mangakahia River @ Gorge plotted against rainfall at Waimatenui No. 2 showing the non-exclusive clustering of points for the two periods: to 1988 and 1989 onwards. The regression lines for Equations 3.4 and 3.5 are plotted.

The three analyses all point to a decrease in streamflow yield of about 150 mm/year as a consequence of the mid-1980s burst of planting, the change taking place once the earlier planted trees had reached about 6 years old. The decrease that resulted from planting 15% of the catchment over 6 years is a lot higher than expected being equivalent to 1000 mm change for a catchment completely afforested from pasture. While perhaps 440 mm of this change might be attributed to increased interception by the new plantations compared to pasture (based on 22% of precipitation (Rowe et al. 2002)) and there will be some increase in dry-canopy evaporation, not all this decrease in yield can be explained by the extent of afforestation that has occurred

in this catchment.
The annual minimum 7-day low-flow series for Mangakahia River at Gorge is shown in Fig. 3.12. This series has non-significantly different means for the periods to 1988 and from 1989 onwards of 0.54 mm/day and 0.48 mm/day, respectively. Both the Cox & Stuart test for trend comparing the 13 values at each end of the sequence, and the Mann–Whitney test for differences in the means were unable to detect differences in the data. One point worth noting in this long sequence is that minimum values of about 0.36 mm/day occur throughout the study period. Comparisons between Kaihu River at Gorge and Mangakahia River at Gorge records from 1971 to 2000 show no trends that could be attributed to afforestation. Both catchments are in the Waipoua hydrological region, which is reflected in the similar mean low flows.

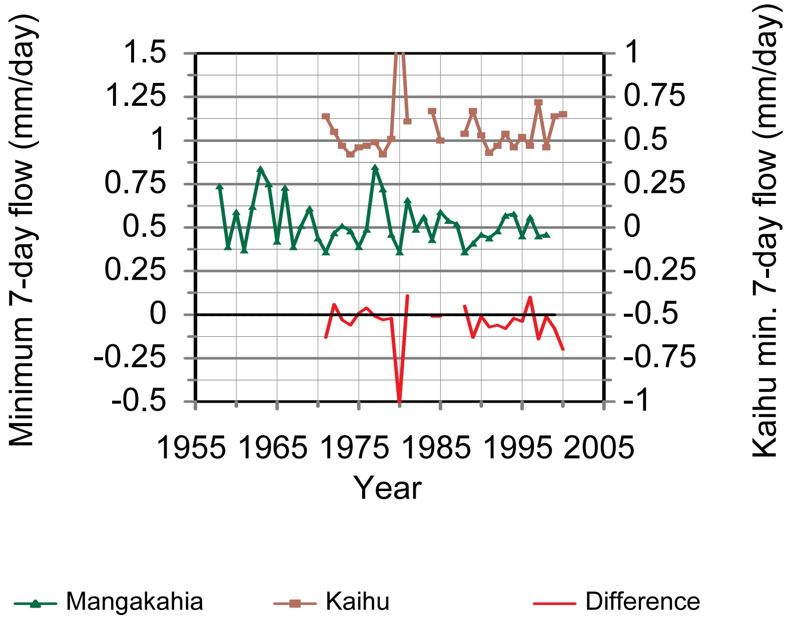

Fig. 3.12 Annual minimum 7-day low flows for the Mangakahia River at Gorge. The Kaihu River data were offset for clarity.

3.2 Mangahahuru Suite

To the east of the Mangakahia Suite is a second set of catchments with substantial plantation forests to the north and north-east of Whangarei (Table 3.5). The main catchment is the Mangahahuru Stream and there are short-term records from small catchments at Glenbervie.

Table 3.5 Northland Region: Mangahahuru Suite catchments with land cover at 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Mangahahuru @ County Weir	Dec 1968		20.5	Exotic + native
Ngunguru @ Dugmores Rock	Aug 1969		12.5	Native + pasture
Glenbervie @ Quarry	Dec 1976	Jan 1985	0.63	Exotic
Glenbervie @ Pines	Apr 1979	Jul 1990	0.155	Exotic
Glenbervie @ Log Bridge	Apr 1979	Jul 1990	0.126	Exotic
Puketurua @ Puketitoi	Jan 1964	Aug 1986	2.48	Pasture

Mangahahuru Stream

The longest running data set is from the Mangahahuru Stream, which drains the majority of Glenbervie Forest and lies within the Whangarei hydrological region. In 1964, the land cover was a mix of scrub and native forest with some pasture (NZMS-1 N20 3rd Edn 1964) but by 1986 it was predominantly plantation forest with a small (15%) native forest component (NZMS-260 Q06 1st Edn 1989). Subsequently about 1 km^2 (5%) of the native forest was converted to exotic plantation (TUMONZ (Vision Software 2002)).

The Ngunguru River to the east has a cover of 35% pasture with the balance in native forest and scrub (NZMOW 1980) and, being in the Whangarei hydrologic region, can be used as a control catchment. The Puketurua catchments to the west and Kokopu Stream to the south-east are pasture catchments that only have records for the first part of the Mangahahuru record. Rainfall records or published normals from Hikurangi (NIWA site A54622), Glenbervie Forest (NIWA site A54631 or 546301), Noble Todd (NIWA site 546413) and Pole Rain (NRC site 546416) indicate that rainfall over the Mangahahuru and Ngunguru catchments would be about 1800 mm/year, but none of these records spans the streamflow record.

For the 32-year period 1969–2000 only 24 years at Mangahahuru and 27 years at Ngunguru could be used because missing records were such that reasonable estimates to fill the gaps could not be made. Compared to a control catchment, we would predict a change in flow over the early years up until about the mid-1980s as the plantation was established and stable flows thereafter while the forest was maturing. However, a comparison of the Mangahahuru Stream and the Ngunguru River annual flow series using mass curves, trend tests, and plots of annual values before 1980 and after 1982 did not show any trend with time (Fig. 3.13). Perhaps the six critical years of missing records about 1980 when forest establishment was occurring may have made detection of trends impossible. It is equally feasible that the change from mainly scrub and native forest with a lesser amount of afforestation of pasture was hydrologically not great enough to be detected and small changes were masked by annual variability of streamflows.

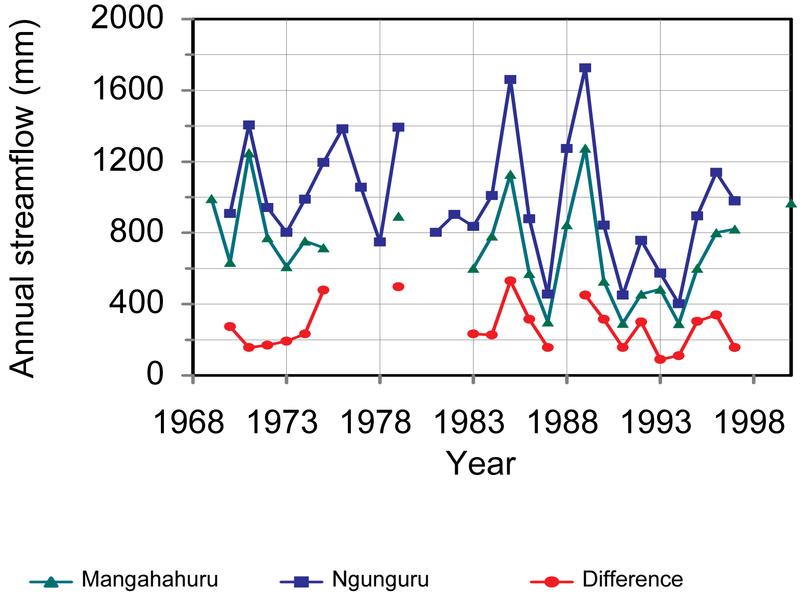

Fig. 3.13 Difference between the annual streamflow measured for the plantation catchment at Mangahahuru Stream and that for the native forest control catchment, the Ngunguru River.

There are average annual streamflow differences of 280 mm between the two catchments, with Ngunguru River having higher streamflow, 980 mm/year compared to 700 mm/year at Mangahahuru Stream, but there is no clear land-cover difference to explain this and catchment rainfalls estimated from the normals are thought to be similar. Annual mean 7-day low flows for Mangahahuru Stream and the comparison with Ngunguru River are shown in Fig. 3.14. Again, no trend over time in either the low-flow records or in the difference between them was detected using either the Mann–Whitney test or the Kendall's Tau test. The average MALF7 for Mangahahuru Stream was 0.47 mm/day while that at Ngunguru River was 0.56 mm/day for comparable years.

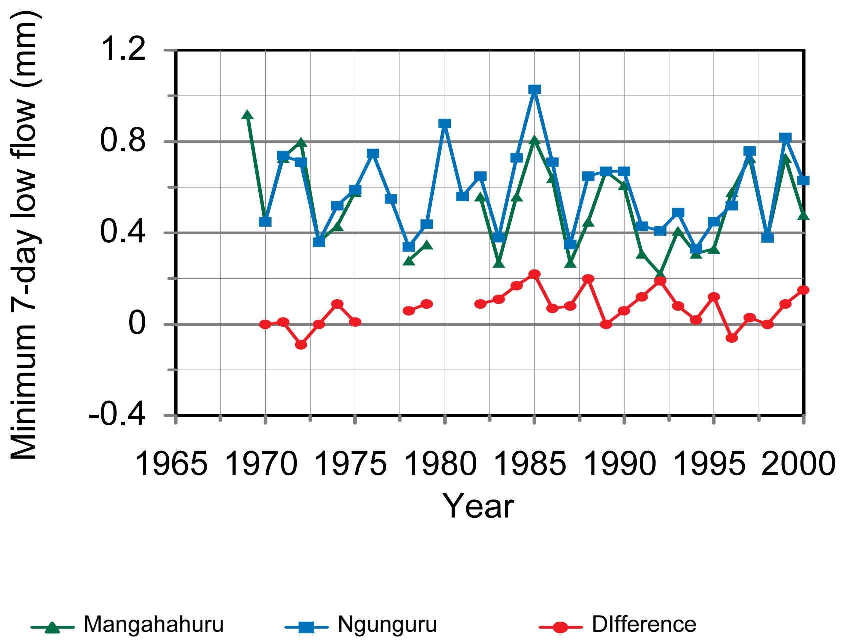

Fig. 3.14 Annual mean 7-day low flows measured at the plantation catchment at Mangahahuru Stream and for the native forest control catchment, the Ngunguru River, and the difference between the two records.

Glenbervie

Three small catchments to the south of the Mangahahuru Stream and on the southern edge of Glenbervie Forest were gauged at various times in the 1980s. All catchments were in mature plantation having been planted in 1955 (Hicks & Harmsworth 1989). Roading took place from early 1985 in the Log Bridge sub-catchment, which was harvested between October 1986 and February 1987, then burned and planted in radiata pine, although an invasion of gorse covered the catchments in 1989. The Pines sub-catchment suffered 25% wind-throw during Cyclone Bola in March 1988 and, hence, was harvested in November 1988. At the outlet of the Glenbervie Stream, the Quarry site which include both Log Bridge and Pines sub-catchments, streamflow measurements ceased in 1985 because harvesting was taking place upstream. The time span of the adjacent Ngunguru River record to the east makes this the best control catchment. Because flows on either side of the harvest were monitored, Glenbervie data could provide some indication of the differences between a plantation and a bare catchment after harvesting. Average rainfall at Waitangi Road (NIWA site 547312) and Glenbervie Forest (NIWA site A54631 or 546301) indicate the rainfall over the catchments is about 1920 mm/year, which is about 100 mm more than at Ngunguru River.

Until 1986, streamflow yields for the three Glenbervie catchments were very similar. While under mature plantation, the Glenbervie catchments had lower streamflow than the Ngunguru River despite tending to have slightly higher rainfall, about 190 mm/year (Table 3.6). If, in fact, rainfalls for the two catchments are similar, much of this difference may be related to Ngunguru River having a 35% pasture cover.

Table 3.6 Streamflow and rainfall (mm) at the Glenbervie and Ngunguru river catchments. The values in parentheses are streamflow as a percentage of the catchment rainfall index. For Glenbervie this is an average of records from Glenbervie Forest and Waitangi Road raingauges.

Ngunguru rain	Ngunguru flow	Glenbervie rain	Log Bridge flow	Pines flow	Quarry flow
2060	1020 (54)	2080	830 (42)		
1830	940 (51)	1820		760 (42)	
1910	1110 (54)	1970			915 (44)

After harvesting the Log Bridge catchment in 1986 and the Pines catchment in 1988, streamflow increased relative to Ngunguru River and this is shown as differences in Fig. 3.15. Prediction equations developed for the annual streamflows yields measured during the few years of pre-harvest data are:

$$\text{Log Bridge} = -110 \pm 640 + 0.93 \pm 0.59 \times \text{Ngunguru} \qquad r^2 = 0.89;\ \text{SE} = 130;\ n = 5 \quad (3.6)$$
$$\text{Pines} = -190 \pm 300 + 1.02 \pm 0.31 \times \text{Ngunguru} \qquad r^2 = 0.94;\ \text{SE} = 105;\ n = 7 \quad (3.7)$$

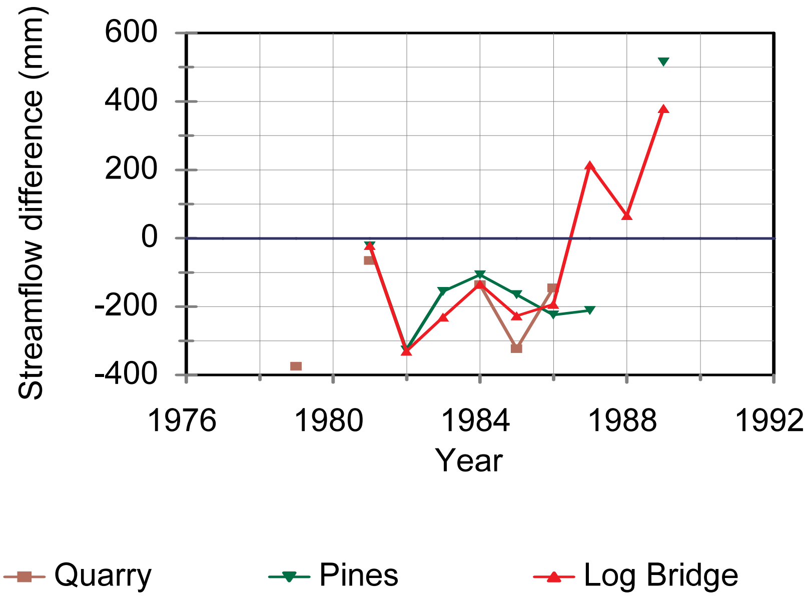

Fig. 3.15 Difference between the annual streamflow measured at the native forest/pasture control catchment, the Ngunguru River, and the streamflow from the Glenbervie catchments.

Predicted streamflow increases after harvesting were over 600 mm in the very wet year, 1989 (Table 3.7). These increases can easily be accommodated by reduced interception (of the order of 22% of rainfall; Rowe et al. 2002) supplemented by reduced dry canopy evaporation after the plantations were cut down. The low increase in 1988 is likely to be a consequence of the very low rainfall in 1987 and the resultant effects on the status of the soil moisture levels.

Table 3.7 Increase in annual streamflow (mm) at the Pines and Log Bridge catchments at Glenbervie predicted from streamflow at Ngunguru River. The values in parentheses are the increases as a percentage of rainfall, which is an average of records from Glenbervie Forest and Waitangi Road raingauges.

Site	1987	1988	1989
Log Bridge	360 (28)	270 (14)	610 (24)
Pines			670 (27)
Rain	1300	1900	2500

MALF7 values are variable at Glenbervie. For 1980–1986, the MALF7 values were: Quarry 0.57 mm/day; Pines 0.53 mm/day; Log Bridge 0.77 mm/day; Ngunguru River 0.71 mm/day. Increases in LF7 were apparent in the years immediately after harvesting (Fig. 3.16). Relative to Ngunguru, the minimum flows at Log Bridge after 1986 were 0.25 to 0.7 mm/day higher while at Pines the increase was about 0.5 mm/day. The decrease at Log Bridge in 1989 and 1990 could be attributed to the invasion of gorse.

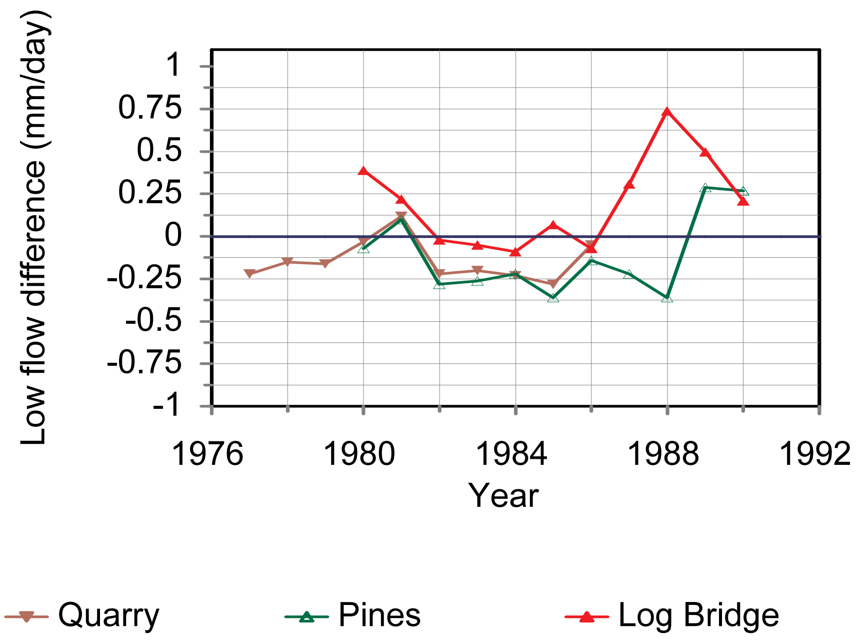

Fig. 3.16 Difference between the annual mean 7-day low flow measured at the native forest/pasture control catchment, the Ngunguru River, and the streamflow from the pine catchments at Glenbervie.

4. Auckland Region

4.1 Wellsford Suite

This suite is made up of catchments centred around Wellsford and listed in Table 4.1. Topuni Forest was established in the mid-1940s and that around Mahurangi in the mid-1970s (Forestry Insights 2002).

Table 4.1 Auckland Region: Wellsford Suite catchments with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Topuni @ Old North Road	Dec 1976	May 1986	0.875	Exotic
Kokopu @ McBeths	Jun 1977	Aug 1986	3.08	Pasture
Tamahunga @ Quintals Falls	Feb 1978		7.97	Pasture + native + exotic
Waiwhiu @ Dome Shadow	Nov 1967		8.03	Native + 47% exotic
Mahurangi @ College	Jun 1982		46.8	Pasture + native + exotic
Hoteo @ Gubbs	Aug 1977		268	Pasture + native + exotic

Topuni River

The gauged Topuni River catchment, a small headwater sub-catchment of the main river, was one of those used by Riddell & Martin (1982) in an analysis of water yield from catchments with native forest, exotic plantations and pasture. At the time of their study, Topuni River would have been in more or less mature plantation forest as it was well established before 1965 (Forestry Insights 2002; NZMS-1 N28 2nd edn 1965). Riddell & Martin (1982) paired this catchment with the Kokopu Stream, a pasture catchment 60 km north-west near Whangarei, but which is located in a different hydrological region as defined by Toebes & Palmer (1969). Kokopu Stream is in the Hokianga region and the Topuni River is in the Waiotira region. For this exercise, the Tamahunga Stream 29 km south-west of Topuni will be used as the control catchment and it has the advantage of also being in the Waiotira region. The Tamahunga Stream had about 50:50 native forest and pasture cover in 1978 (NZMS-260 R09 1st Edn 1981 field check 1978) and about 0.7 km^2 (8% of the catchment) was converted from pasture and scrub to plantation between 1978 and 1998 (NZMS-260 R09 2nd Edn 1998). While the timing of this change has not been determined, the magnitude of the change is such that even if it had occurred in the 1980–1986 period it will not affect the use of Tamahunga Stream as a control catchment.

Rainfall is available for Topuni (NIWA site A64241 1961–1990 normal 1388 mm; Tomlinson & Sansom 1994) 2 km south-west of the gauging station, and at Kaipara Forest (ARC site 642512). Five years of comparable data indicate that Kaipara Forest rainfall is about 16% higher than Topuni, which would give a normal of 1600 mm. As it is located just downstream of the Topuni River gauging site, Kaipara Forest will be used as the rainfall index for the catchment.

A limited amount of rainfall data from the Tuckers raingauge near the Tamahunga Stream gauging station had an average of 1580 mm/year, about 14% more than Topuni for the same period.

The Topuni River has a short record of which only 6 of the10 years of annual data are suitable for analysis, the others having significant missing records. Estimates were made for 1984 and 1985 annual rainfall at Kaipara Forest at 116% of Topuni. Using these data, the 6 years 1980–1985 have an average rainfall index for the Topuni River catchment of about 1470 mm of which streamflow would account for 510 mm (or 35%). Notwithstanding the estimated rainfall values for Kaipara Forest, a regression analysis carried out between Topuni streamflow and Kaipara Forest rainfall explained 99% of the variance in the data (Eqn 4.1).

$$\text{Topuni} = -520 \pm 170 + 0.70 \pm 0.11 \times \text{Kaipara Forest} \qquad r^2 = 0.99;\ \text{SE} = 28;\ n = 6 \qquad (4.1)$$

Rainfall appears to be similar for the Topuni River and Tamahunga Stream catchments. Annual streamflow at Tamahunga Stream was 775 mm compared to 510 mm for Topuni River, i.e., 265 mm higher. If we follow the rule of thumb given in Bosch & Hewlett (1982) that afforestation of 10% of a pasture catchment would result in a streamflow decrease of about 40 mm per year, then a comparison between Topuni River with 100% plantation and Tamahunga Stream with about 50% pasture and 50% native forest should have a difference of about 200 mm. Thus, a difference of 265 mm shows we are in about the right order of change given the uncertainties of catchment rainfall.

The average annual mean 7-day low flow at Topuni River for 1978–1986 was 0.04 mm/day and the stream was dry in 1 of the 9 years (Fig. 4.1). These values are lower than at Tamahunga Stream, which had a MALF7 value of 0.12 mm/day for the same period. No trend with time was expected nor was one obvious.

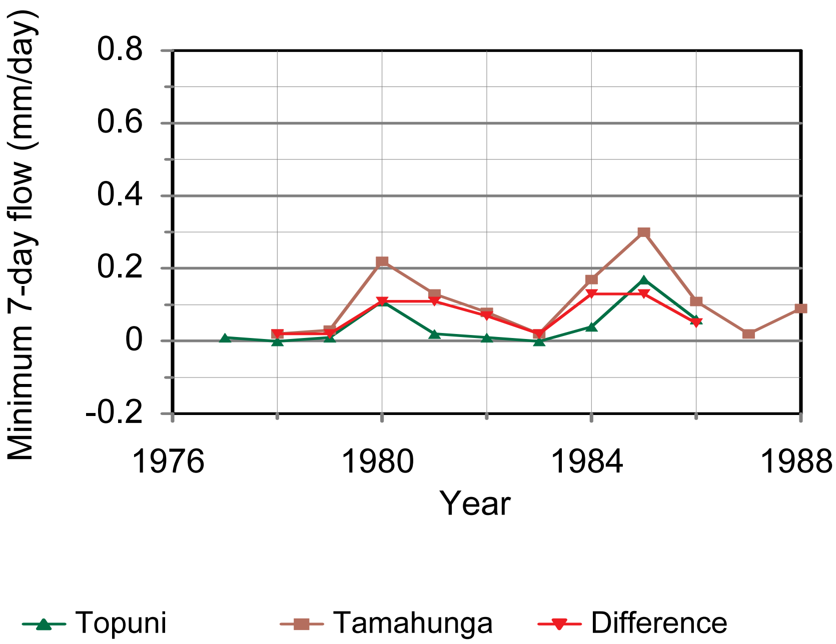

Fig. 4.1 Annual mean 7-day-low flow for Topuni River (plantation forest) and Tamahunga Stream (mixed native forest/pasture) and the difference between them.

Waiwhiu Stream

While there are 10 years of data from Topuni River, the record is of lesser importance to the Waiwhiu Stream, which has the longest record of suitable catchments in the area and has now been through one rotation. The Waiwhiu Stream, 13½ km south-east of Wellsford, was designated the representative basin for the Waiotira hydrological region (NZMOW 1970), and is located within the Hoteo catchment, being about 3% of that catchment's area.

Until 1973, the Waiwhiu Stream catchment was 70% in native forest and scrub and 30% in improved, grazed pasture (NZMOW 1970). Farming stopped in 1974 when scrub was cleared for burning in 1975. In 1975, 350 ha was planted in radiata pine and a further 30 ha was planted in 1977 bringing the total plantation area to 47% of the 803 ha catchment (Carter Holt Harvey compartment maps; Waugh 1980; Rowe & Jackson 1997). Thinning operations took place in the second half of the 1980s.

Harvesting the mature plantation forest began in 1995 with about 145 ha (18% of the catchment) harvested up until 1997 and continuing. Replanting of harvested areas began with 39 ha (5% of the catchment) in 1998 (Carter Holt Harvey compartment maps).

There is, unfortunately, no other long-term record nearby with which to compare changes to the hydrologic regime at the early stage of development, although Waugh (1980) made comparisons with the Ngunguru River included in the Mangahahuru suite, but 80 km to the north. Records from Tamahunga Stream (ARC Site 6501) and Hoteo River (ARC Site 45730) did not start until the late 1970s, shortly after Waiwhiu Stream was planted. As noted previously, a small proportion (8% of the Tamahunga Stream) has been planted, which may not be a problem as far as use as a control catchment is concerned. The Hoteo River, which contains the Waiwhiu Stream, has undergone some forest development (NZMS-260 R09 1st Edn 1981 field check 1978; 2nd Edn 1998). Much of this increase would have occurred in the mid-1980s and was mainly conversion of about 5% of the catchment's native forest and scrub to plantation forest. From the hydrological standpoint, this is unlikely to have any noticeable effect and the Hoteo River record could be considered more or less stable for control catchment purposes. A number of years could not be used because missing data in these two streamflow records were substantial and estimates for these could not be made with any degree of certainty.

Apart from Ngunguru River, the only records spanning the length of the Waiwhiu Stream record are rainfall records from Goat Flat (NIWA site 643610, 1968–1999 average annual rainfall 1970 mm; range 1450–2800 mm) in the Waiwhiu Stream and at nearby sites. Rainfall over the catchment is reasonably uniform with six raingauges located within and around the catchment in a short-term study only varying by up to ± 6% of the mean of the set (Rowe 1999, unpubl. data). Trend analyses (Cox & Stuart test and Kendall's Tau) did not show any trend over time for the Goat Flat record, and plotting mass curves against rainfall from Warkworth (NIWA site A64463) and Leigh 2 (NIWA site A64282) showed these three rainfall sites had consistent records from at least 1972 on. Therefore, Goat Flat rainfall could be considered a good index of the catchment rainfall.

Streamflow from Waiwhiu Stream and Ngunguru River is highly variable, with that from the latter catchment ranging between 400 and 1660 mm/year. Trend analysis on the annual streamflow from Waiwhiu Stream (1970–1980 compared with 1986–1996) did not indicate any changes in flow over time. However, the difference between flows at the Waiwhiu Stream and Ngunguru River (Fig. 4.2) bordered on having a significant trend. Loss of data through missing records, natural year-to-year variation, and different climatic regimes may have masked any significant trends.

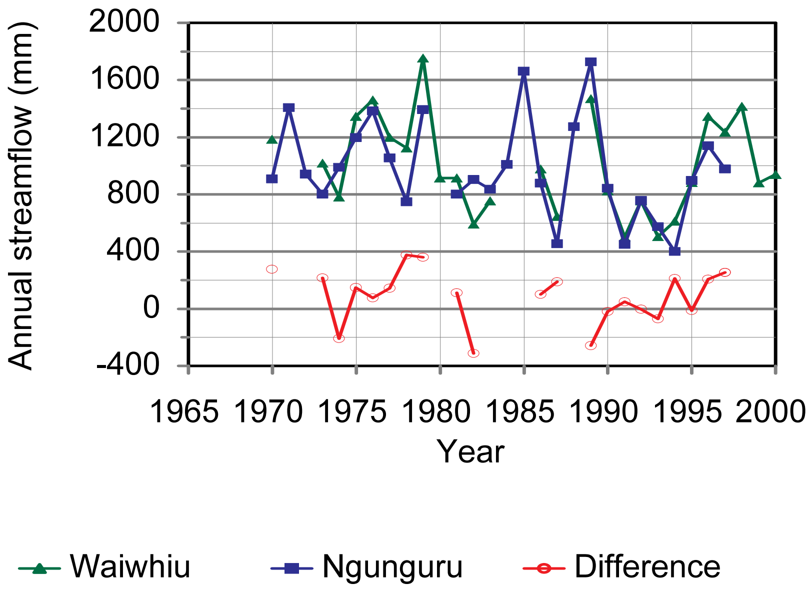

Fig. 4.2 Annual streamflow from the Waiwhiu Stream and Ngunguru River and the difference between them. Forty-seven percent of the Waiwhiu Stream was planted in 1975 and 1977, and harvesting commenced in 1995.

Significant changes are obvious when a mass curve of Waiwhiu Stream streamflow is plotted against Ngunguru River streamflow or Goat Flat precipitation as an index of catchment precipitation (Fig. 4.3). There is a break of slope at about 1980, 5 years after the main planting, when streamflow is smaller relative to precipitation. This decrease in streamflow continues until the end of 1995 when there is an increase as harvesting occurs within the catchment (Table 4.2). Part of these changes are rainfall related so estimates for long-term average rainfall conditions (1970 mm/year) have been made to enable more useful comparison. Post-harvest yields have not returned to the pre-planting levels as harvesting has been distributed over a number of years, so the catchment was not entirely without plantations at any stage.

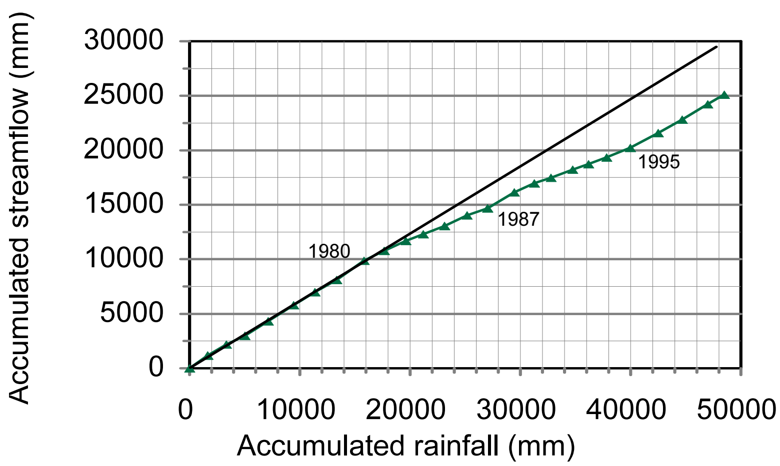

Fig. 4.3 Mass curve of annual streamflow at Waiwhiu Stream against rainfall at Goat Flat. The year 1980 is 5 years after the main planting, 1987 is about the time thinning operations were taking place, and 1995 is

when harvesting began. Some years were not able to be included as significant records were missing.

Table 4.2 Mean annual streamflow (mm and % of rainfall) from the Waiwhiu Stream catchment planted in 1975 and 1977 and harvested from 1995.

Period	Rainfall mm	Streamflow mm (%)	Streamflow (mm) pro rata to average rainfall
To 1980	1960	1200 (61%)	1210
1980–1995	1860	790 (42%)	840
1996–1999	2130	1220 (57%)	1130

When annual streamflow is plotted against precipitation there are obvious differences in the relationships for the pre-treatment period (taken to be up to 5 years after planting, 1970–1980) and the post-treatment period, 1981–1996 (Fig. 4.4). The slightly wider scatter to the pre-treatment data may reflect the various management practices that took place in those years – cessation of grazing and rank pasture growth, scrub clearance, burning, and the invasion of grass and weeds in the early years after plantation establishment. Although harvesting was taking place in 1995 and 1996, these data points fit within the forested period because the area harvested was not extensive enough to cause a discernable effect. The data points after 1996 show streamflow after partial harvesting is tending back to the pre-planting line.

Regression analyses for the calibration and post-treatment periods gave:

Pre-treatment Flow = −580 ± 760 + 0.91 ± 0.38 × Rain $r^2 = 0.82$; SE = 135; $n = 9$ (4.2)
Post-treatment Flow = −970 ± 450 + 0.95 ± 0.24 × Rain $r^2 = 0.90$; SE = 95; $n = 11$ (4.3)

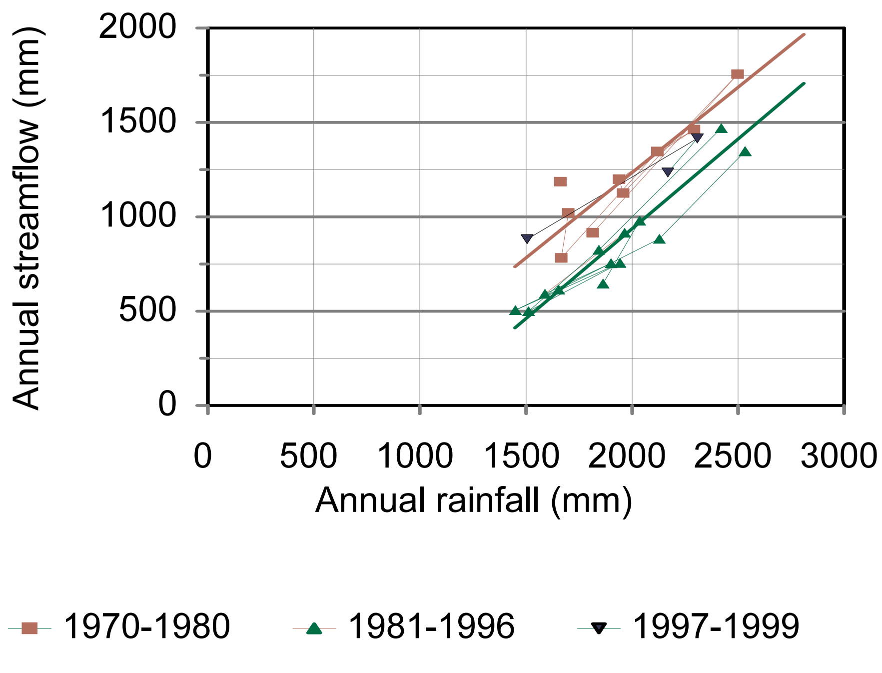

Fig. 4.4 Relationship between annual streamflow for Waiwhiu Stream and precipitation at Goat Flat in the Waiwhiu Stream catchment. 1970–1981 is the calibration period; 1982–1996 the forested period, and 1997 onwards is during the harvest period.

These equations have similar slopes but the levels are significantly different (F_{test} = 35 cf. F_{tab} = 4.4). Fig. 4.5 shows the annual streamflow yield predicted using Eqn 4.2 as if the catchment was still in its original cover. For average rainfall (1970 mm) the difference between the lines amounts to 300 mm/year (this estimate is more reliable than that deduced from the mass curve above). This decrease in yield for a cover change of 47% of the catchment is equivalent to 640 mm change for 100% conversion of a catchment in the original mixed pasture and scrub cover to radiata pine plantations. The change can be accounted for by increased interception compared to pasture (over 200 mm with interception averaging 22% of precipitation (Rowe et al. 2002) as well as increased dry canopy evaporation. The increase in flow after harvesting commenced is also apparent and yields have approached the pre-treatment levels although the harvest was still continuing.

While there were many gaps in the records, which may have affected the ability to detect annual streamflow trends, there was only one in the low flow data set for Waiwhiu Stream (Fig. 4.6). Trend analyses, using both Cox & Stuart and Kendall's Tau tests, could not detect any change in low flows for the Waiwhiu Stream. For comparable data sets, the average of the annual 7-day low flows was 0.30 mm/day and 0.56 mm/day for the Waiwhiu Stream and Ngunguru River, respectively, and post-planting values were similar at 0.29 mm/day and 0.57 mm/day. There was only a very short, 3-year calibration period to compare the Waiwhiu and Tamahunga streams, and these were after planting had taken place but before trends in annual yields were observed. When comparisons were made with the Tamahunga Stream, the three years in the calibration period had average annual 7-day low flows of 0.31 mm/day and 0.09 mm/day for the Waiwhiu Stream and Tamahunga Stream, respectively, and post-planting values were 0.29 mm and 0.09 mm. Of interest is the observation from Fig. 4.6 that there is, for both the Waiwhiu Stream and Ngunguru River, a consistent level at which the streams do not fall below in very dry seasons. This was also a feature of the Tamahunga Stream record. The threshholds were: Waiwhiu Stream 0.10 mm/day, Tamahunga Stream 0.02 mm/day; Ngunguru River 0.35 mm/day.

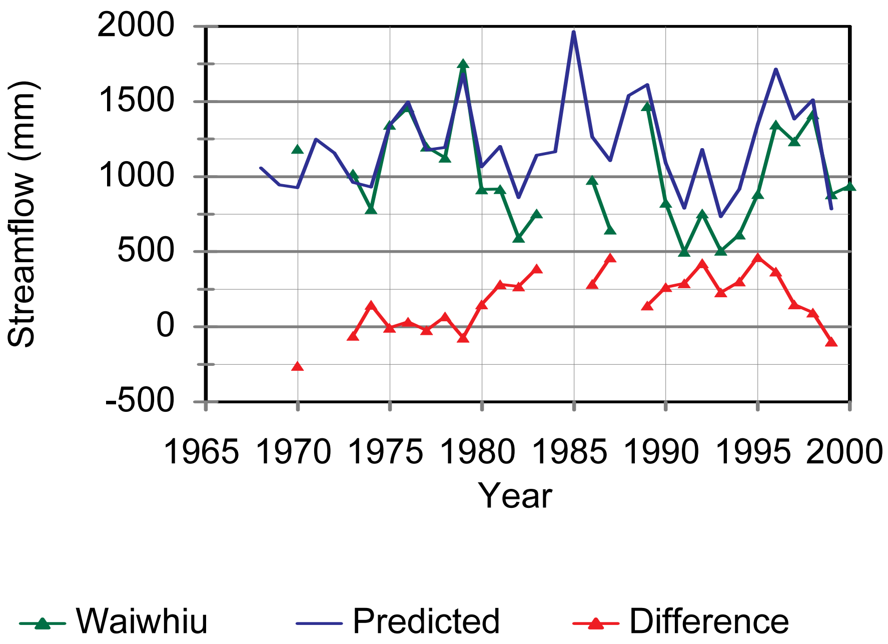

Fig. 4.5 Measured streamflow from the Waiwhiu Stream together with that predicted for the pre-harvest conditions and the difference between the measured and predicted values.

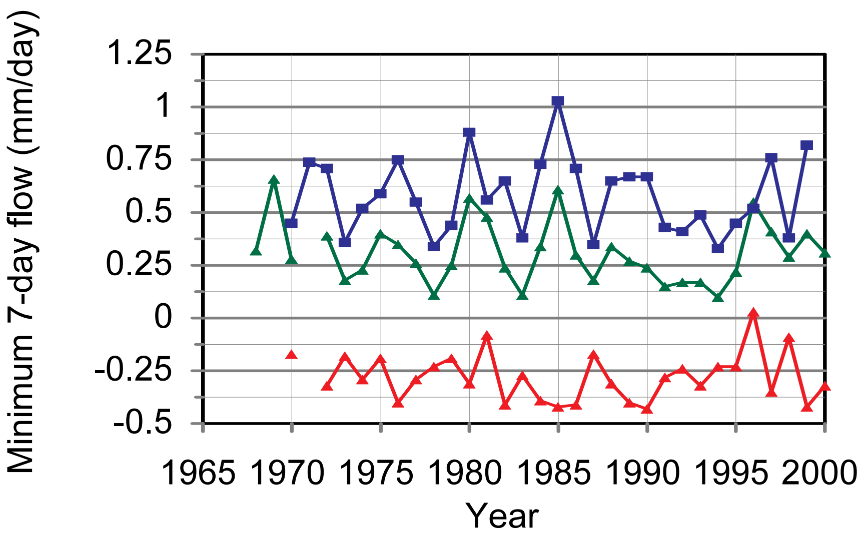

Fig. 4.6 Annual minimum mean 7-day flows for Waiwhiu Stream and Ngunguru River, and the difference between them.

Flood peaks were determined for storms separated using the Hewlett & Hibbert (1967) flow separation technique. The ideal comparison is with other catchments, e.g., the Ngunguru River 80 km away. However, this was not possible as it was difficult to correlate peaks when storm events were different over a such a long distance. There were many instances when high peaks at Waiwhiu Stream were very small at Ngunguru River, and vice versa. Therefore, we have to rely on a comparison of samples for the calibration and treatment periods although missing records mean some years in each set were not considered. Annual flood peaks are summarised in Table 4.3.

Table 4.3 Mean annual flood peaks and ranges from the Waiwhiu Stream catchment planted in 1975 and 1977 and harvested from 1995.

Period	Rainfall (mm)	Annual flood peak (L/s/ha)	Five highest in each year (L/s/ha)
To 1980	1960	48 ± 15 12–103	25 ± 5 3–103
1980–1995	1860	32 ± 8 10–61	16 ± 3 2–61
1996–1999	2130	48 ± 11 36–67	28 ± 7 7–67

Although there seems to be a tendency for the flood peaks in the annual series to be smaller following afforestation, statistically the means are not different. When a bigger sample of storms is considered by taking the five highest peaks in each year, differences are significant and the peaks are of the order of 35% lower on average. The small sample of peaks, both for the annual and the extended data sets, during the harvest period indicates that peaks flows are again similar to those from the pre-planting period although harvesting was not completed.

Streamflow was separated into baseflow and quickflow when determining the flood peak data above (Table 4.4). These data are from different data sets to the earlier analyses because I made different allowances for missing records, which led to different rainfall and streamflow totals.

Table 4.4 Average annual rainfall and streamflow components (mm) from the Waiwhiu Stream catchment planted in 1975 and 1977 and harvested from 1995.

Period	Rainfall	Streamflow	Baseflow	Quickflow
To 1980	1960	1200	600	600
1980–1995	1900	820	450	370
1996–2000	2130	1170	550	620

Prior to the trees having a substantial effect on streamflow, baseflow and quickflow yields were similar. After the trees became established there was a decline, which was greater for quickflow probably as a result of increased interception of rainfall by the trees, greater infiltration resulting from higher infiltration rates under the forest canopy compared to the grazed pasture, and the need to replenish larger soil moisture deficits under the trees. Partial harvesting has led to a return to the early rates for quickflow, but there appears to be a lag with baseflow, which is likely to be a consequence of continued high dry-canopy evaporation from the remaining trees. Seasonal values followed the same trends except for summer when average quickflow increased for the forested state and baseflow remained steady, but this may have been influenced by a few very wet years when tropical storms hit the area.

Mahurangi River

The Mahurangi River has been gauged at the 'College' (ARC site 6806) since 1982. At that time about 17% of the catchment was in plantation forestry with establishment having begun mainly in the 1970s (Forestry Insights 2002). The rest of the catchment was predominantly pasture, although of the order of 10% was in native forest (NZMS-260 R09 1st Edn 1981 field check 1978). By 1998, a further 6% of the catchment had been converted to plantation (NZMS-260 R09 2nd Edn 1998).

A comparison of the annual streamflow data with the Tamahunga Stream (8 of 18 years were available) did not shows any trend over time, nor was there one in the low-flow data (17 of 18 years). This was not an unexpected results as a 6% change in plantation cover, over half from native forest, would be unlikely to produce a detectable effect.

Hoteo River

The Hoteo River (ARC site 45730) located north-west of Warkworth has a mixed cover of pasture and native and plantation forest and contains the Waiwhiu Stream catchment. Plantings began in the mid-1970s (Forestry Insights 2002). Since 1978 there has been an increase of some 12.5 km^2 of plantation from 13% (NZMS-260: R09 1st Edn 1981 field check 1978; Q09 1st Edn 1981 field check 1979) to 18% of the catchment (NZMS-260: R09 2nd Edn 1998; Q09 2nd Edn 1998), much of which was previously in native forest.

Comparisons of annual streamflow yields with Tamahunga River (13 of 22 years) did not show any trend over time, nor was there a trend with minimum 7-day low flows (22 values). These results were not unexpected as there was only a small change in vegetation cover during that time, some being afforestation of pasture but much as conversion of native forest, which would have similar water usage.

4.2 Kumeu Suite

This suite of catchments (Table 4.5) is located to the north-west of Auckland City with production forestry centred on Riverhead Forest where first plantings began in the mid-1920s (Forestry Insights 2002). Little has changed since the mid-1960s (NZMS-1: N37 2nd Edn 1964; N38 3rd Edn 1965; NZMS 260: Q10 1st Edn 1980 field check 1977, 2nd Edn 1995; R10 1st Edn 1981 field check 1977, 2nd Edn 1999). Any changes to the areal extent of plantation since the 1960s that may have occurred would have a negligible hydrological impact being mainly distributed forest management operations. All catchments are located in the Waiotira hydrological region (Toebes & Palmer 1969).

Table 4.5 Auckland Region: Kumeu Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Rangitopuni @ Walkers	May 1975		81.5	Exotic + native +pasture
Huapai @ N Z Particle Board	Mar 1978		6.61	Pasture + horticulture
Kumeu @ Maddren Weir	Dec 1983		47.6	Pasture + horticulture
Ararimu @ Old North Road	Dec 1983		66.8	Exotic + pasture + native

Rangitopuni Stream

The Rangitopuni @ Deacon Road site (NIWA Site 7835; but not in the Rangitopuni Stream catchment) is a catchment entirely within Riverhead Forest and except for about 6% in native forest is mature plantation forest having been established before 1964 (NZMS-1 N38 3rd Edn 1965). Although data were used as one of the plantation catchments analysed by Riddell & Martin (1982), advice from NIWA (K. Walter 2002, pers. comm.) stated that this site measured stage only (1980 to 1986) and that no ratings are filed. Thus, no data can be converted to flow and used for this study.

Rangitopuni Stream measured at Walkers (ARC Site 7805) had an exotic forest cover (Riverhead Forest) of about 14% in 1965 (NZMS-1 N38 3rd Edn 1965) and there was no change by 1999 (NZMS-260 R09 1999). The balance of the catchment is about 50:50 in pasture and native forest. For comparison catchments, the most suitable appears to be the mainly pastural and horticultural Huapai Stream (ARC site 45301) catchment where recording began 3 years after Rangitopuni Stream, and Kumeu River (ARC Site 45315), also in pasture and horticulture with some native forest, where records began 8 years after.

Interpolation of rainfall normals (Riverhead Forest A64751; Waimauku site A64752; Whenuapai Aerodrome A64761; Henderson A64861; Helensville A64641; Okura Point A64672 (NZMetS 1973; Tomlinson & Sansom 1994)) indicate approximate annual catchment rainfalls of 1300 mm for Huapai Stream, 1550 mm for Kumeu River, and 1400 mm for Rangitopuni Stream.

The stable land use in Rangitopuni Stream over the period of streamflow record is reflected in annual yields and mean 7-day low flows that show no trends with time. Streamflow yields and MALF7 values from the three catchments are similar (Table 4.6).

Table 4.6 Mean annual streamflow yields (mm and % of rainfall) and mean annual 7-day low flows for Rangitopuni Stream, Huapai Stream, Kumeu River and Ararimu Stream.

	Rangitopuni	Huapai	Kumeu	Ararimu
Mean annual streamflow	580 (41)	580 (45)		
Mean annual streamflow	570 (41)		680 (44)	
MALF7	0.04 ± 0.02	0.08 ± 0.03		
MALF7	0.04 ± 0.01		0.08 ± 0.02	
MALF7		0.10 ± 0.05	0.09 ± 0.03	0.11 ± 0.02

Ararimu Stream

The Ararimu Stream, with a large proportion of Riverhead Forest (about 45% plantation coverage with the balance about 60:40 pasture to native forest), has many missing records, negating the usefulness of the annual flow data set. There will have been little change in the extent of plantation cover here as Riverhead Forest is a mature forest subject to normal forest operations. More information is available for MALF7 values (Table 4.6), which were similar to those for Kumeu River and Huapai Stream. A comparison between these catchments could not detect any time trends in the LF7 values, a result to be expected considering the more or less stable land cover throughout the period.

5. Waikato Region

Areas with significant production forest in the Waikato Region are centred on the Coromandel Peninsula, the Moumoukai catchments in the Hunua Range, the Tokoroa Suite on the Mamaku Plateau, and the Purukohukohu experimental catchments near Rotorua.

5.1 Coromandel Suite

The catchments comprising the Coromandel Suite are listed in Table 5.1. Records from this suite, with the exception of the Tairua River, are only about 10 years' long. When streamflow recording began in 1991 at Opitonui River (Kaimai hydrological region, Toebes & Palmer 1969) and Wharekawa River (Taupo rhyolite hydrological region, Toebes & Palmer 1969) these catchments had plantation forests covering about 60% and 40%, respectively, of their areas (NZMS-260: T11 2nd Edn, 1993; T12 3rd Edn 1991).

Table 5.1 Waikato Region: Coromandel Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Opitonui @ D/S Awarua	Jun 1991		29	Exotic + native
Mahakirau @ E309 Road	Sep 1987	Mar 2000	20.5	Native
Wharekawa @ Adams Farm	Jun 1991		46.5	Exotic + native
Waiwawa @ Rangihau Road	Jul 1991		120	Native + scrub + pasture
Tairua @ Broken Hills	Jul 1975		118	Native + pasture + scrub

Plantation conversion from mostly scrub cover in the Opitonui River catchment took place between 1965 and 1982 (NZMS-1 N44 3rd Edn 1966, field check 1965; NZMS-260 T11 1st Edn 1984, field check 1982) so it was in a more or less stable state when flow records began. Missing records at both the Opitonui River and Mahakirau River, the closest catchment to act as a streamflow control site, meant that it was not possible to make comparisons on an annual basis. Seven values were available for comparisons of minimum mean 7-day low-flow values and the means were 0.63 and 0.97 mm/day for Opitonui River and Mahakirau River, respectively. These differences, shown in Fig. 5.1, may be rainfall or geology related rather than land use as both catchments are more or less fully forested.

Tairua Forest in the Wharekawa River catchment was established about 1930 (Forestry Insights 2002) and there has been little change as evidenced from topographic maps (NZMS-1 N49 3rd Edn 1967, field check 1965; NZMS-260 T11 2nd Edn 1993). Plantations cover about 60% of the catchment with native forest making up most of the balance. Thus, the catchments could be considered to contain mature, stable stands. The records are too short to look for any trends but 7 years of comparable annual data give a mean yield from the Wharekawa River of 1370 mm with that from the Tairua River at Broken Hills being higher at 1570 mm. Again, this could be rainfall related as an estimate for the Wharekawa River found by rough interpolation of a number of dispersed gauges from Environment Waikato data and NZMetS (1973) normals was about 2100 mm, whereas that for the Tairua River may be much higher as there are high-rainfall stations in the Kauaeranga River to the west. The stable land cover is also reflected in the lack of any trend in the differences between Tairua River and Wharekawa River minimum flows (Fig. 5.1) where LF7 values that averaged 0.66 mm/day and 0.61 mm/day, respectively, are likely to reflect the differing rainfall regimes.

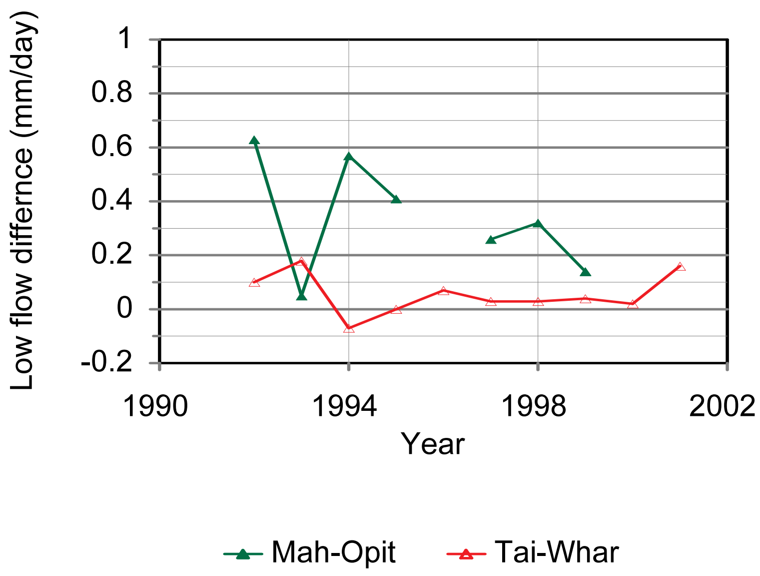

Fig. 5.1 Difference in minimum 7-day low flows between native forest catchments and the nearest catchment with significant plantation cover. Mah-Opit is Mahakirau River less Opitinui River and Tai-Whar is Tairua River less Wharekawa River.

5.2 Moumoukai catchments, Mangatawhiri, Hunua Ranges

Watercare Services and its precursor organisations have collected rainfall and streamflow data from three experimental catchments since the late 1960s at Mangatawhiri in the Hunua Ranges, south-east of Papakura (Table 5.2). Streamflow monitoring began in 1967 on the three catchments while still in native scrub (Barton 1972; Barton & Card 1979; Herald 1978, 1979). The catchments are located in the Hunua hydrological region (Toebes & Palmer 1969).

Barton (1972) gave an indication of streamflow changes that took place in the few months after scrub clearance while Herald (1978, 1979) presented the first longer-term streamflow data for the North and South catchments. Herald's data are for a shorter period and are slightly different from the annual streamflows calculated from data in Barton & Card (1979), possibly having been adjusted for climatic variations. A number of Auckland Regional Council (ARC) reports also contain an analysis of the effects of vegetation change on streamflow.

Table 5.2 Watercare Services Moumoukai catchments at Mangatawhiri, Hunua Ranges

Catchment	Area (ha)	Wetland (ha)	Land cover after 1970
Moumoukai North	8.84	0.17	Native Scrub
Moumoukai Central	11.42	0.40	*Cryptomeria japonica*
Moumoukai South	14.98	0.81	*Pinus radiata*

Vegetation change

Barton (1979) reported that in 1968 the vegetation on all catchments was a mixture of ferns and native scrub. Later in that year all large vegetation was felled reducing the cover to bracken and low scrub. Unfortunately, this included the North catchment, which was to be used as the control catchment upon which to base the effects of changes in the Central and South catchments. In March 1970, the vegetation in Central and South catchments was burned and in August they were planted in Japanese cedar (*Cryptomeria japonica*) and radiata pine, respectively. The burn off in South has subsequently been reported as poor (ARC 1990). There are small wetlands in the lower part of the catchment that were not planted (Table 5.2) (Barton & Card 1979).

Release cutting was carried out in North and South catchments in 1971 and 1972 (also in 1973, 1974 and 1975 in Central). Pruning of South took place in December 1975, January 1978, and in December 1978 to January 1979 when thinning to 300 sph was also carried out. By 1978 the understorey under dense radiata pine canopy was thin or non-existent; *Cryptomeria* growth in Central was not as good as expected with dense groundcover, and dense scrub had also regenerated in North. Harvesting the plantations had not taken place by early 2003.

Data

For this project, instantaneous streamflow at one-hourly intervals and one-hourly rainfall totals for 1968 to 2000 were provided by Watercare Services.

The rainfall data as delivered have been used, apart from making estimates for a number of months with obvious missing data that were shown by monthly plots between the three sites: North: September 1968, October and November 1997; South August 1997 to January 1998: Central August and September 1997. Tight regression relationships for monthly rainfall totals between the three catchments allowed estimates to be made for these months, which completes the data sets with little significant error.

One complicating, and potentially significant, factor in these analyses is the possibility that there has been some change at the control catchment in the first few years of the study. Here, scrub was recovering from the 1968 clearing so control catchment yields may have decreased while this happened. This will affect the estimated magnitude of any change in streamflow as a consequence of afforestation from scrub.

Further comments gleaned from ARC reports indicate there may have been a leak under the South (radiata pine) catchment weir, which may overemphasise the diminishing flow after afforestation, but this is believed to be less than 1% of the total flow (ARC 1990). As long as this leak is consistent, this is no problem for this study as we are looking at changes, with absolute amounts of secondary importance.

Average annual rainfall at Moumoukai North for the period 1968– 2000, with allowance made for obvious missing records, was 1735 mm. There is some slight variation across the catchments with the equivalent averages being 1690 mm for Central and 1700 mm for South. The annual rainfall series for North showed no long term trend, only regular cycles at about 10-year intervals. The rainfall records from North and South are consistent with each other as shown by a straight-line mass curve. A regression relationship determined between the annual totals for these two sites is:

$$\text{South} = 0.97 \pm 0.08 \times \text{North} + 10 \pm 130 \qquad r^2 = 0.957;\ \text{SE} = 50;\ n = 33 \text{ pairs} \qquad (5.1)$$

The residuals from this regression showed the approximately10-year cycle but no other trend. Therefore, the rainfall data from North can be used as the index of rainfall for the study.

The presence of missing data in the streamflow records for the three catchments during 1998 to 2000 limited the data set for annual yield purposes to the 30-year period 1968–1997 as it was not felt prudent to make estimates for these data. Screening by plotting monthly flows of the three catchments against each other did not show any obvious discrepancies.

Streamflow from North (the scrub catchment) has to be used as the control upon which to assess changes at South and Central after afforestation. Fig. 5.2 shows there is a good relationship between streamflow from North and annual rainfall at North which explains over 88% of the variation in the data:

$$\text{Flow} = 0.80 \pm 0.10 \times \text{Rain} - 540 \pm 200 \qquad r^2 = 0.881;\ \text{SE} = 45;\ n = 30 \text{ pairs} \qquad (5.2)$$

The residuals from the relationship do not show any trend with time and a mass curve of North flow against rainfall for the first six years does not show any discernable trend indicating that flow changes as a result of scrub recovery after the pretreatment felling may not be large, or the recovery is very slow at least. Therefore, North should be satisfactory as the control catchment.

The mass curve of accumulated streamflow for South and Central show similar trends to North at the early period and then obvious deviations from North occur as the cedar and pine stands grow (Fig. 5.3). The planting of cedar in the Central catchment had a lesser effect on water yield than did the planting of radiata pine in South as show by the smaller deviation from the scrub line.

Fig. 5.4 shows the annual streamflows yields from the three catchments and also the change in flow at the afforested catchments over time as the flows become smaller compared to North. The change in yield began later in Central, about 1975 = age 5 years, than the change in flow at the pine catchment, 1973 = age 3 years, which must reflect a fast regeneration of scrub vegetation at South where there was a poor burn during the pre-planting operations – the pines would be too small to have any effect.

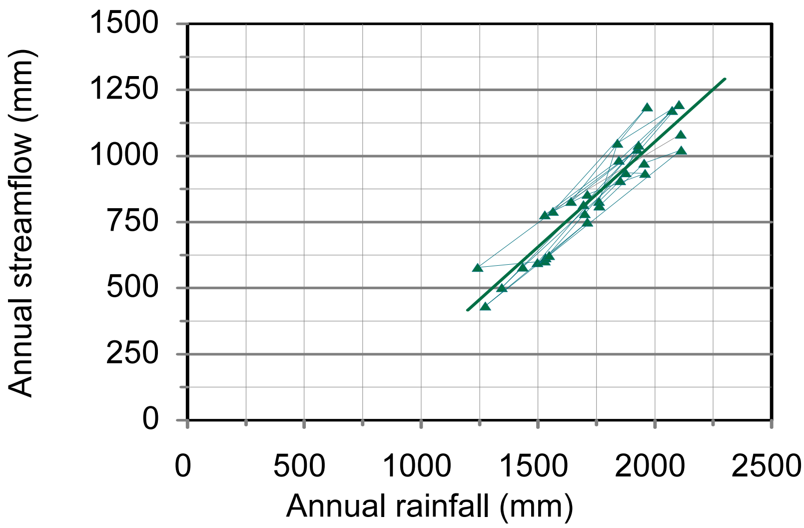

Fig. 5.2 Relationship between annual streamflow and precipitation at Moumoukai North. The line is that for Eqn 5.2

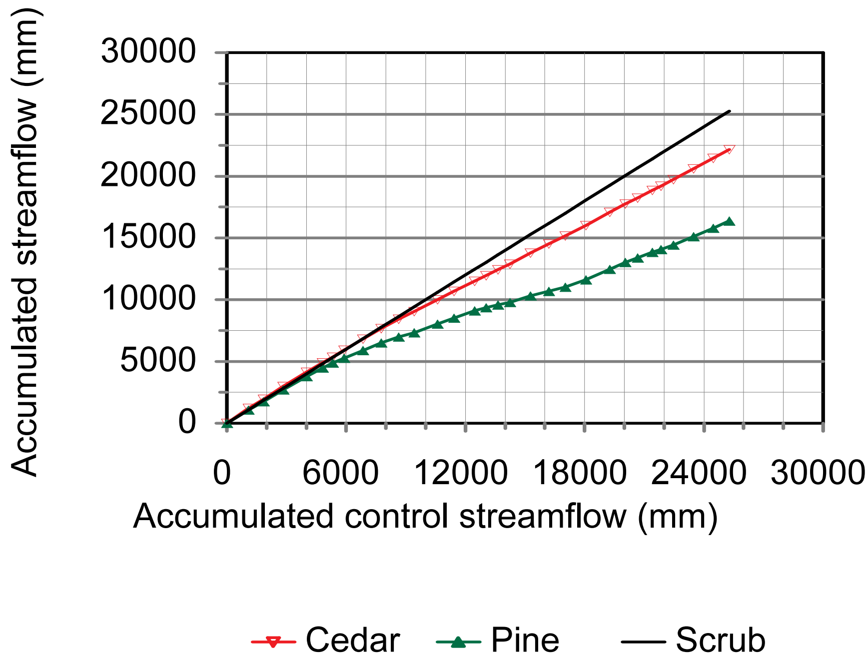

Fig. 5.3 Accumulated streamflow at the Moumoukai catchments for the period 1968 to 2000 showing the divergence from the scrubland (North = control) flows with time as both pine (South) and cedar (Central) plantations became established.

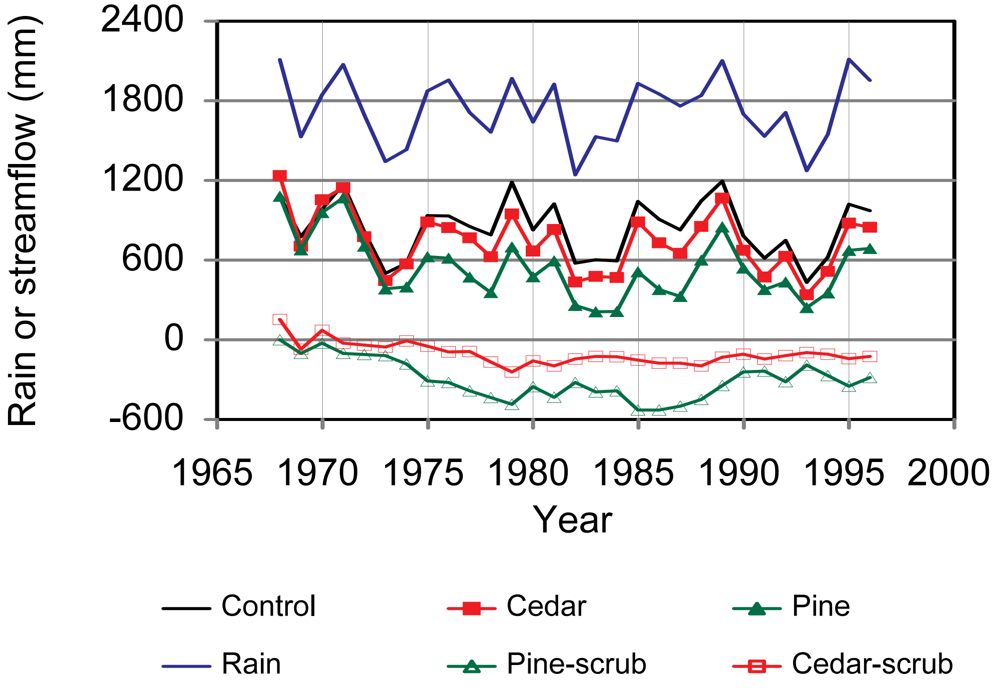

Fig. 5.4 Annual rainfall for North and the annual streamflows for the three catchments: North in scrubland; South in pine; Central with cedar. Measured differences in streamflow between the planted and scrub catchments are also shown.

Of interest is the apparent increase in streamflow at the South (pines) catchment in the later years of the data series. Plotting South v North annual yields against rainfall by tree-age classes shows a decrease in yield as scrub regenerates and the young plantation grows towards canopy closure (Fig. 5.5). There is a further decrease in yield over the middle of the rotation as the trees mature (years 13–18) but this trend is reversed as flow increases when the catchment has the mature plantation (>18 years old). It is possible that we can attribute this last change to lesser water use by the trees (a lowering of the trees' physiological needs?) in the mature years as reported in some overseas literature (see for example Cornish 1989).

Based on the visual split for the calibration data in Fig. 5.5 (2 years before, the year of, and 4 years after, planting) surprisingly good equations were determined with North streamflow alone. For example, Eqn 5.3 derived for the calibration period explained 98% of the variation in the data. An attempt at an alternative calibration with both North streamflow and North rainfall explained a similar amount of the variation but had much larger confidence limits on the regression parameters, making it less useful. Regression equations were also calculated for the later three stages of tree growth (Eqns 5.4 to 5.6).

Calibration	South flow = 1.16±0.21 × North flow – 230±180	r^2 = 0.977; SE = 50; n = 7	(5.3)
Age 5–12	South flow = 0.79±0.30 × North flow – 190±270	r^2 = 0.873; SE = 58; n = 8	(5.4)
Age 13–18	South flow = 0.76±0.30 × North flow – 260±250	r^2 = 0.926; SE = 48; n = 6	(5.5)
Age 19–27	South flow = 0.81±0.13 × North flow – 120±110	r^2 = 0.968; SE = 37; n = 9	(5.6)

The post-calibration equations have very similar slopes, with the intercepts varying according to the positions of the data groupings in Fig. 5.5. Although these equations have wide confidence limits, each consecutive pair has significantly different levels (Eqn 5.3 v 5.4 F_{test} = 71.5, F_{tab} = 4.8; Eqn 5.4 v 5.5 F_{test} = 11.6, F_{tab} = 5.0; Eqn 5.5 v 5.6 F_{test} = 75.4, F_{tab} = 4.8).

Of note is the significantly different regression slope in Eqn 5.3 compared to the others (e.g., Eqn 5.3 v 5.4 $F_{test} = 6.7$, $F_{tab} = 4.8$), which might cast doubt on the calibration equation because it could be reflecting a change of state at the control catchment as the vegetation recovered from the large scrub clearance. Notwithstanding, Eqn 5.3 was used to predict streamflow at the pine catchment for the duration of the study period as if the catchment was still in scrub because the relationship between North rainfall and North streamflow did not change over time as noted above.

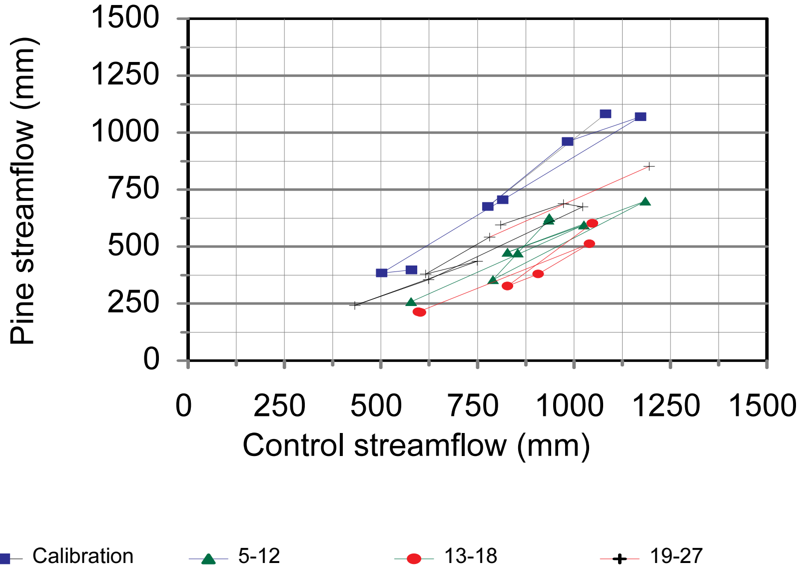

Fig. 5.5 Relationships between annual streamflow at North and South for various age classes of pines.

Streamflow at South during the calibration period was 90 mm/year less than from North and this is also shown by the prediction line in Fig. 5.6. The difference between the predicted and measured streamflows for South totalled 6140 mm over the 23 years, or 270 mm/year, reached about 450 mm in a wet year and 200 mm in a dry year in mid-rotation. For the various forest stages, the differences in yields are given in Table 5.3.

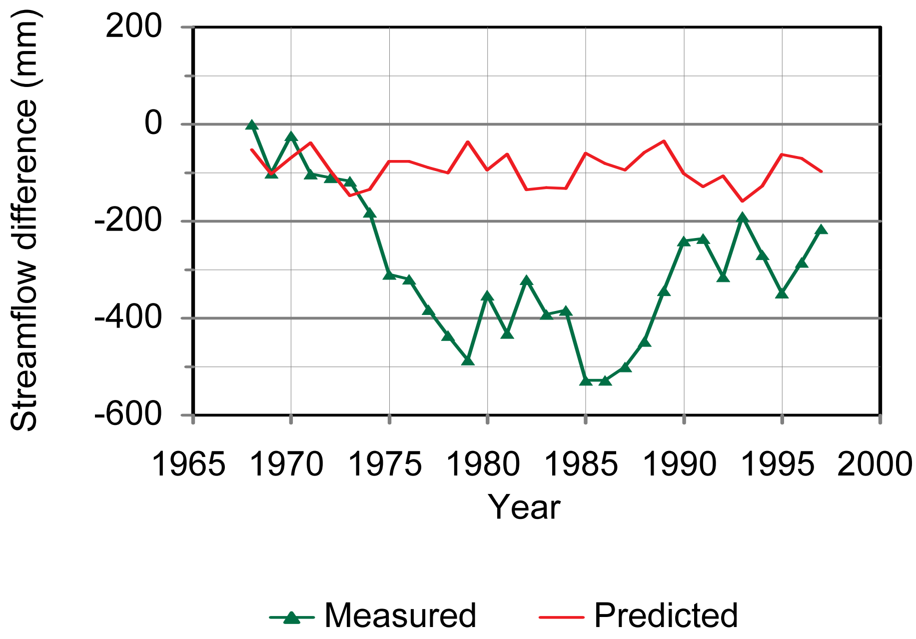

Fig. 5.6 The differences in annual streamflow yields between North and South over time. Measured values are South streamflow less North streamflow; the predicted values are North less South streamflow calculated from Eqn 5.3 representing the pre-treatment vegetation at South. The decrease in flow as a result of afforestation by radiata pine is the difference between these lines.

Table 5.3 Average rainfall (mm) and streamflow yields (mm) for South in pines, both measured and predicted, for the catchment in trees of differing age classes.

Period	Rainfall	Predicted Streamflow	Measured streamflow	Reduction
Calibration	1720	750	750	0
5–12 years	1740	810	510	300
13–18 years	1740	750	380	370
19–27 years	1750	700	530	170

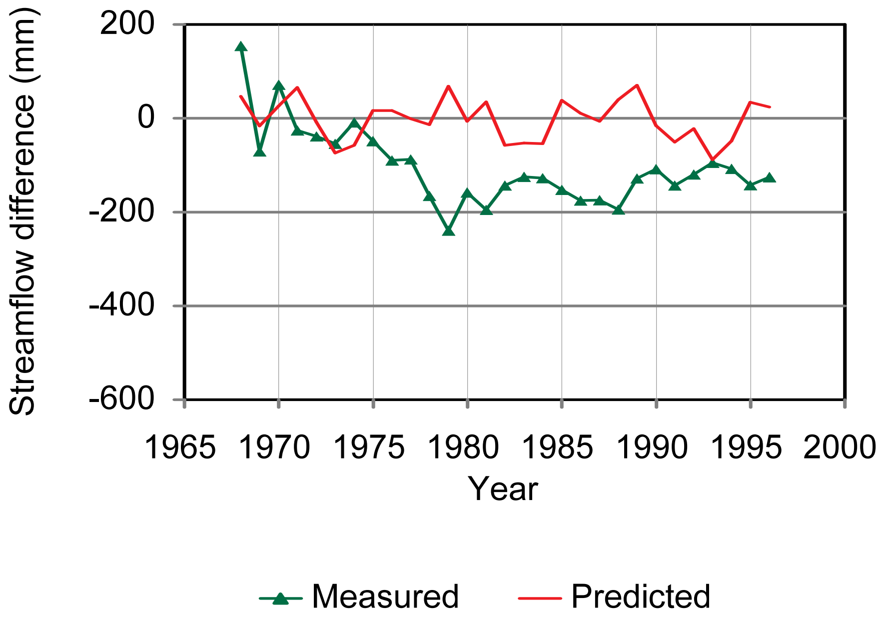

Fig. 5.7 The differences in annual streamflow yields between North and Central over time. Measured values are Central streamflow less North streamflow; the predicted values are North less Central streamflow calculated from Eqn 5.7 representing the pre-treatment vegetation at Central. The decrease in flow as a result of afforestation by cedar is the difference between these lines.

A similar analysis was carried out on the annual streamflows at North (control) and Central (cedar). The calibration equation used six years of data, three years being after planting (Eqn 5.7). The difference between measured flow from the cedar catchment and that predicted if the catchment had remained in scrub (Fig. 5.7) is much smaller than that shown for the radiata pine catchment: total decrease 3140 mm or 140 mm/year; maximum decrease of the order of 350 mm (cf. 450 mm for pines).

$$\text{Central flow} = 1.21 \pm 0.41 \times \text{North flow} - 180 \pm 380 \text{ mm} \qquad r^2 = 0.989;\ \text{SE} = 80;\ n = 6 \quad (5.7)$$

Minimum mean 7-day low flows were determined for North, the scrub-covered control catchment, and the equivalent flow determined for South, the pine catchment. Minima usually occurred at any time between January and May.

LF7 values at North and South vary considerably from year to year (Fig. 5.8). At South there is a reduction in low-flow levels after planting as shown by the increasing difference between the catchments. As for annual flows, this difference was getting smaller in the latter half of the study. The high variation in South LF7 values and the reversed trend after mid-rotation is the reason why trend tests could not pick any trend with time.

Like Fig. 5.5 for annual flows, there is a separation in the low-flow values for the calibration and following periods (Fig. 5.9). Unlike annual flows, however, these separations are not as clear and there are some significant outliers from the trends.

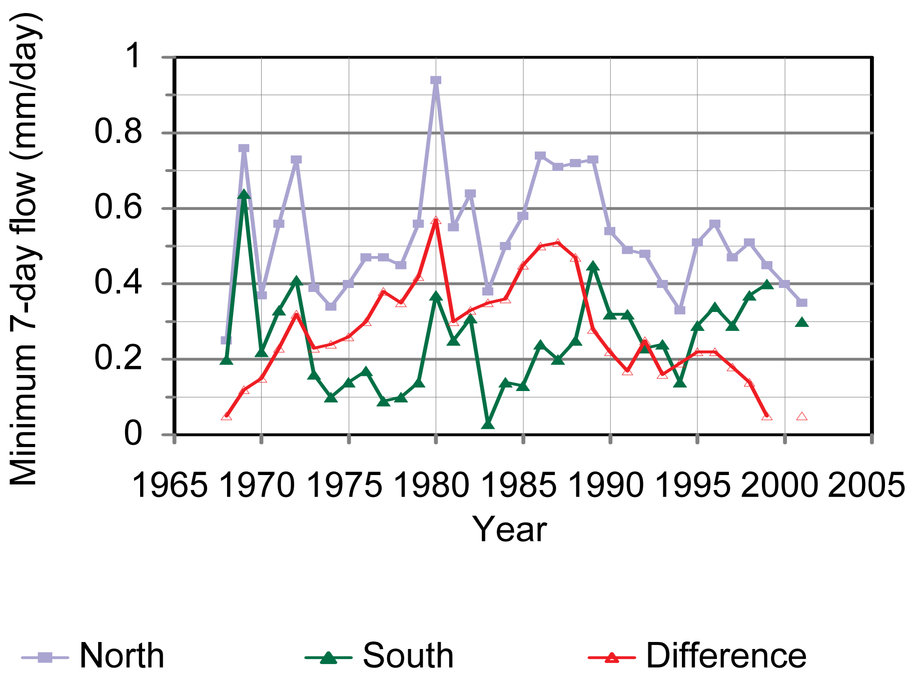

Fig. 5.8 Annual minimum 7-day low flows at Moumoukai North (scrub control) and South (pine) catchments

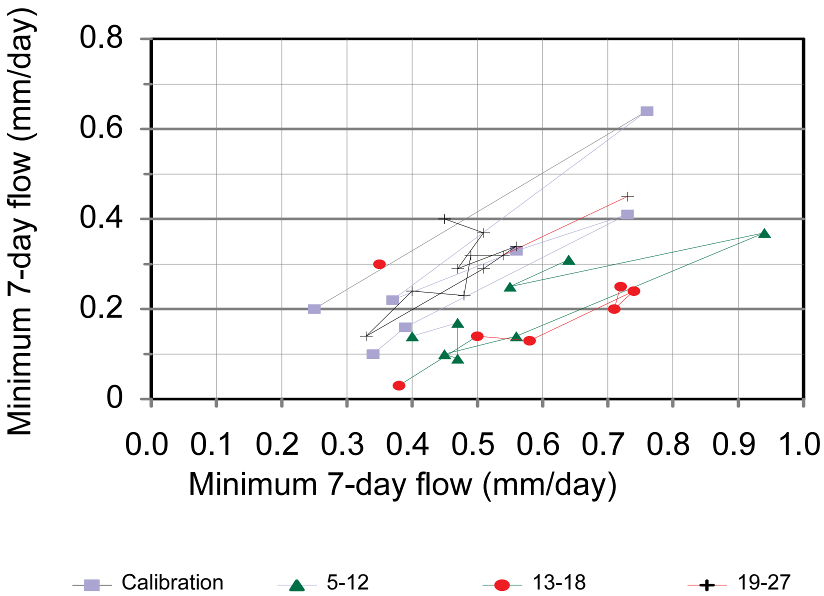

Fig. 5.9 Annual minimum 7-day flows at the South radiata pine catchment compared to those at the scrub-covered control catchment.

While there is a scatter of points when the LF7 at South is compared to North (Fig. 5.9), on average the differences after planting are distinct (Table 5.4). MALF7 values at North are more or less similar for the four stages of pine growth at South where they have decreased by about 0.2 mm/day while the trees grow. However, there is a return to pre-planting levels at South once past mid-rotation (Figs 5.8 and 5.9; Table 5.4).

Table 5.4 Mean annual low-flows (mm/day) for North (scrub) and South (pine) catchments.

Site	Calibration	5–12 years	12–18 years	19–27 years
Moumoukai North	0.49 ± 0.14	0.56 ± 0.11	0.61 ± 0.11	0.48 ± 0.06
Moumoukai South	0.29 ± 0.13	0.20 ± 0.07	0.17 ± 0.16	0.31 ± 0.05
Difference (North-South)	0.2	0.36	0.44	0.17

Peak flows

Flow separation by the Hewlett & Hibbert (1967) method was used to demarcate storms. Peaks at North were the base for comparison with the planted catchments and, on average, over 80 storms each year separated out. Up to three peaks were separated out in any given day, the criterion for a minimum storm size being set at 0.25 mm. Data sets were also generated for South and Central catchments. Although the timing of the majority of peaks at North and the planted catchments coincided, a difference of more that 6 hours meant they were not considered comparable and were rejected from the data set. In each year, there were about 10 events at North that did not allow comparison with South and vice versa. The peak flows making up the data set will be slightly lower than the actual peaks as the database used was instantaneous flows at 1-hourly intervals.

An annual peak-flow series (Fig. 5.10) was derived and a quick screening using mass curves of the peak flows shows that at about 3 years after planting, peak flows began to decrease at South when compared to those from North (Fig. 5.11); this can also be seen in Fig. 5.10 where the gap between the two lines widens. Annual peak flows at North ranged between 90 and 4.8 L/s/ha.

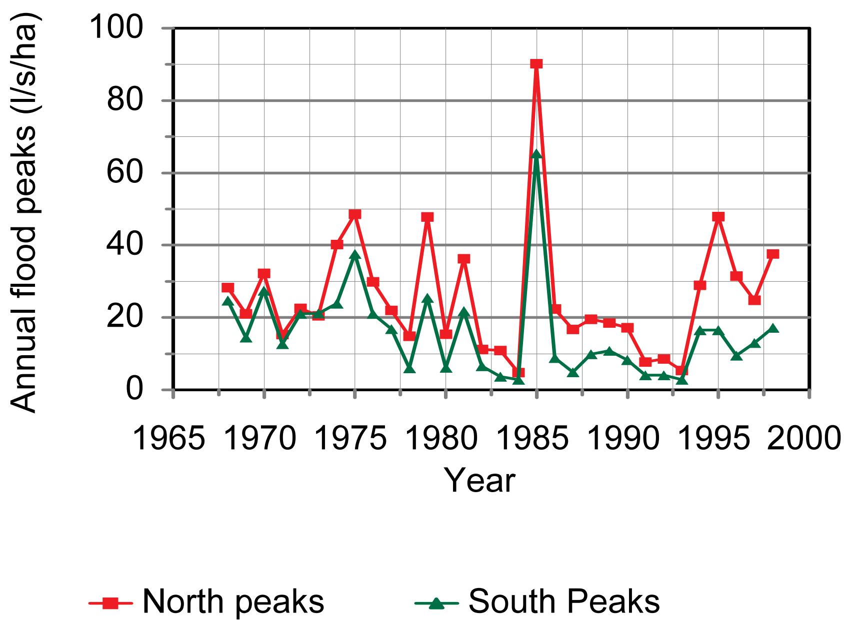

Fig. 5.10 Annual peak flow series for Moumoukai North (scrub control) and South (pines) catchments.

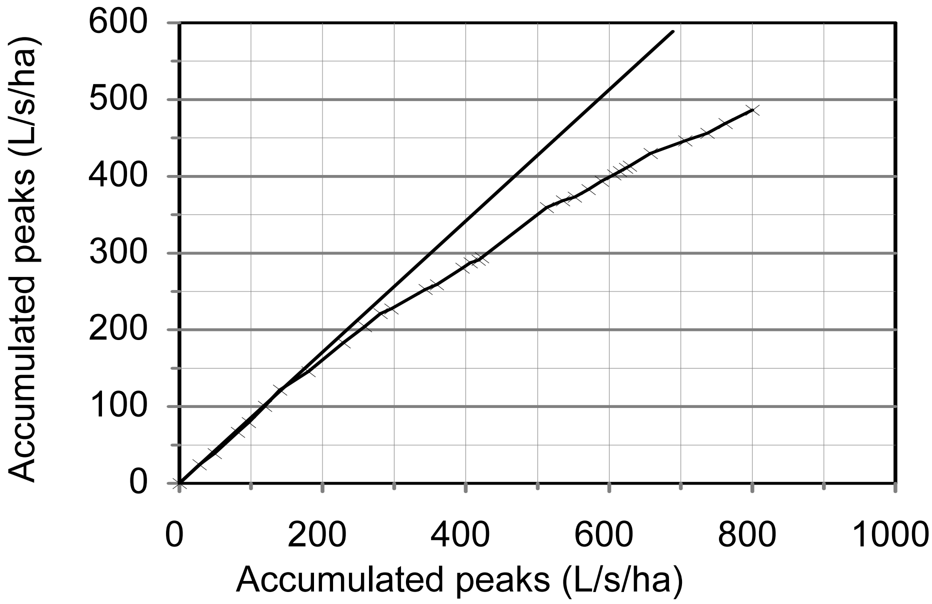

Fig. 5.11 Mass curve of annual maximum floods peaks (L/s/ha) for Moumoukai South in pines v Moumoukai North in scrub.

Because there seemed to be little difference between the two catchments for the first 6 years, data for 1968–1973 were used to determine a calibration regression upon which to assess change:

South = 0.86±0.56 × North + 0.17±13.4 l/s/ha $\qquad r^2 = 0.820$; SE = 2.72; $n = 6(5.8)$

Based on this equation, predictions were made for the South catchment flood peaks. Storm peaks declined by about 8 L/s/ha (Table 5.5) and, unlike water yields which appeared to be increasing at the end of the study period, there is little sign of change (Fig. 5.11).

Table 5.5 Annual flood peaks (L/s/ha) for North (scrub) and South (pine) catchments.

Site	Calibration	Post-calibration	Prediction
Moumoukai North	23.9 ± 4.4	26.4 ± 7.3	
Moumoukai South	20.3 ± 4.2	14.6 ± 5.3	22.9

Over 560 storms were separated out with corresponding data for North and South catchments over the 30-year period. These have been summarised in Table 5.6 by flow class and 6-year time periods throughout the study and the factor South/North plotted in Fig. 5.12. During the calibration period, South storm peaks were about 0.85 of North in all flow classes. In the four subsequent periods average flows at North in all but the > 20

L/s/ha flow class were similar to the calibration period. In the period 4–9 years after planting, storm peaks at South had decreased considerably in relation to North, and these were tending to stay more or less lower throughout the rest of the study. The smallest flow class was least affected and there is some variability due partly to small sample sizes, especially in the >20 L/s/ha samples

Table 5.6 Average storm peaks for differing size classes and for 6-year periods throughout the study at Moumoukai catchments North (scrub covered control) and South (planted in radiata pine); 1968–1973 is the calibration period.

	>20 L/s/ha			10–20 L/s/ha			5–10 L/s/ha			1–5 L/s/ha		
Period	North	South	No.	North	South	No.	North	South	No.	North	South	No.
1968–1973	25	21.8	5	14.2	12.4	14	7.21	6.07	20	2.25	1.91	84
1974–1979	35.6	22.3	7	14	8.5	14	7.44	3.93	11	2.38	1.25	61
1980–1985	48.3	29.8	3	12.6	5.3	7	7.02	2.99	13	2.1	1.26	89
1986–1991	22.5	8.8	1	15.2	6.9	15	6.71	6.05	19	2.13	1.52	84
1992–1997	31.6	13.8	6	12.4	6.4	9	6.85	3.28	13	2.21	1.58	88
Total			22			59			76			406

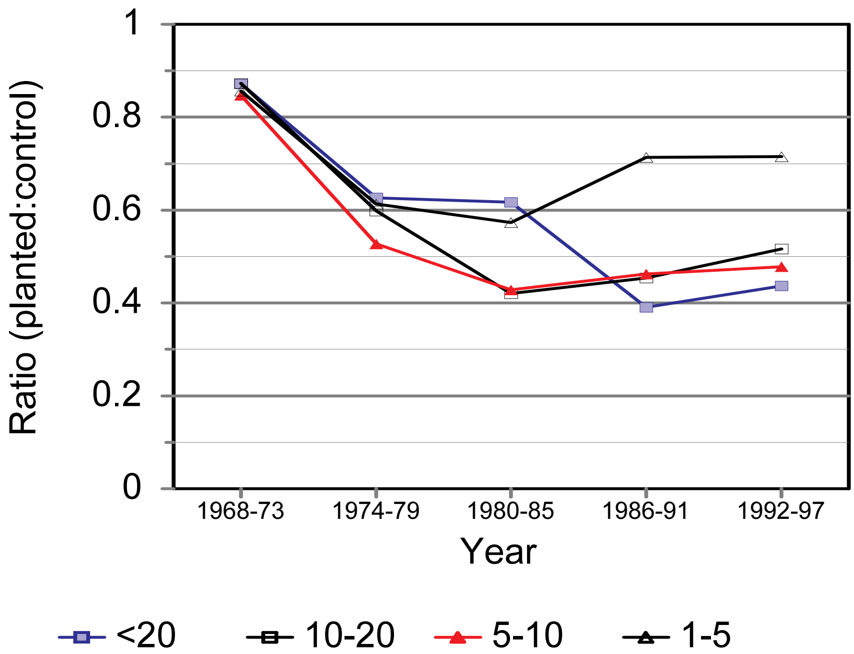

Fig. 5.12 Ratio of average storm peaks from the planted South catchment to that from the-scrub covered North catchment at Moumoukai.

5.3 Tokoroa Suite

A suite of catchments near Tokoroa (Table 5.7) has mixed land cover with pine plantations in a number of catchments. They are part of the Taupo Pumice hydrological region (Toebes & Palmer 1969) and have a substrate of volcanic origin, much of it ash deposits. Dell (1982) carried out a 3-year study in parts of these catchments and noted much of the plantation establishment had begun in 1969, which predated flow recording; further planting has occurred since. Much of the plantation area had been established in native forest, regenerating forest or scrub.

Table 5.7 Waikato Region: Tokoroa Suite catchments with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Waimakariri @ Waimakariri Road	Dec 1977	Apr 1987	77	Exotic + native
Oraka @ Pinedale	Jul 1979		136	Exotic + native + pasture
Waipapa @ Ngaroma Road	Apr 1964		137	Native + pasture

Although the 3 years of Mamaku streamflow data presented by Dell (1982) (Table 5.8) 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 50% and 14% of annual precipitation, respectively. It would be anticipated that these should be similar, which brings into question the watertightness of the catchments. There are also questions over the geological influences on springs and groundwater flows disappearing and reappearing in the catchments.

Table 5.8 Water yield from catchments in the Mamaku Plateau (after Dell 1982).

	1979–1980		1980–1981		1981–1982	
	PTTN	Yield mm (%)	PTTN	Yield mm (%)	PTTN	Yield mm (%)
Native forest	2712	1342 (50)	2050	1103 (54)	2350	1175 (50)
Exotic forest	2268	476 (21)	1872	422 (23)	1743	387 (19)
Exotic + native	2227	301 (14)	1820	290 (16)	1485	295 (20)
Pasture + forest	1880	1309 (69)	1458	1079 (74)	1650	1039 (63)

Because (a) the variations in streamflow yield will be more a consequence of regional geology than vegetation cover, (b) much of the land conversion to plantation was established before flow records began, (c) the streamflow record from Waimakariri Stream is short, and (d) there is a lack of suitable control data from which to make comparisons with Oraka Stream (there was no trend in the annual flow record from here), no more analysis has been carried out.

5.4 Purukohukohu Suite

Stations within the Purukohukohu Experimental Basin (30 km south of Rotorua) were established in the 1960s–70s (Table 5.9). There are differences in flow from these catchments that have been attributed to the variable nature of the volcanic geology (Taupo Rhyolite hydrological region) as the catchment geographic boundary may not reflect the hydrologic boundary (Dons 1987). Nonetheless, this suite is one of the better ones monitored in New Zealand. Puruki is one of the few catchments in New Zealand that have been monitored throughout a full rotation of pines.

From pasture, Puruki catchment was planted in 1973, a first thinning was carried out in the various sub-catchments between 1979 and 1981, and again in 1983 at Tahi and 1984 at Toru (Brownlie & Kelliher 1989). Puruki was harvested in 1996–1997 and replanted by 30 September 1997.

Table 5.9 Waikato Region: Purukohukohu Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Purukohukohu @ Weir	Jan 1967	May 1984	1.69	Exotic + pasture + native
Purukohukohu @ Puruorakau	Dec 1968	Jan 1987	0.372	Native
Purukohukohu @ Puruki	Dec 1968		0.344	Exotic
Purukohukohu @ Purutaka	Dec 1968		0.225	Pasture
Purukohukohu @ Puruki-Rua	Feb 1971	Jan 1995	0.087	Exotic
Purukohukohu @ Puruki-Toru	Feb 1971	Jan 1995	0.138	Exotic
Purukohukohu @ Puruki-Tahi	Dec 1972	Jan 1995	0.059	Exotic
Puruwai @ Gorge	May 1972	Oct 1994	0.278	Native
Te Waru @ Puruhou	Dec 1979	Jan 1987	0.35	Pasture

Dons (1987) carried out a four-year comparative study of three catchments (Purutaka, Puriki and Puruwai) when the pines were aged 8–11 years. He suggested that the hydrologic boundary for Purutaka was not the topographic boundary and for some, but not all, analyses he used an adjusted area. While this may be relevant if we are trying to assess differences between various land-uses at any particular time, this report is more interested in change. As long as a control catchment can be found with stable cover to provide an index for comparison, watertightness may not be an issue. Only two of the catchments have been monitored since the inception of the study: Purutaka, which has been maintained in pasture, and Puruki, which was monitored initially in pasture, then throughout one forest rotation to include harvesting, and then for a few years thereafter. Data from the Puruki sub-catchments (Rua, Toru, and Tahi) have not been used in this study.

Rainfall

Rainfall has been measured at site No. 4 at the head of the Purukohukohu Basin. Over the 30 years of record, the average was 1590 mm with a range from 1200 to 2120 mm. There is no overall trend with time as shown by the Cox & Stuart test for trend and an almost straight line when accumulated rainfall is plotted over the 30-year time frame. There is some variation brought about by sequences of wet and dry years.

Streamflow

The variability of streamflow yields in the region is demonstrated in Table 5.10 where comparative yields are given for four of the Purukohukohu catchments under more or less stable land covers. While rainfall will vary from catchment to catchment, it may not be large, as data from three catchments in Dons (1987) had a range of 6%, 1398–1484 mm. There is over 100% difference in streamflow yield from two pasture catchments, one of which has a yield smaller than the two native forest catchments, which is contrary to general expectations. This difference can be attributed to the problems in determining true catchment areas (Dons 1987) or can be attributed to different drainage characteristics in the two catchments with one contributing more to deep seepage than the other, this not being measured as streamflow at the weirs. Another factor that may influence the yields is the presence of springs in at least one catchment. The relationships between Puritaka and the other three catchments as determined by regression analysis were all highly significant, explaining between 85% and 95% of the variation in the data.

Table 5.10 Comparative annual streamflow yields (mm) from Purukohukohu catchments under stable land-cover.

Period	Purutaka Pasture	Te Waru Pasture	Puruwai Native forest	Puruorakau Native forest
1980–1986	250	530	360	280
1973–1986	300		430	
1969–1986	310			330

Because records from Puruorakau and Te Waru ceased in 1987, and that from Puruwai has a 5-year gap from 1987, by default Purutaka is the only long-term candidate as a control catchment upon which to assess any changes in streamflow at Puruki as a consequence of afforestation. The mass curve of Purutaka streamflow against No. 4 rainfall is a straight line indicating a very good correlation between them, which confirms the use of Purutaka as the control catchment (Fig. 5.13). While we could use No. 4 rain to predict streamflow at Puruki, the use of a streamflow record at a site with the same, or similar, rainfall regime usually is better for prediction purposes.

In the second year after planting Puruki (the point where accumulated rainfall = 10 000 mm in Fig. 5.13) there is a discernible decrease in streamflow, as shown by the deviation from the initially straight line, which is attributed to, initially, regrowth of rank grass (Waugh 1980) then tree growth. An interesting feature of the mass curve in Fig 5.13 is the upward trend in streamflow as the trees matured. This phenomenon was also seen in the pine catchment at Moumoukai indicating that perhaps there is a physiological change affecting tree water use at this time in the rotation, and is also reflected in the shifting relationships between Puruki and Purutaka over time (Fig. 5.14).

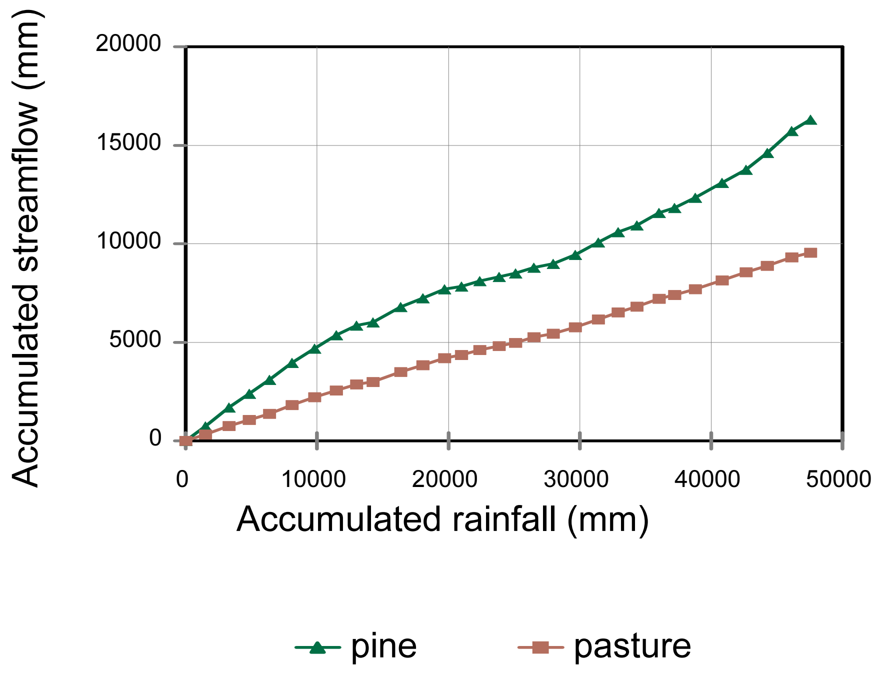

Fig. 5.13 Mass curve of streamflow at the Purutaka pasture catchment and Puruki in pines plotted against No. 4 rainfall showing changes at Puruki as the forest matured. The origin is the beginning of 1970, which is the beginning of the rainfall record.

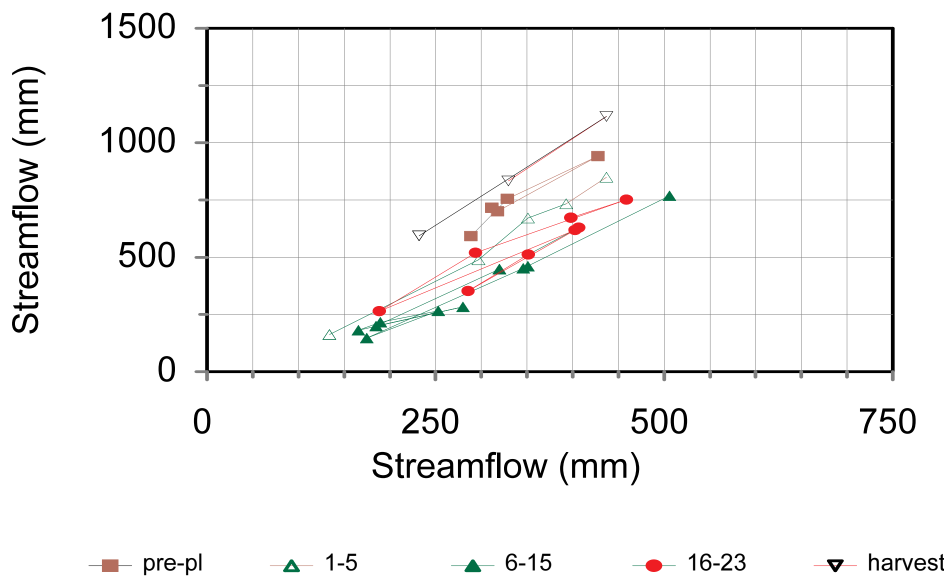

Fig. 5.14 Relationship between streamflow yields at Puruki with pines and the Purutaka pasture catchment showing the varying relationship with forest management and stand age (pre-pl = pre-planting; harvest = during/after harvesting).

Equations 5.9 to 5.11 were established for each of the land management stages (determined by eye) in Fig. 5.14, except for the harvest/post-harvest data.

Pre-plant	Puruki = −150±280 + 2.29±1.02 × Purutaka	r^2 = 0.945; SE = 34; n = 5 (5.9)
1–5 years	Puruki = −50±120 + 2.27±0.35 × Purutaka	r^2 = 0.993; SE = 26; n = 5 (5.10)
6–15 years	Puruki = −140±70 + 1.75±0.25 × Purutaka	r^2 = 0.971; SE = 35; n = 10 (5.11)
16–23 years	Puruki = −90±190 + 1.80±0.54 × Purutaka	r^2 = 0.917; SE = 50; n = 8 (5.12)

Although these equations have wide confidence limits, Eqns 5.9 and 5.10 have significantly different levels (F_{test} = 53.8, F_{tab} = 5.6) as do Eqns 5.11 and 5.12 (F_{test} = 11.8, F_{tab} = 4.5) while Equations 5.10 and 5.11 have significantly different slopes (F_{test} = 9.3, F_{tab} = 4.8) and levels (F_{test} = 41.2, F_{tab} = 4.8). Thus, each grouping can be considered different populations reflecting the plantation growth stage and its use of water.

To determine the change in streamflow from Puruki between the forested and pasture states, the calibration equation Eqn 5.9 was used to determine streamflow from Puruki as if it was still in pasture (Fig. 5.15). As expected the first five years upon which the relationship was determined shows a very good fit, giving support to the use of Eqn 5.9 for model calibration. After that, there is a diminishing yield reaching a maximum of about 350 mm per year before dropping back to about 250 mm. Superimposed on that generalisation is the effect of rainfall and it can be seen that in dry years the differences are not as large as in wet years, although this relationship is weak with a wide scatter of points. Average yields for the phases of land use and tree growth are listed in Table 5.11. Over the 23 years from planting to harvest, the reduction in water yield is 5100 mm or 220 mm/year. Streamflow during and after harvesting is higher than in the pre-plant pasture state and would reflect lower water use because the catchment would have been nearly devoid of growing vegetation after harvesting.

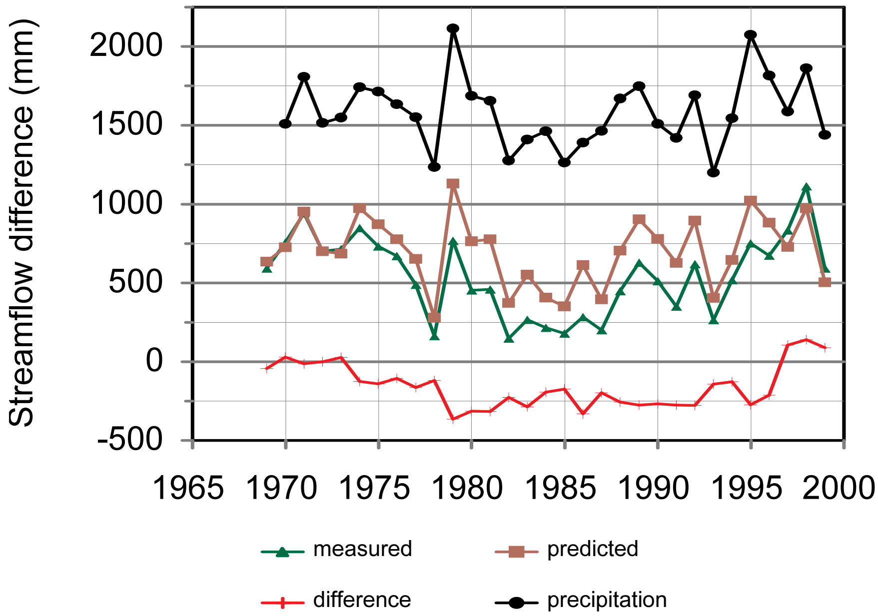

Fig. 5.15 Rainfall from No.4 gauge and streamflow from Puruki in pines, both measured and predicted as if still in pasture. The difference between predicted and measured Puruki streamflow is the effect on streamflow as a result of afforestation.

Table 5.11 Average rainfall (mm) and streamflow yields (mm) for Puruki, both measured and predicted, and for Purutaka for the catchment in pasture, in trees of differing age classes, and during/after harvest.

Period	Rainfall	Predicted streamflow	Measured streamflow	Reduction	Purutaka streamflow
Calibration	1600	740	740	0	340
1–5 years	1580	710	580	130	330
6–15 years	1540	610	340	270	280
16–23 years	1630	770	540	230	350
After harvest	1630	740	850	110	340

Low flows

Minimum 7-day low flows for Puruki and Purutaka are shown in Fig 5.16. MALF7 determined for the various stages of the forest rotation showed that when both catchments were in pasture, Puruki had a higher LF7 values than Purutaka (Table 5.12). During the study Purutaka dried up for short periods in four years but Puruki did not, even with plantation cover. Compared to Purutaka, there was little change in LF7 in the first five years after planting but there were decreases as the trees grew. When the catchment was in mature trees, LF7 increased to pre-treatment levels compared to Purutaka but this period and during harvesting were wetter than the earlier periods (Table 5.11). Whether this increase in low flows is due to the general rainfall increase or to the trees using less water is debatable but during/after harvesting there is a clear rise that can be attributed to the removal of the trees and the more or less bare-ground situation.

Table 5.12 Mean annual 7-day minimum flows(mm/day) for Puruki (pines) and Purutaka (pasture) catchments

Site	Calibration	1–5 years	6–15 years	16–23 years	Harvest
Puruki (pines)	0.13 ± 0.05	0.14 ± 0.10	0.06 ± 0.04	0.15 ± 0.10	0.25 ± 0.12
Purutaka (pasture)	0.03 ± 0.02	0.06 ± 0.06	0.05 ± 0.03	0.05 ± 0.04	0.04 ± 0.06
Difference (pines less pasture)	0.1	0.09	0.01	0.1	0.21

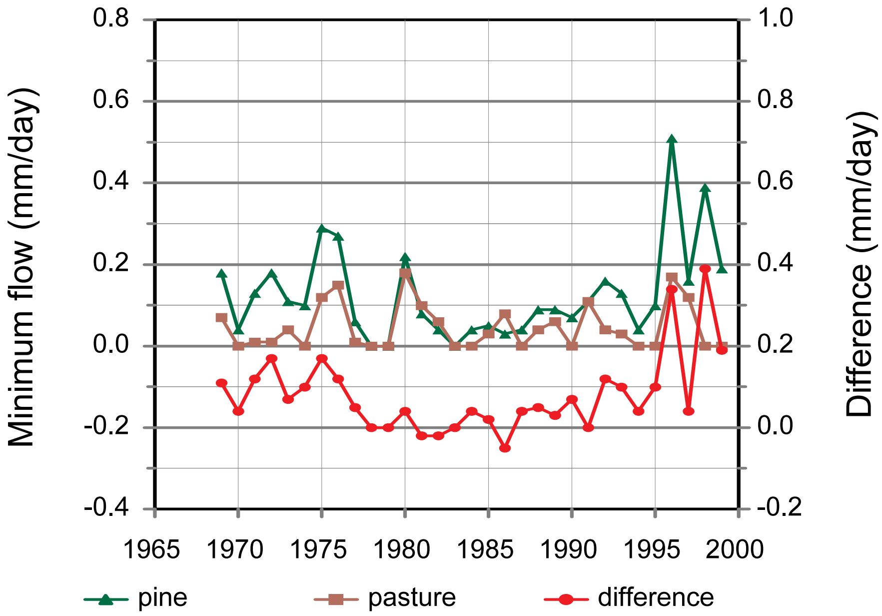

Fig 5.16 Annual 7-day minimum flows (mm/day) for Puruki (pines) and Purutaka (pasture) catchments.

Storm peaks

Storm peaks were derived as two series. The first series was the largest annual storm at Puruki (Fig. 5.17) and the second series contained all storms at Puruki where there was an equivalent storm at Purutaka above 1.0 L/s/ha.

From Fig. 5.17 it is obvious that the presence of a forest cover has had an ameliorating effect on storm runoff in that there are no flood peaks greater than 5 L/s/ha from the first year after planting until after harvesting was carried out. This is confirmed when the larger data set was used (Table 5.13). Prior to planting, flood peaks at Puruki and Purutaka were of the same order of magnitude. After planting, flood peaks at Puruki decreased considerably compared to Purutaka where average peaks in all flow classes remained about the calibration period levels. Even after harvesting, the few flood peaks remained at levels below Purutaka even though soil moisture levels would have increased and conditions would have been more favourable for increased flood peaks to be generated. Improved soil infiltration characteristics after cessation of grazing and establishment of trees would account for this.

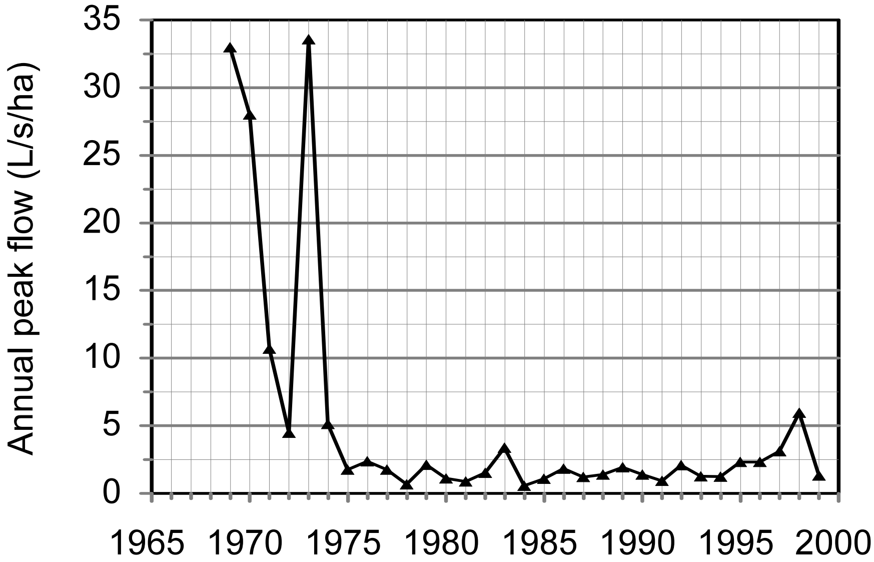

Fig 5.17 Annual flood peak series for Puruki. There are no large floods while the catchment was covered in pines.

Table 5.13 Average storm peaks for differing size classes for five stages of land management at the Puruki (Pki) and Purutaka (Ptaka). Calibration period is 1969–1973.

	>20 L/s/ha			10–20 L/s/ha			5–10 L/s/ha			1–5 L/s/ha		
Period	Pki	Ptaka	No.	Pki	Ptaka	No.	Pki	Ptaka	No.	Pki	Ptaka	No.
Calibration	21.3	29.1	4	17.5	15.5	4	7.07	6.48	6	3.33	1.91	19
1–5 years			0	1.8	15.8	4	1.16	7.49	4	1.47	2.95	18
6–15 years			0	1.5	12.5	1	1.31	7.58	5	0.91	1.86	38
16–23 years	2.3	21.5	1			0			0	1.1	2.05	38
Post-harvest	6	22	1	1.3	10.1	1	2.1	7.35	5	1.32	1.98	16
Total			6			10			20			129

Quickflow and baseflow

The streamflow regime at Puruki is dominated by the very large baseflow component, about 90% at Purutaka and 80% at Puruki while under pasture (Table 5.14). Thus, as a consequence of afforestation, there is little scope for a substantial reduction in quickflow. There was a small reduction at Purutaka in the middle sections of the study when rainfall was slightly lower, while at Puruki there was a larger reduction because amounts were higher to begin with. The bulk of the flow reduction came from baseflow, which reached about 300 mm in the middle of the plantation rotation.

Table 5.14 Quickflow and baseflow (mm and % of total flow) for five stages of land management during the study at Puruki and Purutaka catchments.

		Quickflow		Baseflow	
Period	Rainfall	Puruki	Purutaka	Puruki	Purutaka
Calibration	1600	140 (19)	50 (14)	600 (81)	290 (86)
1–5 years	1580	70 (12)	30 (9)	510 (88)	290 (91)
6–15 years	1540	40 (11)	30 (10)	340 (89)	250 (90)
16–23 years	1630	50 (8)	30 (9)	540 (92)	320 (91)
Post-harvest	1630	110 (13)	50 (15)	(740 (87)	280 (85)

6. Bay of Plenty Region

Three possible sets of catchment with substantial plantation forests were identified in the Bay of Plenty Region based on the Pokairoa Stream, the Kaituna River, and the Tarawera River.

Streams were monitored in the Pokairoa Stream catchment (Pokairoa Stream @ Railway Culvert NIWA site 14550; Pokairoa Stream @ Whiteley NIWA site 15469; Poumako Stream @ Ridgeway Road NIWA site 15471; Mangaharakeke Stream @ Parapara Road NIWA site 14572) about 18 km south-east of Rotorua from 1993 to 2001. Harvesting commenced at about the time monitoring began (Rowe et al. 2001d). There are, therefore, no good long-term control catchments as harvesting occurred in all catchments within 3 years of recording commencing. Increases in flow were identified but the lack of a suitable, stable control catchment means that the increases could not be easily related directly to the areas harvested.

While the Kaituna River Suite held early promise, the main flow record at Te Matai (EBOP site 14614) is tidal, and there is also outflow from Lake Rotoiti, thereby ruling out this station for simple comparative analysis.

The Tarawera River (EBOP site 15302) has been subject to analysis a number of times with the Whakatane River (NIWA site 15514) being used for comparison (Dons 1986; Pang 1993). No further analysis is being carried out here but Dons reported that for planting 28% of the Tarawera River catchment, land-use change caused a flow reduction of 4.5 m^3/s or 13% of the calibration period flow. This change in flow yield is equivalent to 160 mm for the whole catchment, or 570 mm for the area planted; annual rainfall was of the order of 2000 mm.

7. Gisborne District

The major area in the Gisborne District that has undergone afforestation is about 45 km to the north-west of Gisborne. Extensive planting of eroding hill country began in the Mangatu/Waipaoa area of the Gisborne District in 1960 (Allsop 1973). Therefore this region has the potential for evaluating changes in flows resulting from forest establishment. The sites of interest are listed in Table 7.1.

Table 7.1 Gisborne District: Mangatu Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Waipaoa @ Waipaoa Station	Jan 1979	Mar 1987	183	Exotic + native
Waipaoa @ Kanakanaia Bridge	Jan 1960		1580	Exotic + native + pasture
Mangatu @ Omapere	Aug 1983		183	Exotic + native
Waihora @ No. 3 Bridge	Dec 1986		110.6	Pasture
Waikohu @ No. 1 Bridge	Jul 1978		26.4	Pasture + native
Waikohu @ Mahaki	Oct 1979		144	Pasture + native
Waingaromia @ Terrace	May 1979		175.3	Exotic + pasture

About 10.6 km^2 of the Mangatu River catchment was in plantation in 2002 (NZMS-260 X16 2002), about 6% of the area, with the balance in native forest and pasture. Plantation establishment began in 1960 (Allsop 1973) and there was no major change in extent of plantations between the early 1970s (NZMS-1 N79 1st Edn 1973, field check 1970; N88 1st Edn 1974, field check 1970) and the present. Flow recording did not begin until the trees were at mid-rotation in 1983 and the record can be considered continuous from 1986 to 2000. Mangatu River is located in the Raukumara hydrological region.

The upper Waipaoa River catchment, also in the Raukumara hydrological region, has the most extensive area of plantations. By 1999 about 104 km^2 (57% of the catchment) was in plantation with the balance mainly in pasture (NZMS-260 Y16 1999). As for the Mangatu River catchment, the establishment of plantations began in 1960 and by 1974 at least 44 km^2 had been planted (NZMS-1 N79 1st Edn 1973, field check 1970; N80 1st Edn 1973; N88 1st Edn 1974, field check 1970; N89 1st Edn 1965, field check 1963) with the balance by 1984. Flow records did not begin until after the majority of the forest had been planted, ceased after 8 years and had many missing records.

Flow recording at the Waingaromia River began in 1979, before any significant plantations were established. By 1984, 9% (14.6 km^2) had been planted (NZMS-260 Y16 1st Edn 1984; Y17 1st Edn 1984), this having taken place after 1965 (NZMS-1 N89 1965, field check 1963). No more significant plantations were established by 1999 (NZMS-260 Y16 1999; Y17 1998; TUMONZ (Vision Software 2002)). The Waingaromia River is located in the East Coast hydrological region and was designated the representative basin for that region with annual rainfall about 1650 mm (NZMOW 1970).

Waikohu River @ No. 1 Bridge (denoted Waikohu1) and @ Mahaki (Raukumara hydrological region), and Waihora River (East Coast hydrological region) catchments are predominantly pasture covered with no, or very little, plantations present (NZMS-260 X17 1st Edn 1985; NZMS-260 Y17 1998; TUMONZ (Vision Software 2002)), hence, provide opportunities as control catchments.

The Waipaoa River @ Kanakanaia Bridge (denoted Kanakanaia) has been gauged since 1960 when planting in the catchment began. At this site the Waipaoa River contains all other catchments in this suite, thus integrating all changes that have taken place. The majority of the plantations are in the Mangatu River, upper Waipaoa River and Waingaromia River catchments with only an additional few square kilometres of plantations scattered throughout the catchment. Summing the plantations from these sub-catchments and allowing for the additional plantations outside these, we get an estimate of about 150 km^2 planted between 1960 and 1984 with little planted since. This is about 9.5% of the catchment in plantations.

Apart from the upper Waipaoa River, the amount of conversion from pasture to plantation forest as shown by the maps is small, and as such, hydrological effects may be difficult to detect especially as most flow records began after the main plantation establishment, the data from Waipaoa at Kanakanaia being the exception. The upper Waipaoa River with over 50% afforested would have been a real candidate for analysis but the commencement of flow recording after most of the plantation establishment had taken place, the short duration of the record, and the number of missing periods makes it almost impossible to use. Similarly, there are few rainfall records that could be used as a surrogate for the streamflow records against which to make assessments of change.

Rainfall

Rainfall records spanning the period 1960 to 2000 from the region are few, only Waipaoa Station (NIWA site D87281) having a long -term record, but there are substantial gaps in the late 1980s–1990s when flow records were being collected at most stations. Interpolation of normals from about 25 stations in and around the Waipaoa system (NZMetS 1973; Tomlinson & Sansom 1994) gives an indication of the annual rainfall for the different catchments: Mangatu River catchment rainfall = 1700 mm, range from about 1150 mm at the gauging station to over 2500 mm at the top; Upper Waipaoa River 1900 mm, range 1350–2500 mm; Waikohu River 1500 mm, range 1100–2000 mm; Waingaromia River 1600 mm, range 1300–2000 mm; average 1650 mm (NZMOW 1970); Waihora River 1400 mm, range 1200–1900 mm.

The average of all complete years of rain at Waipaoa Station, 1352 mm, was almost the same as the 1961–1990 normal (1359 mm; Tomlinson & Sansom 1994). For 1981 to 2000 (less 5 years of missing data) when most streams were being gauged the average rainfall at Waipaoa Station was 1290 mm.

Streamflow

Attempts at producing mass curves between the streamflow stations and Kanakanaia or with Waikohu1 were hampered by missing records at one or other of the sites in each pair. Reasonably consistent relationships over a 10-year period were found for Kanakanaia and Waikohu against Waikohu1 and for Mangatu, Waingaromia, Waikohu and Waikohu1 against Kanakanaia. These all indicate that in the 1990s, at least, there were no changes of note happening to the streamflow regime at these sites. One change was noted when Mangatu was compared to Waikohu1; a decrease in flow occurred in the mid-1990s but there was no significant planting of pasture going on in the few years before that time. The change was not picked up when Mangatu was plotted against Kanakanaia. Because the major afforestation had occurred much earlier (1960s to mid-1980s), no trends were expected, and except for the one unexplained change at Mangatu River, none were detected.

Streamflow yields for the catchments are shown in Table 7.2 with yields from Kanakanaia being used for the comparison – there is little difference there between periods. The rainfall data have been determined from interpolation of rainfalls normals noted above and must be considered to be very approximate because there are steep rainfall gradients to the north-west of the region where rainfall can exceed 2500 mm, i.e., the headwaters of Mangatu, Waipaoa, and Waikohu rivers. Within these limitations, it could be inferred that the Waipaoa River catchment has the lowest yield with respect to rainfall.

Table 7.2 Streamflow yields (mm & approximate %) and approximate average catchment rainfalls (mm) for the Mangatu catchment suite.

Site	Dominant vegetation	Approximate rainfall	Years	Streamflow	Kanakanaia streamflow
Waipaoa	Plantation	1900	4	530 (30)	640
Mangatu	Pasture	1700	13	1050 (60)	630
Waingaromia	Pasture	1600	16	650 (40)	610
Waihora	Pasture	1400	9	540 (40)	570
Waikohu1	Pasture	1500	17	1000 (70)	630
Waikohu	Pasture	1500	18	870 (60)	630

Low flow

The annual minimum 7-day low flows were extracted for the catchments but no trends were detected, probably because the vegetation was more or less stable for the measurement periods at the planted catchments, with the exception of Kanakanaia. MALF7 for Kanakanaia, the only station with a long-term record, is 0.17 mm/day with a range of 0.03–0.39 mm/day (Fig. 7.1). There appears to be a minimum value of the order of 0.05 mm/day in the very dry years.

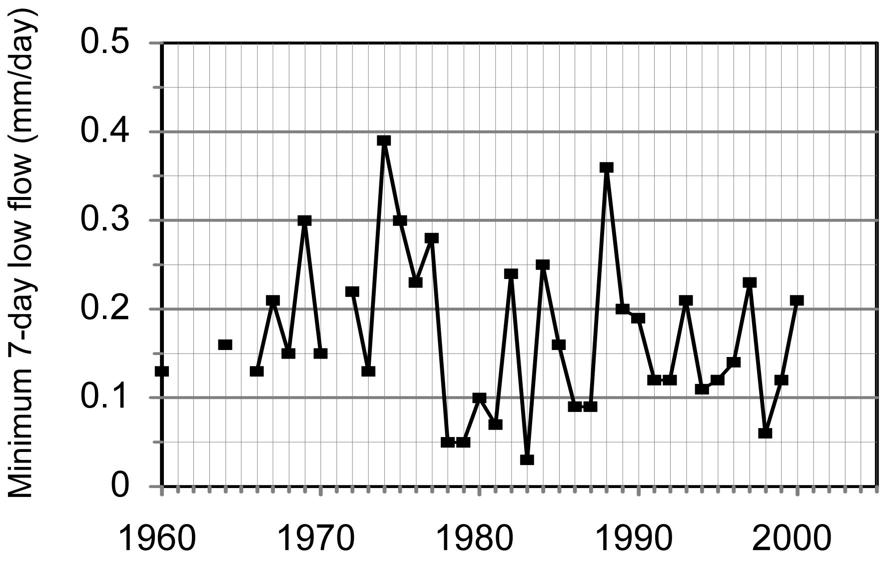

Fig. 7.1 Annual minimum 7-day low flows for the Waipaoa River at Kanakanaia

Comparisons between catchments for given periods are listed in Table 7.3. It appears that geology may have a part to play in the low flows listed here in that the MALF7 values are considerably lower for the Waingaromia and Waihora rivers than for the other rivers. The geology here is sandy or muddy siltstones while the westernmost rivers have shattered argillites and sandstones to the west and mudstones and siltstones to the east (Toebes & Palmer 1969). Rainfall is also lower in the Waingaromia River and Waihora River catchments. Mangatu River has the highest MALF7, which is likely to be a consequence of the high rainfall in the head of the catchment. No land-use factor can be attributed to these data.

Table 7.3 Mean annual minimum 7-day low flows (mm/day) for catchments in the Mangatu suite.

Period	Mangatu	Mangatu	Waikohu	Waikohu1	Kanakanaia	Waingaromia	Waihora
1960–2000					0.16		
1979–1986		0.2		0.3	0.12		
1984–2000	0.51		0.14	0.31	0.16	0.02	
1987–2000	0.51		0.14	0.29	0.16	0.02	0.04

8. Hawke's Bay Region

Hawke's Bay has one of the most extensive networks of gauged rivers with plantations in New Zealand and I have divided the area into a northern region about Wairoa and a southern region centred on Eskdale north of Napier. Included in the Esk Suite region is a paired catchment study set up in the Pakuratahi and Tamingimingi streams. Many of the exotic forests established in these catchments existed well before streamflow measurements began, some as early as the 1940s (Forestry Insights 2002), hence the records generally will reflect mixed land use with mature forests.

8.1 Wairoa Suite

Table 8.1 lists catchments in the northern part of the Hawke's Bay Region that have areas of plantation forests or which can be used as stable control catchments to assess streamflow changes. These are supplemented by three catchments in the Gisborne District to the south-west of Gisborne: Te Arai River, Gentle Annie Stream, and McPhails Stream.

Table 8.1 Hawke's Bay Region: Wairoa Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Kopuawhara @ Railway Bridge	Apr 1981		54.5	Exotic + native + pasture
Te Arai @ Pykes Weir	Jan 1984		82.7	Pasture + native +exotic
Gentle Annie @ Weir	Oct 1983	Jan 1993	3.2	Pasture
McPhails @ Waingake Road	Nov 1983		3.98	Pasture
Ruakituri @ Sports Ground	Oct 1985		512	Pasture + native
Hangaroa @ Doneraille Park	May 1974		596	Pasture + native
Waiau @ Ardkeen	Mar 1988		1315	Native + pasture + exotic
Mokau @ SH38	Jan 1990		36.7	Native
Aniwaniwa @ Aniwaniwa	Dec 1988		50.8	Native
Hopuruahine @ The Caskades	Dec 1989		61.9	Native
Mohaka @ Glenfalls	Mar 1961		997	Native + pasture + exotic
Mohaka @ Ruapunga	Feb 1957		2370	Pasture + native + exotic

Kopuawhara Stream

One of the early plantation forests in the Hawke's Bay Region was Wharerata Forest in the Kopuawhara Stream catchment (Northern Hawke's Bay hydrological region, Toebes & Palmer 1969). Originally in pasture and scrub (NZMS-1 N106 1st Edn 1953; N107 provisional series 1944), Wharerata Forest would have been planted in the 1950s–1960s before stream recordings began, and covers 64% of the catchment above the gauging station (NZMS-260 X19 1st Edn 1990; Y19 1st Edn 1990). The nearest potential control catchments against which to assess change are the Te Arai River centred 15 km to the north and McPhails Stream a further 10 km north. Of these, the Te Arai has a small area of plantation, about 1 km^2, with the majority of the catchment in pasture (NZMS-260 X18 1st Edn 1986; TUMONZ 2000 (Vision Software 2002)). The Hangaroa and Ruakituri rivers to the north-west are other potential control catchments but are further away and an order of magnitude larger. Rainfall in the top half of the catchment is approximately 2450 mm based on interpolations of 1941–1970 normals from Sea View Station (NZMetS site D87981), Tarewa (NZMetS site D87982) and Mangatoto Station (NZMetS site D87972). Rainfall in the lower reach would be smaller than this, possibly of the order of 1800 mm, but there is little information upon which to make interpolations.

Streamflow records began at Kopuawhara Stream after the forest was established and contain many, significant, missing values, which means it is not possible to make good comparisons with other sites such as the Te Arai River and McPhails Stream. There are no suitable rainfall records either that encompass the flow record. The data available are shown in Fig. 8.1 and there is no trend obvious from this well- established forest.

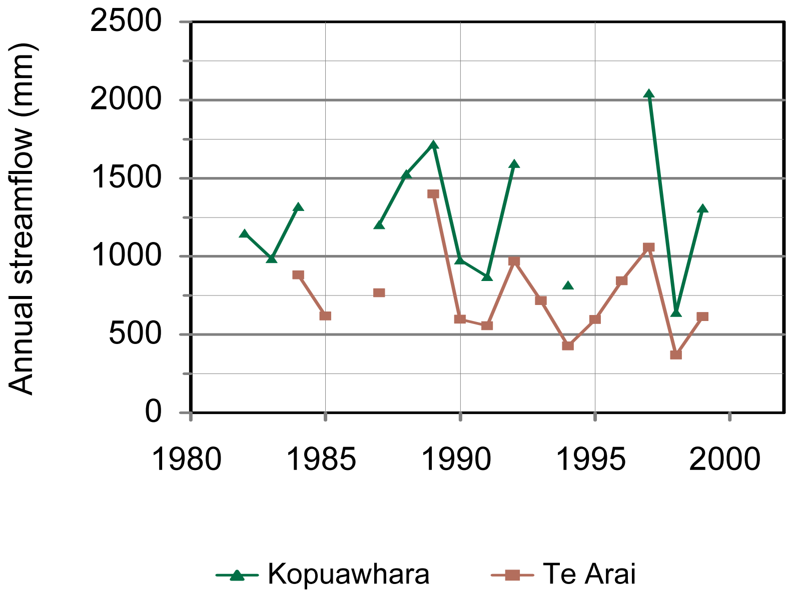

Fig. 8.1 Annual streamflow from the Kopuawhara Stream and the Te Arai River.

The almost complete series of LF7 data obtained for Kopuawhara Stream show no trend with time; the comparison with the Te Arai River being shown in Fig. 8.2. This was expected as the plantation had been well established by the time recording began.

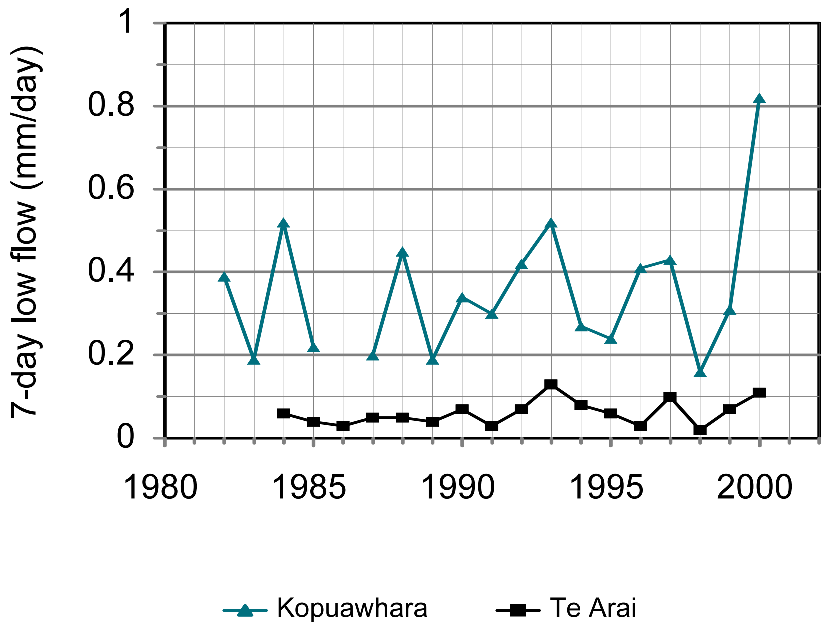

Fig. 8.2 Annual minimum 7-day low flow from the Kopuawhara Stream and the Te Arai River.

Mohaka River @ Glenfalls

The Mohaka River has been gauged at two sites, at Ruapunga since 1957 and upstream at Glenfalls since 1961. At Glenfalls, the Mohaka River catchment is nearly 1000 km^2 in area and in the Northern Hawke's Bay, Waikaremoana and Kaweka hydrological regions. The main plantation development commenced in the 1950s at Mohaka Forest and in the 1970s Awahohonu Forest was started (Forestry Insights 2002). By 2000, about 93 km^2 (9% of the catchment, mainly Awahohonu Forest) had been planted above the Glenfalls gauging station, at least on-third by 1979 (NZMS-260 V20 1st Edn 1979) with further development probably shortly thereafter. Before planting the land had been in pasture and scrub (NZMS-1 N114 2nd Edn 1974).

Good flow records have been obtained for the Mohaka River @ Glenfalls (herewith referred to as Glenfalls) and missing records were generally able to be approximated from the adjacent Ngaruroro River @ Kuripapango, the Esk River @ Waipunga and the Mohaka River @ Ruapunga (herewith referred to as Ruapunga). Details of the Ngaruroro and Esk river catchments are given in Table 8.2 for the Esk Suite.

No trends were found in the Glenfalls annual streamflow series using trend tests, or mass curves and correlation with the Ngaruroro River. The last approach used a split record, 1962–1980 and 1981–2000, and when Glenfalls annual streamflow yields were plotted against those from the adjacent Ngaruroro River, the groupings of the data points for the two series were superimposed. Annual yields for the periods were 1962–1980 Ngaruroro River 1530 mm, Glenfalls 1240 mm, ratio 0.81; 1981–2000 Ngaruroro River 1450 mm, Glenfalls 1140 mm, ratio 0.79. There would have been about 15–18 years of record that could have been considered pre-afforestation against which to assess any change.

Similarly, an analysis of annual minimum 7-day low flows did not shown any trends over time, the data being shown in Fig. 8.3. MALF7 for each of the two periods were almost the same for each catchment: Ngaruroro River 1.01 mm/day, Glenfalls 1.07 mm/day.

The lack of trend in annual yields and in minimum flows must reflect the small degree of afforestation (less than 10% of the catchment) that has taken place and the distributed nature of the afforestation over time (of the order of 10 years).

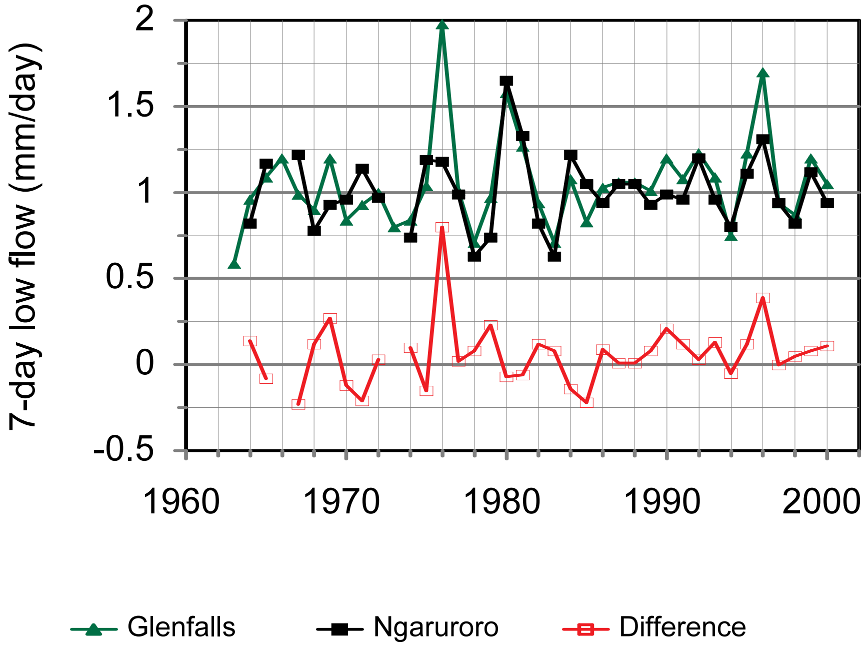

Fig. 8.3 Annual minimum 7-day low flow at Mohaka @ Glenfalls and the Ngaruroro Rivers and the difference between them.

Mohaka River @ Ruapunga

The Mohaka River @ Glenfalls is about 42% of the Mohaka River @ Ruapunga catchment. The larger catchment has a similar proportion of exotic plantation established since the initial plantings in the 1950s at Mohaka Forest, in the 1960s at Kaweka Forest and the 1970s at Awahohonu Forest (Forestry Insights 2002). By the late 1990s, 13% of the catchment had been planted (NZMS-260 W19 1st Edn 1989 reprinted 1994; V19 2000; V20 2nd Edn 1997; U19 1999; U20 2nd Edn 1995). Most of the plantations present in the latest maps were already established by the late 1980s (NZMS-260 W19 1st Edn 1989; V19 1st Edn 1988; U19 1st Edn 1988; U20 1st Edn 1982) with much before about 1970.

The streamflow story for the Mohaka River @ Ruapunga is very similar to that for Glenfalls, mainly because the area above Glenfalls makes up 42% of the catchment above Ruapunga and plantation development has been similar. Trend tests, mass curves and a comparison of 1961–1980 and 1981–2000 data with Ngaruroro River data do not show up any differences over time. Annual yields at Ruapunga have fallen in the second part of the 40-year record but this would have been a rainfall influence as the relationship with the Ngaruroro River has not changed: 1962–1980 Ngaruroro River 1530 mm, Ruapunga 1080 mm, ratio 0.71; 1981–2000 Ngaruroro River 1390 mm, Ruapunga 950 mm, ratio 0.68.

As expected, annual minimum 7-day low flows did not show any trend as a result of the afforestation programme (Fig. 8.4).

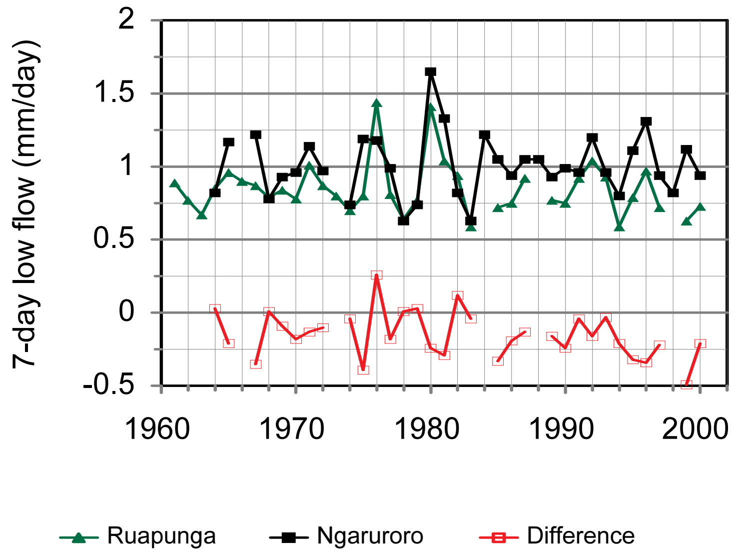

Fig. 8.4 Annual minimum 7-day low flow at Mohaka @ Ruapunga and the Ngaruroro Rivers and the difference between them.

8.2 Esk Suite

Table 8.2 lists catchments in the Hawke's Bay region to the north-west of Napier that have areas of plantation forests or which can be used as stable control catchments to assess streamflow changes. This suite abuts the Mohaka River discussed in Section 8.1

Table 8.2 Hawke's Bay Region: Esk Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Ngaruroro @ Kuripapango	Sep 1963		370	Native + scrub + pasture
Esk @ Berry Road	Jun 1992		58.7	Exotic + pasture
Esk @ Waipunga Bridge	Nov 1963		254	Pasture + exotics + scrub
Tutaekuri @ Puketapu	Dec 1968	Jun 1980	792.5	11% exotics + 57% pasture
Tutaekuri @ Puketapu F/W	Apr 1978		792.5	11% exotics + 57% pasture
Mangaone @ Rissington	Jun 1990		218	Pasture + exotics
Ngahere @ Ngahere Weir	Feb 1968		0.521	Native + Scrub

Esk River @ Waipunga Bridge

Two sites on the Esk River, which is mainly in the Tangoio hydrological region, have been gauged for streamflow, at Berry Road and downstream at Waipunga Bridge where the Berry Road sub-catchment is about 23% of the catchment's total area. The Esk River @ Berry Road had an area of about 12 km^2 in plantation in 1997 (NZMS-260 V20 2nd Edn 1997; NZMS-260 V19 2000). All but 2.6 km^2 was planted by 1967 (NZMS-1 N114 2nd Edn 1967, field check 1966) with the other 2.6 km^2 planted after 1979 (NZMS-260 V20 1st Edn 1979). Flow records began in 1992 so they apply to a catchment with about 21% mature plantation forest with the balance in pasture. The short record precludes any analysis for trends.

The Esk River @ Waipunga (hereafter referred to as Waipunga) record is more useful beginning in 1963 and having 37 years of data to 2000; it is also the representative basin for the Tangoio hydrological region (NZMOW 1970). First planting in the Esk Forest began in the 1920s at Waikoau (Black 1990) then at Esk Forest in 1950 (Forestry Insights 2002). Black (1990) notes that the bulk of the planting took place in 1960–1961 and 1968–1970. Stand areas were: mid-1960s at least 20 km^2 (NZMS-1 N114 2nd Edn 1967; N124 2nd Edn 1962); 1979 50 km^2 (NZMS-260 Map V20 1st Edn 1979) nearly all by 1971 as indicated by Black (1990); 1997 66 km^2 (NZMS-26 V20 2nd Edn 1997). At 1997 the area planted was 26% of the catchment. Streamflow has to be compared to the flow record from the Ngaruroro River as it is the closest river with no afforestation having taken place. However, the rainfall regimes are likely to be quite different.

An analysis of the annual flow records as a mass curve against the nearest long-term rainfall record spanning the length of the streamflow record, Rukumoana (NIWA site D96261) just outside the western edge of the Esk River catchment, could not detect a trend in annual flow. Three split-sample comparisons of Waipunga streamflow for 1963–1980 and 1981–2000 plotted against Rukumoana rainfall, or Napier aerodrome (NIWA site D6481) rainfall, or Ngaruroro River streamflow could not separate the two periods as the points for each grouping overlapped.

Unlike the annual yield record, the low-flow record at Waipunga showed a decline in low flows when the 1981–2000 period was compared to the 1963–1980 record: MALF7 1963–1980 0.85 mm/day; MALF7 1981–2000 0.70 mm/day; ratio 0.82. At the same time, rainfall at Rukumoana decreased by 12% from an average of 1650 mm to 1450 mm and this is the likely cause of the observed decrease in low flows, not the small vegetation change that would have occurred during the later period. It should be noted that there was no equivalent change at the Ngaruroro River, but there are no readily available long-term rainfall records from that catchment to check on rainfall variations. In addition, the correlation between low flows from the two rivers (Fig. 8.5) is not as strong as for annual yields and this may be related to rainfall differences, or to different hydrological natures of the two catchments as they are in different hydrological regions, the Kaweka for the Ngururoro River and the Tangoio for the Esk River.

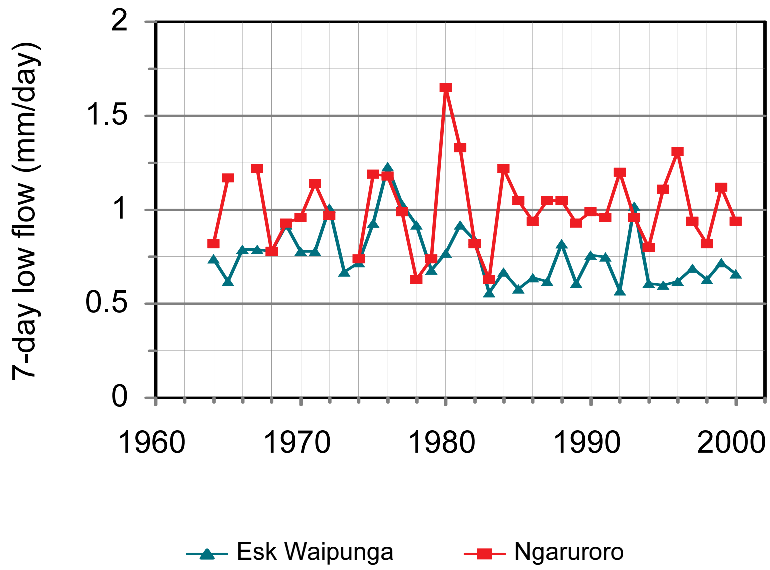

Fig. 8.5 Annual minimum 7-day low flows for the Esk River @ Waipunga and the Ngururoro River.

Tutaekuri River

The Mangaone River (also in the Tangoio hydrological region) had about 21% of the catchment in plantation in 1997 (NZMS-260 V20 2nd Edn 1997) of which about half was established pre-1979 (NZMS-260 V20 1st Edn 1979) with only 2 km^2 before 1962 (NZMS-1 N124 2nd Edn 1962). With the flow record being short (less than 10 years) and not starting until 1990 when most of the forest could be considered mature, no further analysis was done on this station.

The Mangaone River is one of the tributaries of the Tutaekuri River that extend up into the Kaweka hydrological region and has additional plantings outside the Mangaone River catchment. The Tutaekuri River has been measured at Puketapu since 1968, but there was a change of recording site in 1978 that may have an impact on the flow records used here. Some small patches of plantation were established by 1962 (NZMS-1 N124 2nd Edn 1962) and this had increased to about 13 km^2 by 1970 (NZMS-1 N123 2nd Edn 1970), 74 km^2 by 1980 (NZMS-260 U20 1st Edn 1982; V20 1st Edn 1979) and about 120 km^2 by the mid-1990s (NZMS-260 U20 2nd Edn 1995; U21 1st Edn 1983, revised 1996; V20 2nd Edn 1997; V21 1999). This amounts to 15% of the Tutaekuri River catchment.

Annual yields from the Tutaekuri River were compared to those from the Ngaruroro River (Fig. 8.6) and with Napier and Rukumoana rainfalls. A split-sample comparison, 1969–1981 and 1982–2000, did not indicate any substantive differences between these periods with, in each case, one data group overlying the other suggesting both groups were from the same population. However, mass curves of Tutaekuri River flow showed a decline in streamflow from 1981 onwards of 200 mm/year against Ngaruroro River (Fig. 8.7), and 120 mm/year against Rukumoana and against Napier rainfalls. These estimates were based on the ratio between yield at Tutaekuri and values from the other sites adjusted, again in proportion, for the lower recorded values in the second period.

The breaks in the mass curves were abrupt suggesting that a gradual process of diminishing yields resulting from afforestation distributed over time, say over 20 years or so, may not be the reason for the change. To support that, about 15 % of the catchment had been planted between 1970 and the mid-1990s with 60% of that before 1980. We would expect a decrease of less than 40 mm/year at about 1980 compared to 1970 if the rule '40 mm decrease for 10% afforestation' of Bosch & Hewlett (1982) were to apply and perhaps another 20 mm decrease between 1980 and the mid-1990s. The potential change is much smaller than measured and occurred about 3 years after the change of recorder site and function to a flood warning site. A more detailed analysis and more intimate knowledge of the data may elucidate the reasons for the change.

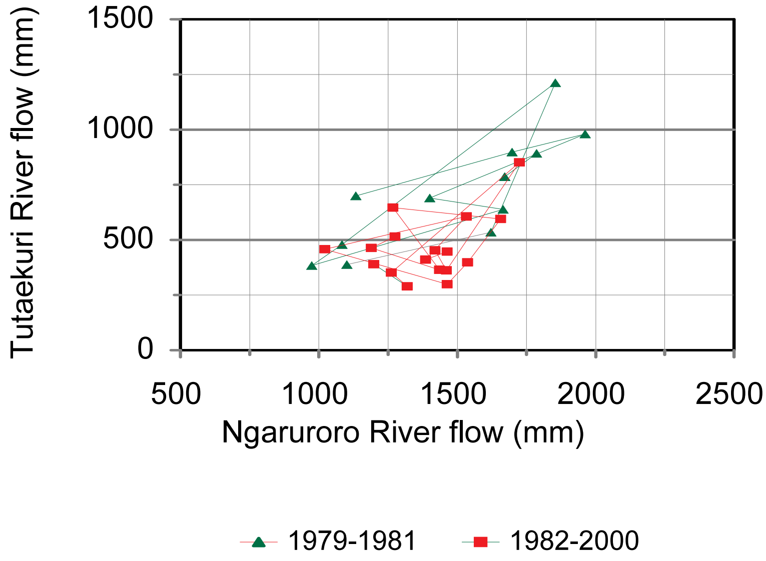

Fig. 8.6 Flow at Tutaekuri River compared to that of the Ngaruroro River for two periods showing the data could be from the same population.

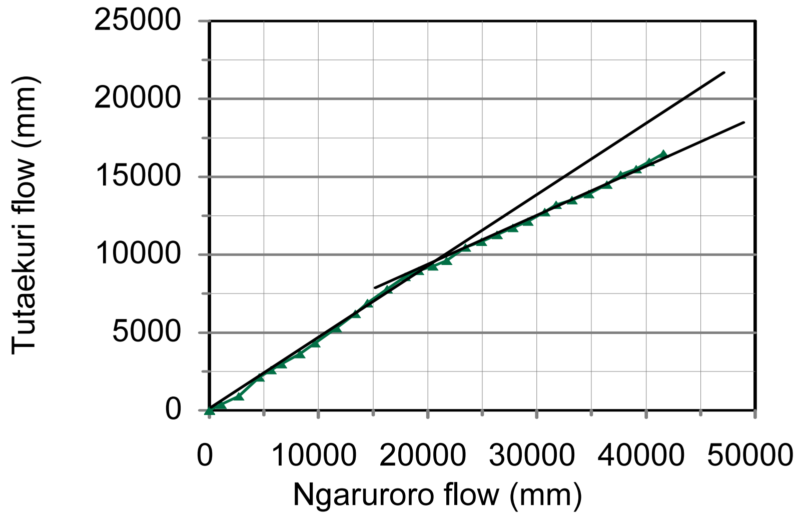

Fig. 8.7 Mass curve of flow at Tutaekuri River compared to that at the Ngaruroro River. The change in slope indicates diminished recorded streamflow at Tutaekuri River from about 1981.

Minimum 7-day low flows at the Tutaekuri River (Fig. 8.8) site have also shown a substantial decline in the 1982–2000 period where they averaged 0.38 mm/day compared with the 1978–1981 period average of 0.63 mm/day, while at the Ngaruroro River there was virtually no change, 1.04 and 1.00 mm/day, respectively. For the same reasons given previously, this decrease could either be a reflection, at least in part, of the lower rainfalls in the second period, which averaged only 82% of the first period rainfall at both Rukumoana and at Napier, or there may be a vegetation change component to the decrease, but it could also be related to the change in parameters of the measurement site.

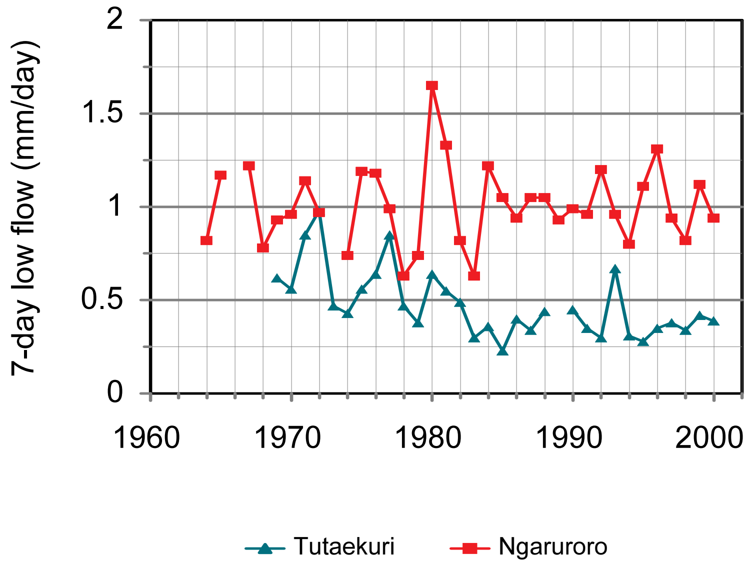

Fig. 8.8 Annual minimum 7-day low-flow series from Ngaruroro and Tutaekuri rivers.

8.3 Pakuratahi study catchments

This study in the Hawke's Bay located 18 km north-west of Napier consists of two catchments (Table 8.3). The study, which is a co-operative venture between Landcare Research, the Hawke's Bay Regional Council and a number of forestry companies, was established in 1993 to compare the impacts of forestry operations and pastoral farming on sediment yield and stream water quality (Fahey & Marden 2000).

Table 8.3 Hawke's Bay Region: Pakuratahi study catchments with land cover in 2001.

Site	Start of gauging	Area (km^2)	Land cover
Tamingimingi @ Top Ford	Apr 1993	7.99	Pasture
Pakuratahi @ Forest Glade	Sept 1993	3.44	Exotics

The Pakuratahi Stream catchment was planted in radiata pine in 1971–1972. In mid-1997, preparation began for harvesting, which was completed in September 1999. Annual streamflow for the two catchments is given in Fig. 8.9. Three years of pre-treatment data, which includes the year when pre-harvest roading, etc. began, produced a good linear relationship between the two catchments:

$$\text{Pakuratahi} = 30 \pm 350 + 0.86 \pm 0.83 \times \text{Tamingimingi} \qquad r^2 = 0.994;\ \text{SE} = 11;\ n = 3 \quad (8.1)$$

Prior to harvesting, the three years of data show that streamflow yields from Pakarutahi Stream averaged 380 mm and from Tamingimingi Stream 410 mm, only 30 mm more for a stream in pasture compared to an adjacent stream in plantation forest. These are very close figures for catchments with such different land covers. Rainfall, as an average of a gauge near the top of the Tamingimingi Stream and near the bottom of the Pahuratahi Stream, was 1290 mm for the two catchments. There is no information on rainfall differences between the two catchments to comment further on the close yields from the two land covers.

There was an increase in streamflow of about 50 mm in the first year of harvesting determined as the difference between that measured at Pakuratahi Stream and that predicted by Eqn 8.1. from Tamingimingi streamflow. This increased to about 100 mm/year for the last year of harvest and the next 2 years. Severe drought years, e.g., 1998, have been part of the study and this may have influenced the yield increases noted, especially for 1998 which I have included as the first year after harvest. The study is continuing, so more information will become available on yield changes as the new crop of trees begins to have an effect.

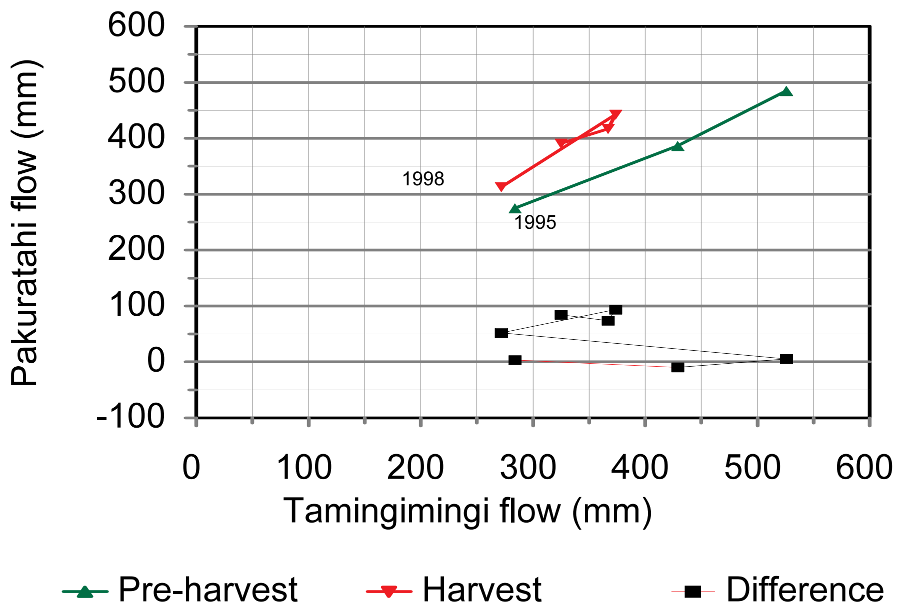

Fig. 8.9 Annual streamflow from the Pakuratahi study catchments. The ‘difference’ points are measured values less that predicted using Eqn 8.1 and correspond to the measured values directly above them.

The minimum 7-day low flows are interesting in that values are lower at the Tamingimingi Stream with pasture than under mature pine forest in the Pakuratahi Stream (Table 8.4), which is contrary to the usual situation where all geologic and climate factors are equal. There does, however, appear to be a response to the harvest with the Pakuratahi Stream average value increasing while at the Tamingimingi Stream there was no change.

Table 8.4 Pakuratahi study catchments: Mean annual minimum 7-day low flows (mm/day). 1994–1997 (four data points); 1998–2001 (three data points; that for 2002 at Tamingimingi is suspect).

Site	1994–1997	1998–2001	Land cover
Tamingimingi	0.5	0.49	Pasture
Pakuratahi	0.59	0.64	Exotics

9. Manawatu-Wanganui Region

9.1 Mangaetoroa Suite

The Mangaetoroa Stream is the representative basin for the West Raetihi hydrological region (NZMOW 1970; Toebes & Palmer 1969) and had about 48% in exotic forest cover in 1994 (NZMS-260 T20 2nd Edn 1994). This had been largely established since about 1983 (except for 1.3 km^2 established some time after 1968 (NZMS-1 N121 1st Edn 1968)) when the present area of plantation was in mainly native forest (NZMS-260 T20 1st Edn 1983). Thus, the period of record for the Mangaetoroa Stream encompasses the transition of large areas of native forest to plantation forest. The balance of the catchment is in pasture.

Control catchments are the Makotuku River, with an entirely different geology and shape being a long, narrow catchment up the slopes of Mount Ruapehu (Southern Tongariro hydrological region), and Manganui-o-te-Ao River, with mixed, volcanic-based geology (West Raetihi, Southern Tongariro and Tongariro hydrological regions) although this does not have a full length record for comparison purposes (Table 9.1). There is also a rainfall record from Scarrows (HMW site 954210) near the centre of the catchment and this will be used as a rainfall index for the site.

Table 9.1 Manawatu-Wanganui Region: Mangaetoroa Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Mangaetoroa @ School	Dec 1968		33.2	Exotic + pasture
Makotuku @ SH49A	Feb 1968		20.8	Native + pasture
Manganui-o-te-Ao @ Ashworths	Aug 1961	Aug 1980	332	Native + pasture

There is no detectable change in annual streamflow from the Mangaetoroa Stream over the period of record as shown by period summaries in Table 9.2, by differences with Makotuku River yields (Fig. 9.1) and when pre- and post-1984 data were plotted against Makotuku River (Fig. 9.2). The first period, 1968–1984, has the Mangaetoroa Stream mainly in native forest and pasture whereas the later period, 1985–2000 has substantial conversion to plantation. The conversion of forest to forest is the likely reason why there is no detectable streamflow yield changes with the change in land use.

Table 9.2 Streamflow yields (mm) from Mangaetoroa Stream and Makotuku River and annual rainfall (mm) at Scarrows.

Period	Scarrows	Mangaetoroa	Makotuku
1968–1984	1610	820	1290
1985–2000	1720	910	1370

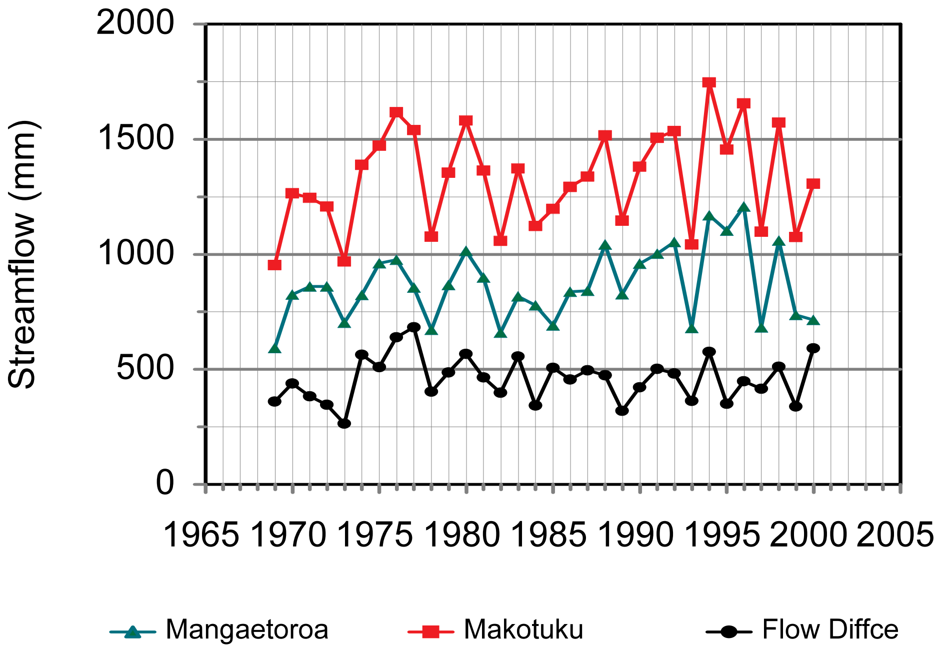

Fig. 9.1 Streamflow yields from the Mangaetoroa Stream and the Makotuku River and the difference between them.

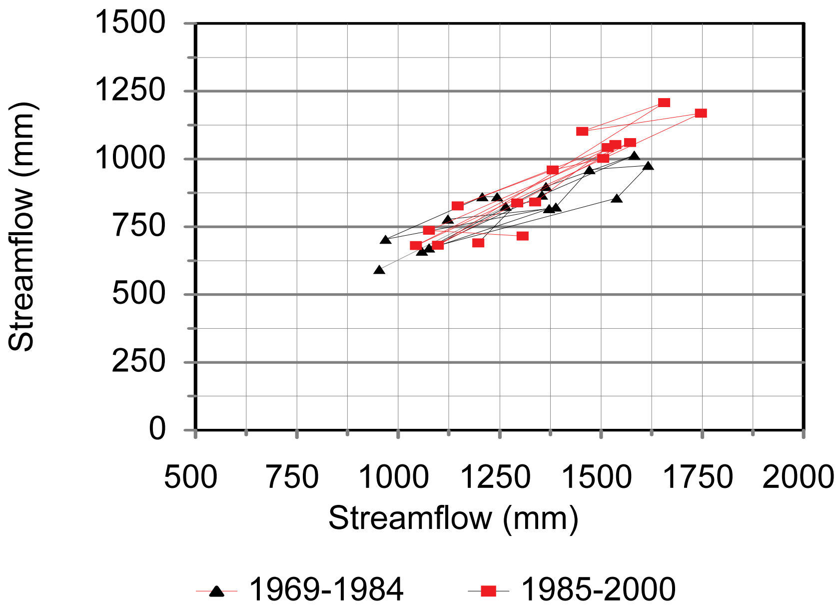

Fig. 9.2 Streamflow yields from the Mangaetoroa Stream plotted against yields from the Makotuku River

Low flows

Similar analyses were carried out for low flow with the same result – no change as a result of the conversion of native forest to plantation (Fig. 9.3). Table 9.3 has the MAFL7 values for Mangaetoroa Stream and Makotuku River.

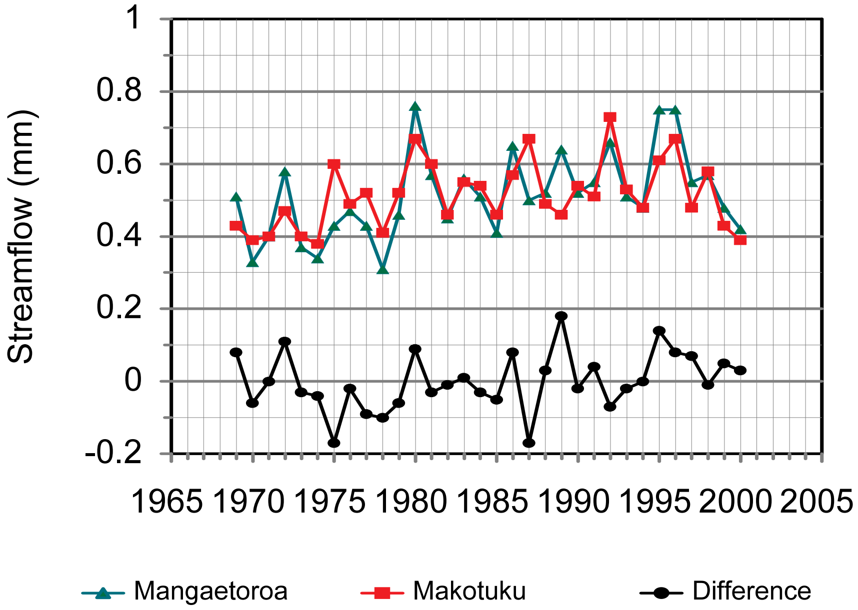

Fig. 9.3 Annual minimum 7-day low flows (mm/day) from Mangaetoroa Stream and Makotuku River and the difference between them.

Table 9.3 Mean minimum 7-day low flows (mm/day) from Mangaetoroa Stream and Makotuku River.

Period	Mangaetoroa	Makotuku
1968–1984	0.47 ± 0.05	0.50 ± 0.05
1985–2000	0.56 ± 0.05	0.54 ± 0.05

9.2 Tokiahuru Suite

In the Tokiahuru Suite (Table 9.4), exotic plantations (Karioi Forest) were established in the Whangaehu Stream and Tokiahura Stream on the southern flanks of Mt Ruapehu. These streams are mainly located in the South Tongariro and East Raetahi hydrological regions (Toebes & Palmer 1969).

Table 9.4 Manawatu-Wanganui Region: Tokiahuru Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Mangawhero @ Ore Ore	May 1962		506	Pasture + native
Whangaehu @ Karioi	Nov 1962		492	Pasture + exotics + native
Tokiahuru @ Whangaehu Junction	Aug 1979	Jan 1994	220	Native + exotics + pasture
Waitangi @ Tangiwai	Nov 1967	Jan 1994	63.5	Pasture

Flows have been significantly reduced in the Whangaehu River since 1979 with flow from several tributaries diverted into the Tongariro power scheme and, therefore, its suitability for analysis of land-use change is negated from then on. This leaves the Tokiahuru Stream as the only gauged river with substantial plantation forests suitable for analysis. Here, the majority of the plantation, about 47 km^2 (21% of the catchment) had been established prior to 1971 (NZMS-1 N122 2nd Edn 1971) and another 8 km^2 (4%) between 1971 and 1982 (NZMS-260 T20 1st Edn 1982). Little change has occurred thereafter. Thus, a total of 25% of the catchment has been converted to plantation but virtually none since flow records began. The mainly pasture Waitangi Stream (South Kaimanawa and East Raetahi hydrological regions (Toebes & Palmer 1969); representative basin for East Raetahi (NZMOW 1970)) and Mangawhero Rivers (West Raetahi hydrological region) can be used as control catchments against which to assess change.

No noticeable changes in the flow regime were found when mass-curve comparisons were made between Tokiahuru Stream yields and those from Mangawhereo River or Waitangi Stream, or with an index of precipitation, that from Waitangi (NIWA Site 954510). This was confirmed when a split record from Tokiahuru Stream was plotted against Waitangi Stream and the first grouping was overlain by the second. These were not unexpected observations as plantation establishment had taken place before flow records began, and was only for 25% of the Tokiahuru Stream catchment, much from native forest. There were large differences in yields from the Tokiahuru Stream and Waitangi Stream, and these were likely to be both a function of the catchment precipitation and differing hydrologic responses to highly varied volcanic-influenced geology (Table 9.5).

Table 9.5 Streamflow yields (mm) from Tokiahuru suite catchments and annual rainfall (mm) at Waitangi.

Period	Waitangi rainfall	Tokiahuru	Waitangi	Mangawhero
1980–1986	1150	1060	460	790
1987–1993	1190	1120	540	890

10. Wellington Region

Catchments with small amounts of plantation forests have been identified north of Wellington and centred about Upper Hutt (Table 10.1).

Table 10.1 Wellington Region catchments with land cover in 2001.

Site	Start of gauging	Area (km^2)	Land cover
Pakuratahi @ Truss Bridge	May 1978	37.2	Native + exotic
Orongorongo @ Upper Dam	Feb 1979	7.1	Native
Wainuiomata @ Manuka Track	Jun 1982	27.1	Native
Akatarawa @ Cemetery	Feb 1979	113.5	Native + exotic
Whakatiki @ Dude Ranch	Sep 1976	46	Native
Tauherenikau @ Gorge	Mar 1976	112	Native
Hutt @ Kaitoke	Dec 1967	88.8	Native

10.1 Pakuratahi River

Plantations have been established both above (about 2.6 km^2, 7% of the catchment) and below the streamgauging station in the Pakuratahi River (WRC site 29843), about 12 km east of Upper Hutt. Wellington Regional Council (WRC) records indicate most planting was undertaken during 1961–1969 and the presence of the early plantations is confirmed by topographic maps (NZMS-1 N161, 3rd Edn 1974) with little change thereafter (NZMS-260 S27, 1st Edn 1980, limited revision 1998). These plantations were established over 10 years before streamflow recording began so any changes resulting from afforestation will not be detectable in the available record. Streamflow records from the nearby Orongorongo River (WRC site 29503) and Wainuiomata River (WRC site 29606) in native forest could be control catchments but missing records mean this is not feasible for annual flows. Rainfall from a gauge at Centre Ridge (WRC site 151210) in the lower reaches of the Pakuratahi River and another at Orongo Swamp (WRC site 152010) in the Orongorongo River catchment can be used as indices of catchment rainfall. All catchments are in the Wellington hydrological region (Toebes & Palmer 1969).

Although it is not possible to determine if any trends are present in the annual flows, comparative yields for the two forested catchments are Pakuratahi River 1680 mm (80% of Centre Ridge rainfall) and Orongorongo River 1800 mm (72% of Orongo Swamp rainfall). Both yields are a very high proportion of rainfall indicating the rainfall indices underestimate catchment rainfall.

Complete minimum 7-day low-flow series were obtained for all catchments. However, considering that the plantations had been established before the flow records started, and that they were converted from native forest, no trends were able to be detected. For 1983–1999, MALF7 values were Pakuratahi River 0.54 mm/day; Orongorongo River 0.49 mm/day; Wainuiomata River 0.61 mm/day.

10.2 Akatarawa River

An area from about 8 km north of Upper Hutt in the Akatarawa River has had WRC plantations established since the mid-1970s. The early topographic map (NZMS-1 N161, 3rd Edn 1974) does not show any plantations above the Akatarawa River flow recorder site (WRC site 29844). In 1993 there were about 12 500 ha (11%) in plantations scattered throughout the catchment (NZMS-260 2nd Edn 1993).

Streamflow recording began in 1979 by which time planting in mostly pasture and scrubland was well underway. Adjacent catchments, Hutt River (NIWA site 29808) and Whakatiki River (WRC site 29841), and the nearby Tauherenikau River (WRC site 29521) provide data for comparisons. Rainfall stations in the catchments are Warwicks in the top of the Akatarawa River catchment (WRC site 59007), Blue Gum Spur near the centre of Whakatiki River (WRC site 150010), Phillips near the Hutt River gauging station (NIWA site 150202), and Bull Mound in the headwaters of the Tauherenikau River (WRC site 59310). Plantations in the Whakatiki catchment are mainly in the Wainui sub-catchment, which enters below the Whakatiki streamgauging station, so this site would have been useful as a control catchment but for missing data throughout the streamflow record. These catchments are also in the Wellington hydrological region.

No trends were apparent, or expected, in the annual flow records at Akatarawa River and the comparison sites. Annual yields were variable: Akatarawa River 1430 mm, Whakatiki River 1010 mm, Hutt River 2820 mm, Tauherenikau River 2460 mm, but rainfall is also highly variable across the region ranging from 1960 mm at Blue Gum Spur to 4650 mm at Bull Mound. These rainfall gauges are not considered representative of the catchment rainfalls, only indices.

As for annual flows, no trends were apparent over time at Akatarawa River nor in comparisons with Whakatiki River (Fig. 10.1). Average MALF7 values were 0.84 mm/day at Akatarawa River and 0.66 mm/day at the adjacent Whakatiki River with lower catchment rainfall. The two wetter catchments, Hutt River and Tauherenikau River, had MALF7s of 1.53 mm/day and 1.06 mm/day, respectively.

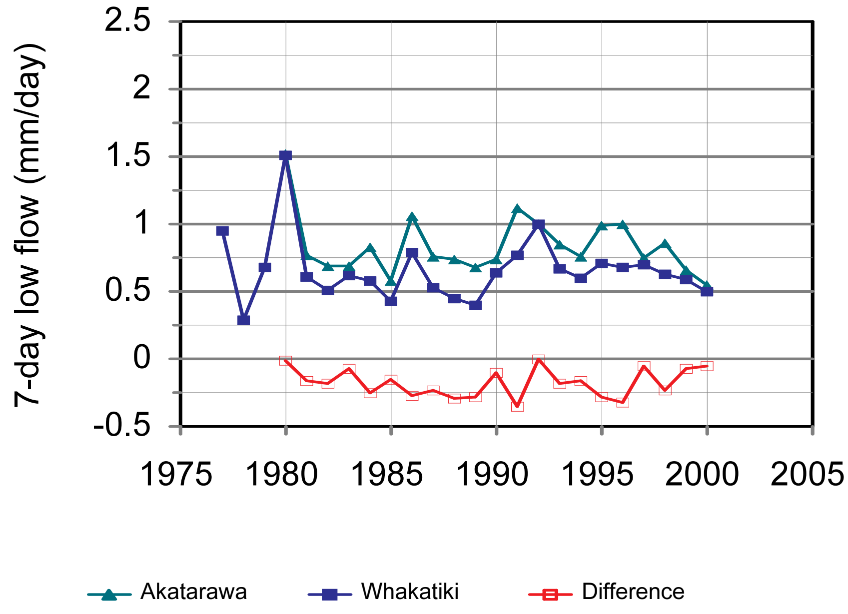

Fig. 10.1 Annual minimum 7-day low flows for the Akatarawa River (native forest with exotic plantations) and Whakatiki River (native forest) and the difference between them (Whakatiki less Akatarawa).

11. Tasman District

The Tasman District is another district where extensive forestry establishment took place in the 1920s– 1930s and again in the 1970s with the major concentration around Golden Downs forest (Forestry Insights 2002).

11.1 Nelson North Suite

This suite includes catchments located mainly to the north-east and west of Nelson city (Table 11.1), although the Wairoa River is a major catchment to the south-east.

Table 11.1 Nelson Region: Nelson North Suite with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Collins @ Drop Structure	Jan 1960		17.61	Exotic + native
Wakapuaka @ Hira	Aug 1978		41.93	Exotic native
Stanley Brook @ Barkers	Dec 1969	May 1994	81.6	Exotics + pasture
South Pigeon tributary @ Bradleys	Dec 1978	Jul 1986	1.29	Exotics
North Pigeon tributary @ Sharpes	Apr 1979	Jul 1986	1.19	Exotics
Wairoa @ Gorge	Nov 1957	Dec 1992	464	Exotics + native + scrub/pasture
Wairoa @ Irvines	Mar 1992		462	Exotics + native + scrub/pasture

Collins River and Wakapuaka River

Both these catchments had significant exotic plantations for many years before the gauging stations were established, these being parts of Rai and Hira forests. By 1960, 460 ha of the 17 600-ha Collins River catchment was in mixed pine species and Douglas fir planted mainly in the 1950s (comment file with data for Collins River Site 58301). Further plantations were established so that by the 1970s about 1400 ha (8% of the catchment) had been planted, much of this as conversion of native forest with the balance planting into scrub (NZMS-1 S15 3rd Edn 1970). Harvesting and replanting has taken place from at least 1980. Forest establishment in the Wakapuaka River catchment would have followed similar establishment patterns and would have been more or less fully established before streamflow records began.

Annual yields from the Collins River catchment have not shown any trend with time when the period

1961–1977 (mean yield 960 mm/year) was compared with 1978–1993 (mean yield 990 mm/year) despite the plantation development (Cox & Stuart test for trend). This was confirmed by a comparison with rainfall from Whangamoa No. 2 (NIWA site G13154) used as an index of catchment rainfall (Fig. 11.1). A comparison with Wairoa River, probably the most suitable long-term streamflow record upon which to make a comparison, showed a wider scatter than Fig. 11.1, a likely consequence of both catchment scale and a differing rainfall regime to the Collins River. Wakapuaka River streamflow follows a similar relationship with Whangamoa No. 2 rainfall. The lack of trend in streamflow data from the Collins and Wakapuaka rivers will be a consequence of the change from one woody cover (native forest and scrub) to another woody cover (plantation forest) and the distributed conversion of small amounts of the catchments over time, which would tend to minimise the rate of any change that might have occurred in the streamflow regime.

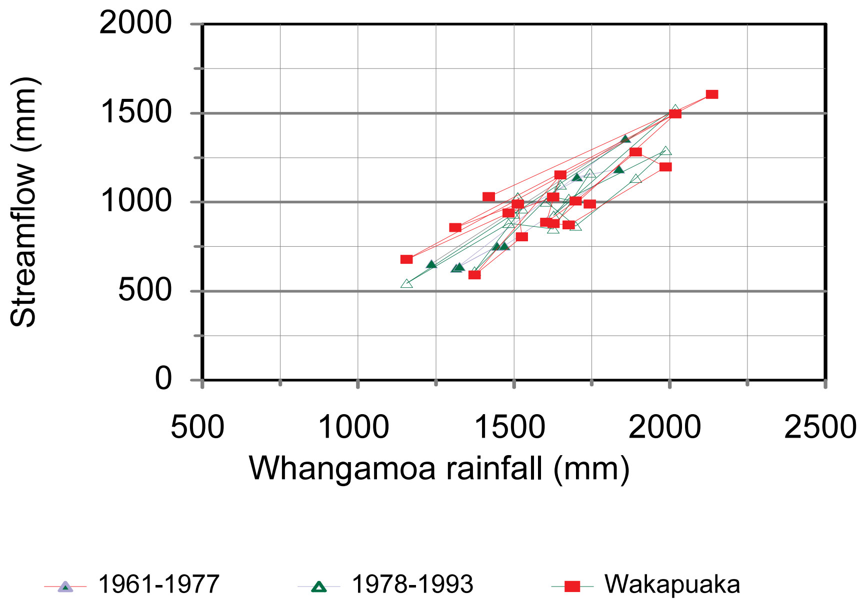

Fig. 11.1 Streamflow at Collins River divided into two periods and at the Wakapuaka River as a function of annual rainfall at Whangamoa No. 2.

As with the annual yields, the annual 7-day minimum flow from the Collins River catchment did not shown any trend with time when the period 1961–1977 (mean 0.36 mm/day) was compared with 1978–1993 (mean 0.32 mm/day) (Cox & Stuart test for trend). During most of the latter period the corresponding minima from the Wakapuaka River were twice as high averaging 0.64 mm/day.

South and North Pigeon

Two catchments with mature plantation cover in the Pigeon Valley, South Pigeon and North Pigeon (planted 1956), were instrumented in 1978–1979. About 83% of South Pigeon was harvested in the 9 months from February 1982 with another 9% on either side of that time. Harvesting in North Pigeon took place in 1984–1985 after harvesting at South Pigeon had been completed (comment files with the data for NIWA stations 57505 & 57506) and 6 months of post-harvest streamflow data are available before the station was closed. The time line of forest management is given in Table 11.2. Any comparisons can only be made for short periods as both catchments were harvested – there is no stable control data throughout the study. There are no other nearby catchments that could be considered reasonable controls for assessing the effects of the harvesting programme on the streamflow regime; the Moutere catchments, although covering this time span, are about 1/30th the size and, hence, will have a markedly different hydrological regime.

Table 11.2 Time lines for the study at Pigeon Valley. F = commencement of flow recording; H = harvesting; X = cessation of recording.

	1978	1979	1982	1983	1984	1985	1986
	OND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAMJJASOND	JFMAM
North Pigeon		F			HHHHHHHHHHH	HHHHHHHHHH	X
South Pigeon	F		HHHHHHHHHH	HH			X

Flow records from both streamflow stations have a number of missing records but estimates were made from the other catchment in the pair to fill most of the gaps and provide an annual record. Precipitation is available from Forks @ Pigeon (NIWA site 133019) but missing records make it unsuitable for use. Alternative data are available for two stations about 7 km to the east of Pigeon Valley at Moutere Hills (NIWA station G13301) and Brightwater No. 2 (NIWA station G13312). The 1961–1990 rainfall normal for Moutere Hills is 1073 mm (Tomlinson & Sansom 1994).

Annual streamflow data are shown in Fig. 11.2. The only full year of data prior to harvesting at South in 1982 indicates that yields from the two catchments were similar. In 1983, the first year after harvest, there was an increase in streamflow of the order of 330 mm in a slightly wetter than average year. Yields from South appear to be diminishing in the third year after harvesting (1985) when compared to the precipitation data, and yields at North appear to be increasing at the same time as a consequence of the harvesting taking place.

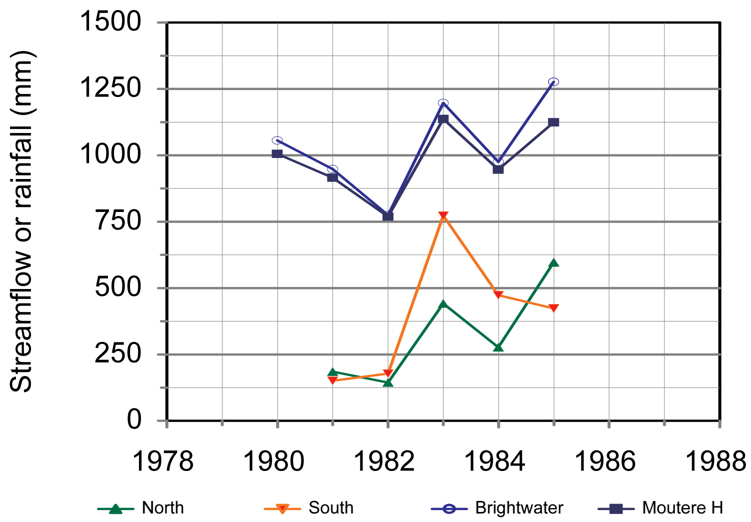

Fig. 11.2 Annual streamflow (mm) from Pigeon Valley sub-catchments North and South, and annual precipitation (mm) from Moutere Hills and Brightwater No. 2.

Both catchments had considerable periods when the streams were dry and this occurred any month of the year. Before harvest, North averaged 245 dry-days/year and the number may have been about 10% smaller at South. After the catchments were harvested there were decreases in the number of dry-days relative to the other member of the pair (Fig. 11.3) with only 80 days in the wetter year after harvest at South and 75 days in the second year of harvest at North.

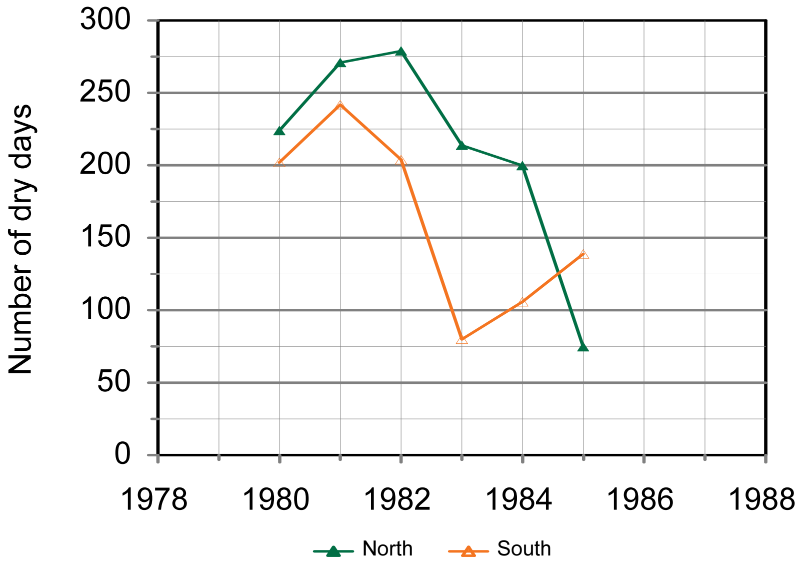

Fig. 11.3 The number of dry-days at Pigeon Valley sub-catchments: South harvested in 1982 and North harvested in 1984–1985.

11.2 Moutere experimental catchments

The Moutere catchments were established as part of the International Hydrological Decade (IHD) programme in the early 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). A range of land-use changes were studied (Table 11.3). Scarf (1970), Duncan (1980, 1995) and Smith (1992) present data from here.

Conversion of gorse scrub to cropping

From Moutere comes the only published New Zealand work of the effects of catchment-scale crop establishment on water yield (Scarf 1970). Catchments 2 and 5 were maintained in pasture and were mob-stocked while catchment 10 (4.5 ha) was converted from gorse to cultivation and cropping in 1965.

A mass curve of flows from the cropped catchment against the pasture catchments showed an increase in flow after gorse clearance of about 130 mm compared to the gorse-covered catchment (Fig. 11.4). After treatment at C10, there was a decrease in the number of days of flow (19% compared to 25%) while the reverse occurred at control catchment 5 (76% compared to 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 11.3 Moutere catchments and treatments (Scarf 1970; Duncan 1980, 1995). Records were not collected between 1988 and July 1991 and ceased in July 1993.

Catchment	2	5	15	8	13	14	10
Area (ha)	3.96	6.95	2.71	4.41	7.65	4.33	4.5
Began	1963	1963	1963	1963	1963		1962
Vegetation	Pasture	Pasture	Pasture	Gorse	Gorse	Gorse	Gorse
Treatment	Gorse in gullies sprayed by 1968	Gorse in gullies sprayed by 1968		Burnt 1970 and line-dozed	Burnt 1970 Misc. land treatment to 1971	To pasture in 1964. Disced 1970	To crops in 1965
Planted			1978: 20% riparian	1970	1971	1970	
Thinned			1984	1978, 1981	1978, 1981	1975, 1981	
Harvested				1991	1991	1991	

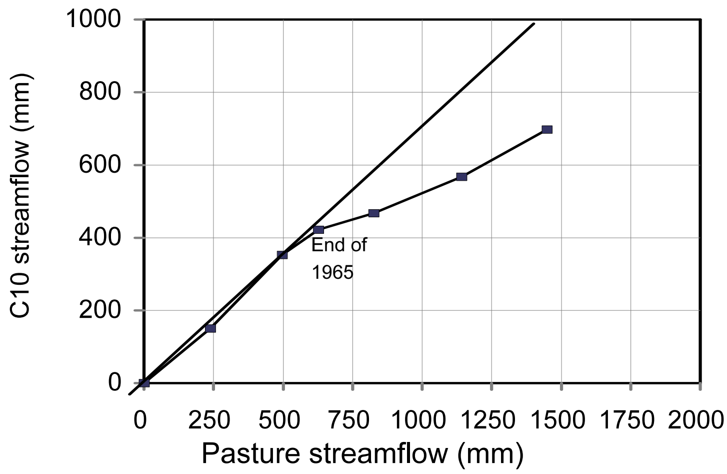

Fig. 11.4 Accumulated streamflow from Moutere Catchment C10 which was converted from gorse to crops compared to the average accumulated from catchments C2 and C5 in pasture.

Conversion of gorse scrub to pasture

The clearance of gorse as the first step to conversion to crops at Moutere 10 led to an increase in streamflow of 130 mm/year (Scarf 1970). Catchment 14 was converted to pasture as an intermediate step before planting pines. From his prediction equation to estimate catchment 14 streamflow from control catchment 5 streamflow, Duncan (1995) showed there was a difference of about +250 mm in the first year that can be attributed to the clearance of the gorse (Fig. 11.5).

Afforestation of pasture and gorse

At catchment 14 there was an increase in streamflow after converting scrub to pasture of about +250 mm in the first year that can be attributed to the clearance (Fig. 11.5) and this increase remained steady while in pasture. From the third year after planting there has been a steady decrease in the expected streamflow from pasture to about 195 mm in 1978. On a seasonal 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. The predicted departure from pasture was 170 mm from age 8 to age 16. Harvesting in mid-1991 led to an increase in streamflow. The largest effect was in the second year as soil moisture levels had taken some time to recharge and yields were similar to that expected if it had still been in pasture (Fig. 11.5).

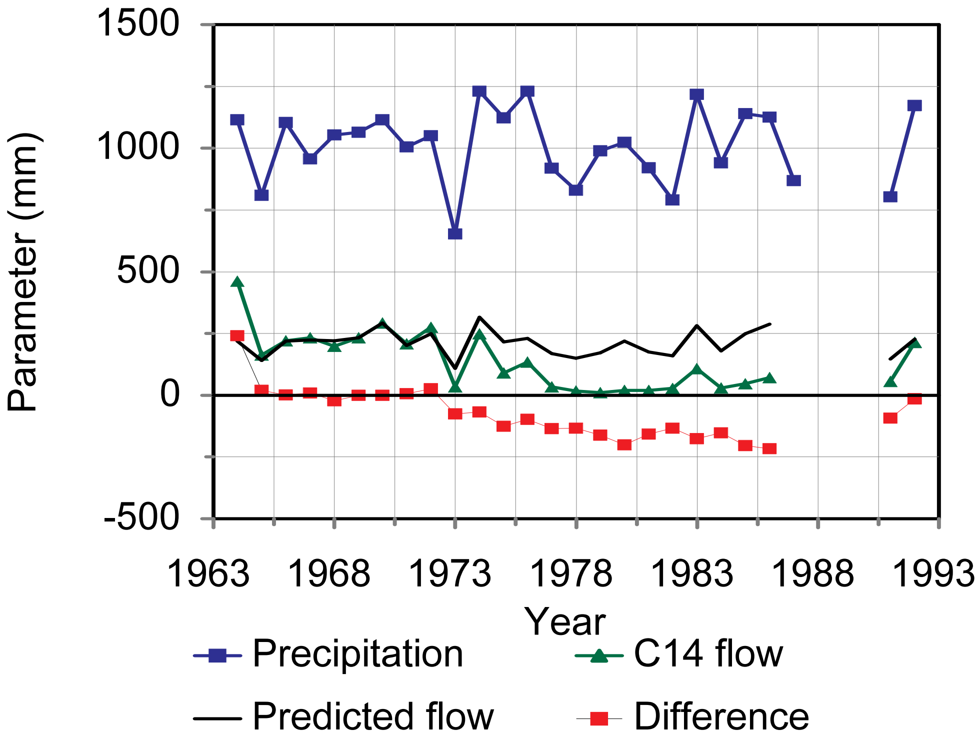

Fig. 11.5 Moutere catchment 14 streamflow and the change in streamflow as a consequence of conversion of gorse to pasture (1963–1970), afforestation of pasture (1970–1986), and harvesting (1991–1992) (after Duncan 1995).

Similar patterns to the conversion of catchment 14 were observed at catchments 8 and 13. The immediate response to burning gorse and line-dozing catchment 8 was to increase streamflow from that predicted for gorse by about 175 mm; similarly, clearing catchment 13 resulted in a 290-mm increase. The response differences are considered slope related as catchment 8 faces south-east and catchment 13 north. Streamflow increases persisted for 4 years at catchment 8 and for 5 years at catchment 13. After the initial increase in flow after land preparation followed by the reduction to pre-treatment levels, streamflow continued to decrease as the trees grew. At catchment 8 from trees aged 6 to 15, streamflow was 100 mm less than when it was in gorse while at catchment 13 it was 26 mm less.

At Moutere the greatest reduction in flood 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 equivalent pasture mean annual flood of 38 L/s/ha. In the follow-up paper, Duncan (1995) used a Log Pearson type 3 extreme-value distribution fitted to the annual maximum series to show that afforestation has reduced flood peaks even in infrequent storms; the mean annual flood is reduced 35% and the 0.02 annual exceedance probability (AEP) peaks averaged about 50% of those from pasture. The timing of large events can affect 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.

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 11.4 after Table 3 in Duncan (1980)), 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 trend in zero-flow days is 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 presented for 1969 and 1978 show there was 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 11.4 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 data set, Duncan (1995) reported that, while under gorse, catchments 8 and 13 averaged 158 days of zero flow compared to an average of 52 days for the pasture catchments 2 and 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.

Afforestation of riparian areas, Moutere

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 11.5). There appears to be inconsistent catchment numbering in this paper compared to the definitive numbering in Walter (2000) and those used by Duncan (1980, 1995); her C2 should be C5 and C4 should be C15 as in Table 11.3.

The result of afforestation was a decrease in total flow, mainly as a decrease in baseflow because there was little change in the quickflow component. Peak flows were reduced in small events, but medium-sized storm peaks were not affected (Smith 1992).

Table 11.5 Precipitation and streamflow (mm), with percentages of rainfall or streamflow in brackets, at

Moutere, Nelson, from Smith (1992). See text for comments on catchment numbering.

		Catchment C2			Catchment C4		
Period	PTTN	Streamflow	Stormflow	Baseflow	Streamflow	Stormflow	Baseflow
1970–1978	1032	271 (26)	97 (35)	175 (65)	214 (21)	76 (35)	138 (65)
1979–1987	1010	266 (26)	97 (36)	169 (64)	161 (16)	70 (43)	91 (57)

11.3 Nelson South Suite

A suite of five catchments (Table 11.6) has been monitored intermittently in the region south of Golden Downs since the mid-1970s. Early results were reported by McKerchar (1980) and by Hewitt & Robinson (1983). There is potentially a major problem with this data set as there are no data available before the three catchments were planted in exotic plantations. Thus, there is a danger of attributing observed hydrological differences to land-use differences when catchment variability may be the reason, but we must assume that the pre-planting hydrology of the native forest, old mixed-forest and pasture catchments has not changed relative to each other. There will have been changes at the other catchments in response to the afforestation.

About 40% of Long Gully was planted in exotic species about 1968, 5% of Rough'ns Creek before 1970 and nearly all the rest between 1970 and the start of the flow recording in 1976, and all of Graham Creek in the three years before flow recording commenced in 1977. No harvesting was planned for Graham Creek until at least 2001 (Fletcher Challenge Forests, pers. comm.).

Table 11.6 Nelson Region: Nelson South suite with land cover at 1975 (after McKerchar 1980).

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Long Gully @ Meads Road	Aug 1973	Mar 1983	2.31	Native + 25-yr-old exotics
Rough'ns @ Weir	Jul 1976	Jun 1986	3.22	Exotics 50% > 6 yr, 40% 1 to 6 yrs
Graham Creek @ Weir	Mar 1977 Sep 1993	Jun 1986 Jun 1998	4.74	Exotics planted in 1974 and 1975
Hunters @ Weir	Apr 1977		5.02	Native
Kikiwa @ Weir	Jun 1977	Jun 1986	2.85	Pasture with reverting scrub

Streamflow is available for up to 8 years in the period 1978–1985 for all catchments. Hunters Gully was continued for another 15 years and Graham Creek re-established in 1993 for another 5 years. Useful records from Long Gully began earlier and finished earlier than the other sites and, therefore, have not been looked at further for this work. Hunters Gully, because of its long-term nature (although 1983 and 1988 have missing data) and stable native forest cover is to be used as the base for comparisons.

Rainfall records from the catchments do not span the streamflow records or have missing records, which limits their usefulness. Records from Blue Glen (TDC site 126942) about 6 km east of Rough'ns Creek and its replacement at Motueka Gorge (TDC site 157008) began later than the streamflow records. There is also another record from Kaka (NIWA Site G12561) that started earlier but is located 14 km to the west. Using Motueka Gorge rainfall as the base, and making proportional adjustments to the long-term average there (1210 mm), relationships with the short records from raingauges in Hunters Gully, Graham Creek and Rough'ns Creek and with Kaka indicate a rainfall gradient from east to west: Hunters Gully at about 1160 mm; Graham Creek 1240 mm; Rough'ns Creek 1330 mm; Kaka 1740 mm per year.

The snapshot of data from about the 1980s indicates that yields from the various catchments may not be too different from each other (Table 11.7) but there are rainfall differences between catchments. Rough'ns Creek with the oldest plantation forest has the lowest streamflow (Fig. 11.6) despite having probably the highest rainfall. Hunters Gully in native forest and Kikiwa Stream in reverting pasture have similar yields and rainfalls would also be similar as they are adjacent catchments. Conventional wisdom would have streamflow from Hunters Gully somewhat smaller than Kikiwa Stream.

Table 11.7 Average annual water yields (mm) from the Nelson South catchments and Kaka rain (mm)

	Kaka rain	Hunters	Graham	Rough'ns	Kikiwa
Cover		Native	Plantation	Plantation	Pasture
Average 1978–82, 1984–85	1620	500	530	440	530
Average 1994–1997	1950	620	580		
Predicted 1994–1997			630		

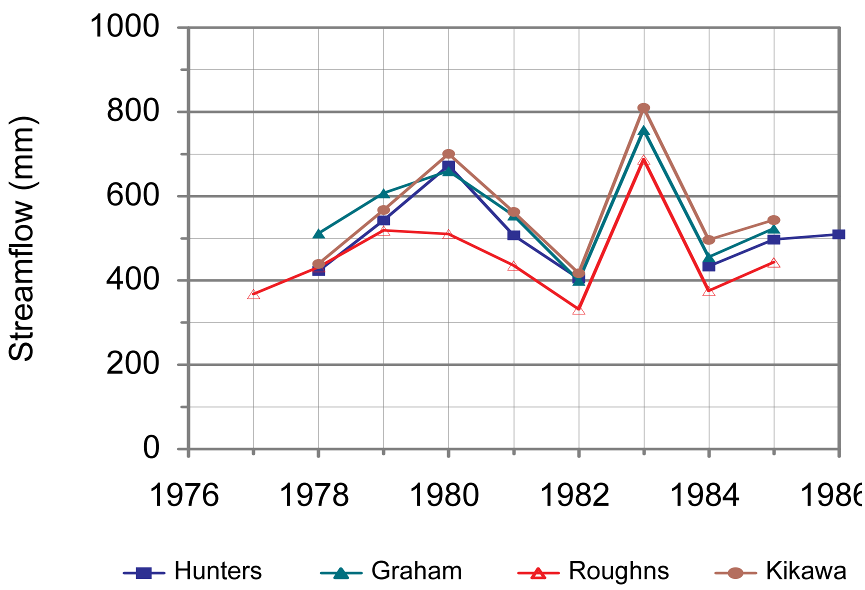

Fig. 11.6 Streamflow yields from catchments in South Nelson; Hunters in native forest; Graham and Rough'ns in plantation; Kikiwa in pasture.

There is one catchment that seems to have changing streamflow (Fig. 11.6). Graham Creek was planted in 1974 and 1975 and, relative to the other sites, has a diminishing flow in 1978 and 1979 after which it seems to remain steady. Unfortunately, there are no data from the time before and at planting upon which to assess a change, and recording was halted prematurely.

Recommencement of recording at Graham Creek in 1993 gives an opportunity to compare the water yields from two age-classes of plantation. Because flow was recorded at a weir, there is confidence that the two disjoint records at Graham Creek will have a comparable basis. As the early years of flow at Graham Creek may have been diminishing, a regression equation was determined between flows from Hunters Gully and Graham Creek using data for the years 1980–1982 and 1984–1985 (Eqn 11.1).

$$\text{Graham} = 50 \pm 210 + 0.92 \pm 0.41 \times \text{Hunters} \qquad r^2 = 0.95;\ \text{SE} = 26;\ n = 5 \qquad (11.1)$$

From this equation predictions were made for annual yields at Graham Creek once flow records began again in 1993 (Table 11.7). Yields at both catchments were higher at this time than the 1970s–80s period but, as shown by Kaka rainfall, this was a much wetter period. The yield at Graham Creek was smaller than expected using Eqn 11.1 and indicated an average increased water usage of 50 mm/year by 20–24-year-old trees than the average usage by trees between ages 6 and 10 years old.

Mean annual 7-day low flows from all catchments are similar at less than 0.07 mm/day (Table 11.8); all 95% confidence limits overlap. Looking at the individual catchments, LF7 values are higher at Hunters Gully, the native forest catchment, than at all the other catchments in every year. In the cases of the two plantation catchments, the catchments do run dry on occasions, with Graham Creek with the younger plantation having the most dry days, whereas Rough'ns Creek would be expected to have more as the trees were older. The lack of data from the pre-planting period precludes making any statement on the effect of afforestation on MALF7 values.

Table 11.8 Mean annual 7-day low flows (mm/day) and the number of dry days from the Nelson South catchments and rainfall at Kaka (mm).

	Kaka rainfall	Hunters	Graham	Rough'ns	Kikiwa
Cover		Native	Plantation	Plantation	Pasture
1978–1986	1620	0.07 ± 0.05	0.02 ± 0.03	0.03 ± 0.02	0.05 ± 0.04
1978–1986 dry days		0	17 ± 18	0.4 ± 1.4	0
1994–1997	1950	0.09 ± 0.04	0.04 ± 0.04		
1994–1997 dry days		0	1.3 ± 2.1		

A comparison of the two periods in Table 11.8 shows that both catchments with data have higher minimum flows and Graham Creek has fewer dry days in the later period, which is obviously associated with the wetter rainfall regime at this time. There is no obvious change in the relationship for MALF7 values for the two catchments so we assume for here, at least, that older plantations have a similar effect on MALF7 to young plantations.

11.4 Donald Creek experimental catchments

The Donald Creek catchments were established by the New Zealand Forest Research Institute in the late

1970s to investigate the hydrological consequences of conversion of native forest to exotic plantations and of selection harvesting of native forests. They are now operated by Landcare Research. O'Loughlin et al. (1978), Pearce et al. (1982), Fahey & Jackson (1997) and Fahey et al. (1998) have reported aspects of the hydrology of these catchments. Catchment treatments are given in Table 11.9. Rainfall over the study period ranged from 1250 to over 2200 mm/year and averaged about 1550 mm.

Table 11.9 Treatments applied to the Donald Creek (DC) catchments, Nelson (from Fahey & Jackson 1997; Fahey et al. 1998).

	DC1	DC2	DC3	DC4
Area	8.57	4.74	7.48	20.19
Began	1977	1977	1977	1977
Harvested	1980: 83% using tractor-based methods	None – control	1981: Selection harvest	1980–1981: 94% using cable systems
Before plant preparation	Part burned (May 1981); Rootraked		None	None
Planted	Sept 1981 1250 SPH			Sept 1981 1250 SPH
Thinned	1986/87 600 SPH			1986/87 600 SPH

SPH = stems per hectare

Although the catchments are adjacent, have the same geology, aspect and slope, and similar relief (O'Loughlin et al. 1978) there is a range in streamflow yields from the catchments under native forest of 160 mm (Table 11.10). Conversion of native forest to pine forest at Donald Creek in Nelson led to an increase in flow as a result of harvesting (Fig. 11.7) with yields in the year of or after harvesting increasing relative to the control catchment DC2; up to 380 mm at DC1 and 520 mm at DC4 where large tracts were clearfelled and up by 260 mm at DC3, which was selection harvested. These increases were generally sustained for 4 years before yields start dropping back towards pre-treatment levels, which were reached after 8–10 years in the cleared catchments. At DC3 yields were still elevated after 14 years while at the same time yields have fallen to (DC1) or below (DC4) those predicted for the native forest condition. It is obvious from Fig. 11.7 that there are also different catchment responses in very wet years (1988 and 1995) when it seems that yields at DC2 did not increase as much as the other catchments. The annual yield patterns for the various management phases at DC1 identified in Table 11.10, the increase after harvesting, the reductions with time through to approaching or falling below native forest levels, etc., are shown in Fig. 11.8; similar patterns were observed for DC3 and DC4.

Table 11.10 Mean annual streamflow yields (mm) from Donald Creek catchments for different stages of management (in years from planting). DC2 is in native forest throughout the study.

	Native forest	0–3	4–10	11–17	11–14	4–12	13–17
DC2 control	580	510	520	640	660	500	720
DC1 measured	640	870	660	730			
DC1 predicted	640	550	550	730			
DC1 less predicted	0	320	100	0			
DC3 measured	570	810	740		860		
DC3 predicted	570	510	520		640		
DC3 less predicted	0	300	220		220		
DC4 measured	730	980				720	820
DC4 predicted	730	630				610	930
DC4 less predicted	0	350				110	−110

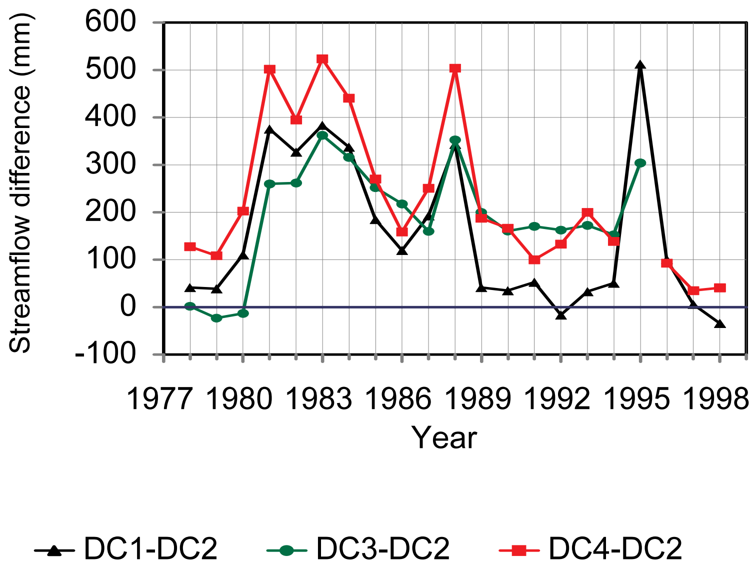

Fig. 11.7 Difference in streamflow yields between the native forest DC2 catchment and that from the three harvested catchments at Donald Creek, Nelson.

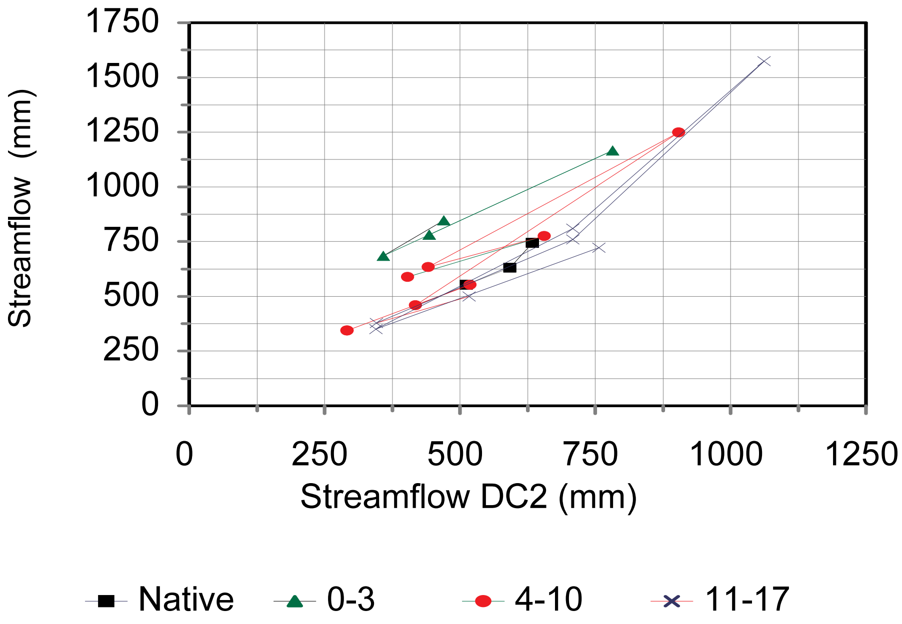

Fig. 11.8 Streamflow from Donald Creek catchment DC1 (83% clearfelled and planted with pines) showing yield trends for various management stages.

Calibration equations relating streamflow at DC2 to the treatment catchments (Eqns 11.2 to 11.4) were based on the first three years of data at each site as these data fell into more or less linear patterns, e.g., DC1 in Fig. 11.8. Because there are only three years of data, there are wide confidence limits on the equation coefficients, therefore, the data should be used with some caution.

$$DC1 = -210 \pm 3300 + 1.48 \pm 5.67 \times DC2 \qquad r^2 = 0.92;\ SE = 40;\ n = 3 \qquad (11.2)$$

$$DC3 = 80 \pm 1020 + 0.85 \pm 1.65 \times DC2 \qquad r^2 = 0.97;\ SE = 12;\ n = 3 \qquad (11.3)$$

$$DC4 = -140 \pm 4600 + 1.50 \pm 7.98 \times DC2 \qquad r^2 = 0.85;\ SE = 55;\ n = 3 \qquad (11.4)$$

Notwithstanding the limitations of the equations, they were used to get the predicted flows given in Table 11.8. Totals gains in flow as determined from the difference between the predicted and measured flows as a result of converting the native forest to pine plantations were 2040 mm at DC1 and 1840 mm at DC4 over 17 years. The lower amount at DC4 reflects water usage in the last few years being less than for the native forest. At DC3, there was a gain in yield of 3600 mm over 15 years and this gain is increasing as flow is still higher than under the original native forest.

Low flows

Comparisons using differences between measured flows adjusted for differences under native forest conditions indicate a maximum rise of about 0.35 mm/day for minimum 7-day low flows as a result of harvesting. However, there are constraints to the differences as DC2, the control, does go dry in many years, the other catchments have not. Differences for the periods selected earlier show that immediately after harvesting, years 0–3, there were mean rises of 0.08 mm/day at DC1 and 0.16 mm/day at DC4 (Table 11.10). Selection harvesting at DC3 for the same phase led to a rise of 0.09 mm/day.

Table 11.10 Mean annual 7-day low flows (mm/day) from Donald Creek catchments for different stages of management (in years from planting). DC2 is in native forest throughout the study. The differences for the post-harvest classes are not adjusted for difference between catchments while under native forest.

	Native forest	0–3	4–10	11–18	11–15	4–12	13–18
DC2 control	0.05	0.03	0.01	0.03	0.01	0.04	0.04
DC1	0.11	0.17	0.01	0.07			
DC1−DC2	0.06	0.14	0.00	0.04			
DC3	0.08	0.15	0.09		0.11		
DC3−DC2	0.03	0.12	0.08		0.10		
DC4	0.16	0.30	0.12			0.12	0.12
DC4−DC2	0.11	0.27	0.11			0.08	0.08

The annual 7-day low flows (as differences between the harvested and control catchment) show that the values stay elevated for about 8 years compared to the native forest state, after which they maintain a level about which there is some variability from year to year (Fig. 11.9).

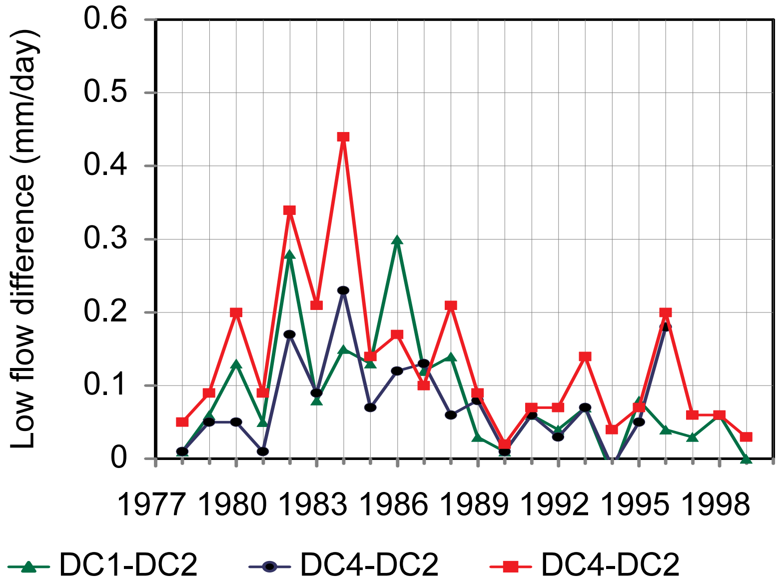

Fig 11.9 The difference between minimum 7-day low flows at the harvested catchments and DC2. Values are not adjusted for catchment differences under the native forest condition.

Peak flows

An annual flood series for the Donald Creek catchments shows increases in peak flows after harvesting and then planting pines in 1980 (Fig. 11.10). Compared to DC2, the control catchment, these peaks have remained elevated for most of the study but approached pre-harvest levels after about 10 years, especially in the smaller flood events.

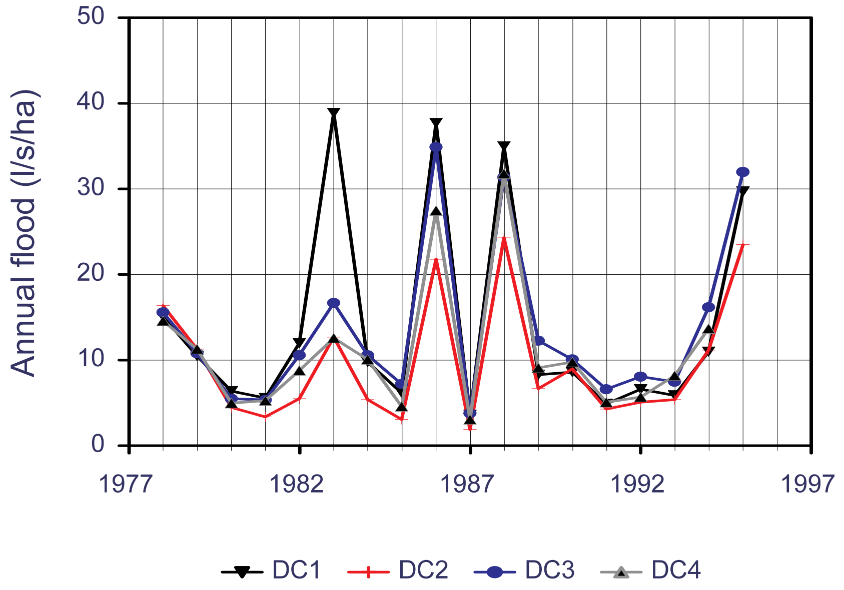

Fig 11.10 Annual series of storm peak flows at Donald Creek. Harvesting DC1, DC3 and DC4 took place in 1980 and 1981.

A second data set comprised all those storms at DC2, the control catchment, that had storm peaks above 2 L/s/ha and the storm peaks from the managed catchments for those storms. Prior to management of the native forest, all catchments had similar mean flood peaks in the four classes of storms extracted (Table 11.11).

At the harvested catchments in the four years after harvesting, storm peaks almost doubled in size in the treated catchments for the 2–5 L/s/ha class, more than doubled in the 5–10 L/s/ha class, and had a variable response in the 10–15 L/s/ha class, but there was only one storm to consider here. As regrowth expanded and the pines matured there was a drop back to near pre-treatment levels by age 11–14 years for the two cleared and planted catchments (DC4 data for the lower-flow classes were not comparable) but remained considerably elevated in the selection-harvested catchment, DC3, suggesting that here the vegetation had not recovered to the same density as before harvesting. The trends in the two higher flow-classes need to be treated with some caution as the results are from only one or two storms.

Quickflow and baseflow

As a consequence of harvesting native forests there were increases in both quickflow and baseflow relative to the unlogged control catchment, DC2 (Table 11.12). Increases in quickflow were about 100–110 mm/year for the four years after harvesting at all catchments, with steady decreases thereafter. Similarly, increases in baseflow after harvest were about 170–220 mm/year with decreases thereafter.

A comparison of event stormflows between the two catchments that were converted to pine plantations and the unlogged DC2 catchment showed increases of about 30% in the five 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).

Table 11.11 Mean storm peak flows for various flow classes and management stages at Donald Creek, Nelson.

	2–5 L/s/ha	5–10 L/s/ha	10–15 L/s/ha	>15 L/s/ha
Native forest sample size	12	1	2	0
DC2	3.3 ± 0.5	5.2	13.8	
DC1	3.8 ± 0.6	6	12.8	
DC3	3.3 ± 0.5	5.4	13.2	
DC4	3.5 ± 0.5	4.7	13	
0–3 years sample size	14	3	2	0
DC2	3.0 ± 0.4	5.5 ± 0.1	11.6	
DC1	5.9 ± 0.9	13.2 ± 3.7	26.8	
DC3	5.2 ± 0.6	12.1 ± 2.2	14.8	
DC4	4.9 ± 0.6	10.5 ± 1.8	9.9	
4–10 years sample size	12	6	0	2
DC2	3.0 ± 0.5	6.7 ± 0.9		23.1
DC1	4.4 ± 0.6	8.8 ± 1.4		36.4
DC3	5.8 ± 1.0	10.8 ± 1.7		33.2
DC4	4.3 ± 0.6	8.9 ± 1.0		29.6
11–14 years sample size	17	4	1	1
DC2	3.3 ± 0.5	5.4 ± 0.3	11.1	23.5
DC1	3.9 ± 0.7	6.2 ± 0.9	11	29.7
DC3	5.6 ± 1.1	7.2 ± 0.9	16.2	32.3
DC4	N/A	N/A	13.7	21.3

Table 11.12 Mean annual quickflow and baseflow from Donald Creek catchments for different stages of management (in years from planting). DC2 is in native forest throughout the study.

	Quickflow				Baseflow			
Period	DC2	DC1	DC3	DC4	DC2	DC1	DC3	DC4
Native forest	200	200	200	210	380	440	370	510
0–3 years	220	330	330	330	310	540	490	660
4–10 years	200	240	300	270	330	420	440	480
11–14 years	240	270	320	290	420	530	530	600

12. West Coast Region

12.1 Maimai experimental catchments

These small experimental catchments were established by the New Zealand Forest Research Institute north-west of Reefton in 1974, and are now operated by Landcare Research (Table 12.1). Located in the Buller hydrological region (Toebes & Palmer 1969) the catchments were established to investigate the effects on stream sedimentation of converting native forest to exotic plantations (Pearce et al. 1976; Rowe et al. 1994; Rowe & Pearce 1994). Nearly 100 reports and papers have been presented on many aspects of hydrology and related aspects including water chemistry, flow pathways and stream ecology. Annual rainfall is of the order of 2450 mm (Rowe et al. 1994). The main experiment did not include catchments M7 and M9 because they had no pre-harvest record.

Table 12.1 Landcare Research Maimai experimental catchments near Reefton.

Site	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
Commenced	Apr 1974	May 1974	Mar 1976	Jul 1974	Feb 1979	Jul 1974	Aug 1974	Sep 1974
Closed	Feb 1993	Feb 1993	Jan 1984	May 1988	Jan 1984	Aug 1995	Apr 1998	
Year of harvest	1978	Not	1976	1978–9	1976–7	1978	1977–8	Not
Extraction method	Cable		Cable	Cable	Tractor	Cable	Cable	
Burning	None		1977	1980	1978	None	1978	
Planting	1978		1978	1980	1978	1979	1978	
Riparian reserve (%)	0		0	5	25	0	0	

Annual flows while in the native forest state were quite variable between catchments ranging between 1140 mm (M15) and 1800 mm (M5) in 1975 (Table 12.1) despite the fact that they are south-facing, have the same vegetation, soils and geology, and lie in a parallel sequence along in the same valley (Powerline Gully, informal name) in the upper part of the Mawheraiti River. The implications are that the hydrologic and topographic boundaries may not be the same, or that we are seeing, at this small catchment scale, natural variation in action.

The 11-year annual water balance (in mm) for the native forest (an average of M6 and M15) was (Rowe & Pearce 1994):

$$\text{Rain} = \text{streamflow} + \text{interception} + \text{transpiration} + \text{seepage}$$
$$2370 = 1290 + 620 + 360 + 100$$

The differences between streamflow from the treated and control catchments after harvesting are shown in Fig. 12.1. This provides further evidence of the variation between catchments as the post-harvest increases in streamflow were variable and not in the perceived severity of treatment. In the year after treatment there was an increase usually between 200 and 250 mm, except for one treatment (M5, clear-felled, herbicide application, no riparian reserve, no burning) 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 streamflow, which returned to pre-treatment 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 pre-treatment levels, at which time the catchments had a dense bracken/honeysuckle understorey beneath 5-m-tall *P. radiata*.

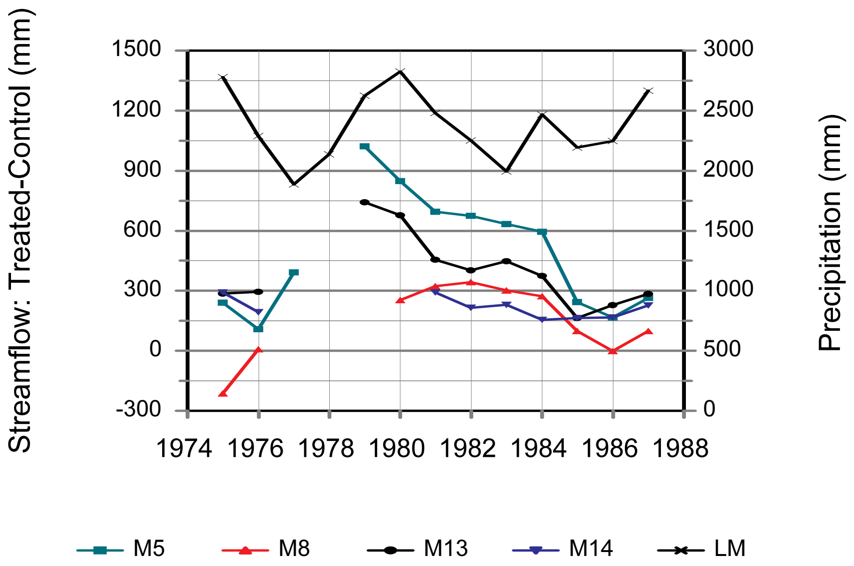

Fig 12.1 Difference between streamflow measured at Maimai control catchments (M6 for M5 and M8; M15 for M13 and M14) and the treated catchments after harvest and replanting.

Low flow

Low flows in this catchment suite have also been variable with the annual averages for the two control catchments, M6 and M15, being 0.04 mm/day (range 0–0.17 mm/day) and 0.15 mm/day (range 0–0.46 mm/day), respectively. It is noteworthy that all catchments tended to dry up or have extremely low flows during extended dry periods even in this high-rainfall region (about 2450 mm/year) where drainage is rapid. Relative to control catchment M15, MALF7 values increased in the order of 0.5 mm/day after harvesting the native forest but began to diminish soon thereafter as revegetation took place (Fig. 12.2). While it appears that the low flows dropped below pre-treatment levels in 1986 and 1987, this may be misleading as the graph line for M6 also dropped suggesting that M15, the reference value, was abnormally high at that time.

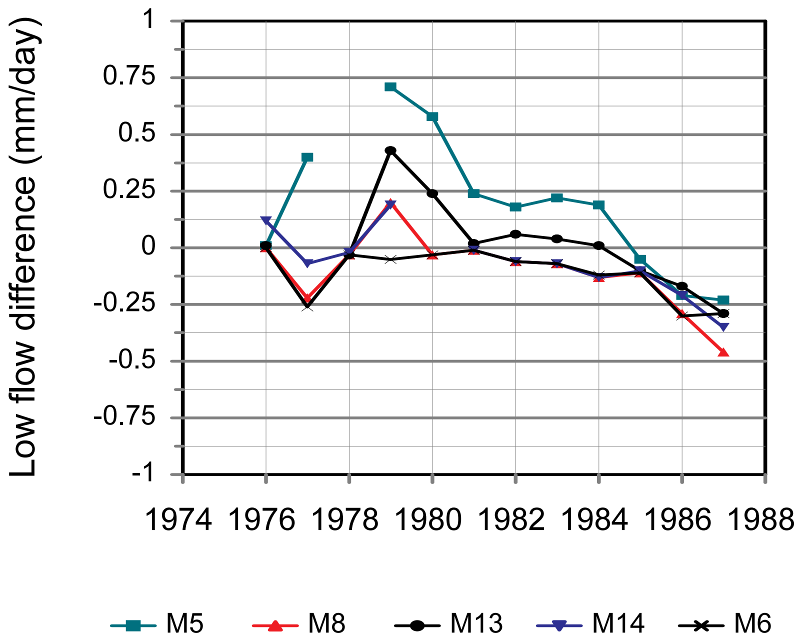

Fig. 12.2 Difference in annual 7-day minimum low flow between the M15 control catchment and the treated catchments and catchment M6.

Storm peaks

The annual series of peak flows was determined for each of the catchments but often there were different storms producing the peak flow at different catchments – another instance of the varying catchment responses to storm rainfalls. Because of this, no analysis of the annual peak flows is presented here.

A series was generated for all storms at M6 greater than 1 L/s/ha and the corresponding storms at M5 and M13 determined. M8 was not considered because records ceased early when the weir was demolished by a debris avalanche and M14 also had a missing period during harvesting and again while the weir was replaced after it, too, was demolished by a debris avalanche. The year 1978 was ignored as well because no records were collected when catchments M5 and M13 were harvested in that year. Results are presented for various management periods in Table 12.2.

The means for the various flow classes while the catchments were under native forest were reasonably consistent with M5 > M6 > M13 > M15, which is also the trend of annual rainfall along Powerline Gully. After harvest there was the expected increase in peaks flows with the increases relative to M6 being greater at M5, which was burned before planting, than at M13 where the logging slash was left on site. Mean peak flows tended back to pre-harvest levels in the 4–8-year period and were indistinguishable from the M6 control catchment values in years 9–14.

Table 12.2 Mean storm peak flows (L/s/ha) for various flow classes and management stages at Maimai, West Coast. The number of storms in each set are given in parentheses.

	1–5 L/s/ha	5–10 L/s/ha	10–20 L/s/ha	>20 L/s/ha
Native forest				
M6	3.0 ± 0.6 (21)	6.8 ± 0.4 (28)	13.2 ± 1.7 (11)	28.6 ± 5.0 (6)
M5	4.1 ± 0.6 (21)	7.0 ± 0.6 (28)	16.3 ± 6.4 (11)	27.7 ± 6.4 (6)
M6	3.0 ± 0.6 (17)	6.8 ± 0.4 (28)	13.3 ± 1.8 (10)	28.6 ± 5.0 (6)
M13	3.5 ± 0.6 (17)	6.3 ± 0.6 (28)	11.1 ± 2.3 (10)	34.3 ± 13.2 (6)
M6	2.9 ± 0.6 (18)	6.8 ± 0.4 (28)	13.2 ± 1.7 (11)	28.6 ± 5.0 (6)
M15	2.2 ± 0.5 (18)	5.1 ± 0.5 (28)	7.2 ± 1.7 (11)	23.4 ± 7.2 (6)
1–3 years				
M6	2.3 ± 0.3 (66)	6.8 ± 0.6 (18)	16.6 ± 1.3 (21)	33.4 ± 19.8 (3)
M5	3.7 ± 0.4 (66)	9.7 ± 0.9 (18)	19.4 ± 1.9 (21)	43.6 ± 27.7 (3)
M6	2.3 ± 0.3 (61)	7.0 ± 0.7 (18)	15.9 ± 1.2 (20)	33.4 ± 19.8 (3)
M13	3.1 ± 0.4 (61)	8.6 ± 1.5 (18)	18.2 ± 2.4 (20)	38.6 ± 17.4 (3)
4–8 years				
M6	2.2 ± 0.2 (69)	6.9 ± 0.4 (40)	13.5 ± 1.2 (20)	28.1 ± 2.3 (5)
M5	2.8 ± 0.3 (69)	8.2 ± 0.9 (40)	14.9 ± 1.5 (20)	32.2 ± 6.9 (5)
M6	2.2 ± 0.2 (74)	7.1 ± 0.5 (38)	13.6 ± 1.1 (22)	28.1 ± 2.3 (5)
M13	2.5 ± 0.3 (74)	7.9 ± 0.9 (38)	15.9 ± 1.9 (22)	33.1 ± 2.8 (5)
9–14 years				
M6	2.8 ± 0.5 (17)	7.2 ± 0.4 (60)	14.1 ± 1.0 (32)	24.7 ± 2.2 (11)
M5	2.9 ± 0.6 (17)	7.0 ± 0.5 (60)	12.7 ± 1.1 (32)	23.4 ± 2.2 (11)
M6	2.8 ± 0.5 (17)	7.2 ± 0.4 (59)	14.0 ± 1.0 (33)	24.7 ± 2.2 (11)
M13	2.9 ± 0.7 (17)	7.0 ± 0.7 (59)	14.4 ± 1.9 (33)	26.1 ± 2.8 (11)

Quickflow and baseflow

As noted earlier, annual flows were variable between catchments under native forest and this variability translates through to quickflow and baseflow components as well (Table 12.3).

Relative to M6, baseflow increased in the 3 years after harvesting by about 360 mm at M5 and 130 mm at M13 before falling back to the pre-treatment averages over the next 6 years. Similarly, quickflow increased 340 mm at M5 and 310 mm at M13 with average values lower in the next 6 years but still above pre-harvest values.

Table 12.3 Mean annual quickflow and baseflow (mm) for various management stages at Maimai, West

Coast.

	Quickflow				Baseflow			
Period	M6	M5	M13	M15	M6	M5	M13	M15
Native forest	880	900	780	560	370	600	520	450
1–3 years	980	1340	1190	810	550	1040	830	590
4–9 years	830	1050	990	710	510	720	630	600

12.2 Larry River experimental catchments

Three small catchments (Table 12.4) instrumented north of Reefton were established on pakihi scrublands in the West Coast lowlands hydrological region (Toebes & Palmer 1969). The purpose was to assess the effects of clearance of 40-year-old mānuka scrub by crushing and burning, followed by drainage of the pakihi and the formation of mounds between the drains, the mounds being planting with radiata pine. After treatment there was regrowth of scrub and fern between the drains with rushes and sphagnum becoming established in the drains (Jackson 1984). Because the area is almost flat, drainage of Larry LA3 and the surrounding area led to an increase in catchment area as feeder drains now carried flow from outside the initial area.

Table 12.4 Larry River catchments and treatments.

	Larry LA1	Larry LA2	Larry LA3
Area (ha)	10.0	11.6	7.2 (9.9 after drainage)
Commenced	April 1983	April 1983	April 1983
Ended	October 1986	March 1888	March 1988
Treatment	Drained and planted in 1982 before weir installation	Control catchment: no treatment	18-month calibration; scrub crushed Oct. 1984; burned Feb. 1985, drained April 1985; planted winter 1985

Annual precipitation and streamflow from two catchments show a clear trend with rainfall (Table 12.5) but there is no clear indication of a change at LA3 as it was cleared and burned in 1984–5, nor after drainage in April 1985. Jackson (1987) noted that, because of the poor drainage and shallow, almost impervious gley podzol soils which remain close to saturation, the catchment hydrology is dominated by quickflow, about 70% of streamflow.

Table 12.5 Annual precipitation from R3 in Larry River LA3, and streamflow for control catchment LA2 and LA3, which was cleared and drained. The year runs from 1 May to 30 April.

	1983–1984	1984–1985	1985–1986
R3 precipitation (mm)	2630	2470	2150
LA2 runoff (mm, % of rain)	1780 (68%)	1500 (61%)	1230 (57%)
LA3 runoff (mm, % of rain)	2040 (78%)	1840 (75%)	1370 (64%)

After drainage of LA3 it appeared that quickflow totals remained about the same but peak specific discharges increased 2–3 times (Table 12.6) and the hydrograph had earlier rises and faster falls (Jackson 1987). Note that L1 had already been treated in the pre-treatment column in Table 12.6 and the average peak flows, which are higher than LA2 and LA3, reflect this. There are obvious increases in average peak flow after treatment at L3 compared to L2, i.e., there are more large flows after treatment. There were more than three times as many peak flows >10 L/s/ha at L3 than at the control L2 (Jackson 1987).

Table 12.6 Average peak flow (L/s/ha) before and after treatment of catchment L3 (from Jackson 1987).

	L2 storm size class	Number of storms	L1	L2	L3
Pre-treatment of LA3	5–9.99	13	16.3	7.3	8.9
	10–19.99	8	17.5	12.9	14
	≥20	4	24.1	22.7	23.4
Post-treatment	5–9.99	10	14.3	7.4	21.3
	10–19.99	3	18.3	13.4	22.5
	≥20	1	32.9	22.3	76.9

13. Canterbury Region

13.1 Ashley Suite

NIWA and Landcare Research (as the New Zealand Forest Research Institute) have both monitored catchments at Ashley Forest in North Canterbury (Table 13.1). These catchments located in the Canterbury Plains hydrological region (Toebes & Palmer 1969) provide a snapshot of water yields from a drier environment with mature pine trees and from a small pasture catchment for comparison. Harvesting the Landcare Research pine catchment took place from October 1985, which provides another dimension to the data from here – the effects of harvesting on water yield.

The Landcare Research Ashley Pines catchment, API, is located within the NIWA Stony Creek catchment. In 1991, all the Stony Creek catchment was in plantation forest (NZMS-260 M34 1st Edn 1991) but previously it was predominantly native forest with small amounts of plantation (NZMS-1 S68, 4th Edn 1977). About two-thirds of Ashley Pines were planted about 1940, and the rest in 1970 and 1979 (Jackson 1985). It is assumed that the rest of Stony Creek was planted about 1979 as the three Stony Creek gauging stations were established then to 'study the effects of forest growth on streamflow' (NIWA comment files accompanying data for Stony Creek site 66207). Stony Creek North and Stony Creek South are sub-catchments of Stony Creek.

Precipitation is about 950 mm/year for the Landcare Research catchments (Jackson & Rowe 1997), which is higher than at a long-term site, Ashley Forest, where the 1961–1990 normal was 774 mm (NIWA site H32252; Tomlinson & Sansom 1994). A comparison of 5 years of data has rainfall at the Pasture catchment raingauge being 122% of Ashley Forest and this relationship was used to generate a precipitation index for the catchments and to extend the period of rainfall record outside that measured.

Table 13.1 Canterbury Region: Ashley catchments with land cover in 2000.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Stony Creek @ Forbes Road	Dec 1979	Aug 1986	6.07	Exotic
Stony Creek South @ Sawbench Road	Jun 1979	Feb 1987	2.6	Exotic
Stony Creek North @ Stony Creek Road	Jun 1979	Aug 1986	1.82	Exotic
Ashley Pines	Oct 1980	Aug 1989	0.229	Exotic
Ashley Pasture	Jan 1981	Apr 1987	0.154	Pasture

Annual Streamflow

Streamflow from the two Stony Creek sub-catchments (1981–1985) averaged about 160 mm/year, which is more than from the Pasture and Pines catchments. This either reflects the difference in scale of the catchments or, when compared to the Pines flow, a younger age structure for North and South because flows are higher. There may also be a rainfall gradient factor superimposed on the vegetation cover factor as North has a higher yield than South, which is higher again than from Pasture. Rainfall does increase from east to west, and probably south to north as well, which is also the spatial trend of those three catchments.

Table 13.2 Mean annual streamflow (mm) and the precipitation index (mm).

	Precipitation	Stony Creek	South	North	Pines	Pasture
1981–1985	810	140	150	170	46	120

Comparisons of streamflow from the Pasture and Pines catchments as a function of the precipitation index are shown in Fig. 13.1. While the three data groups, Pasture, Pines pre-harvest, and Pines post-harvest, show good relationships with the precipitation index, the small sample sizes lead to wide confidence limits on the regression factors and nonsensical relationships, such as streamflow increasing faster than precipitation. It is apparent, however, that before harvesting the water yield from the Pines catchment averaged about 70 mm less than that from the Pasture catchment, and that in the very dry year, 1982, with precipitation about 660 mm, there was essentially no flow from either catchment. After harvesting at Pines, there was an increase in streamflow towards the pasture data trend. There was only one post-treatment comparative point for both Pasture and Pines, the wettest year of the short record when Pines streamflow was only half (400 mm) of that from the Pasture (800 mm).

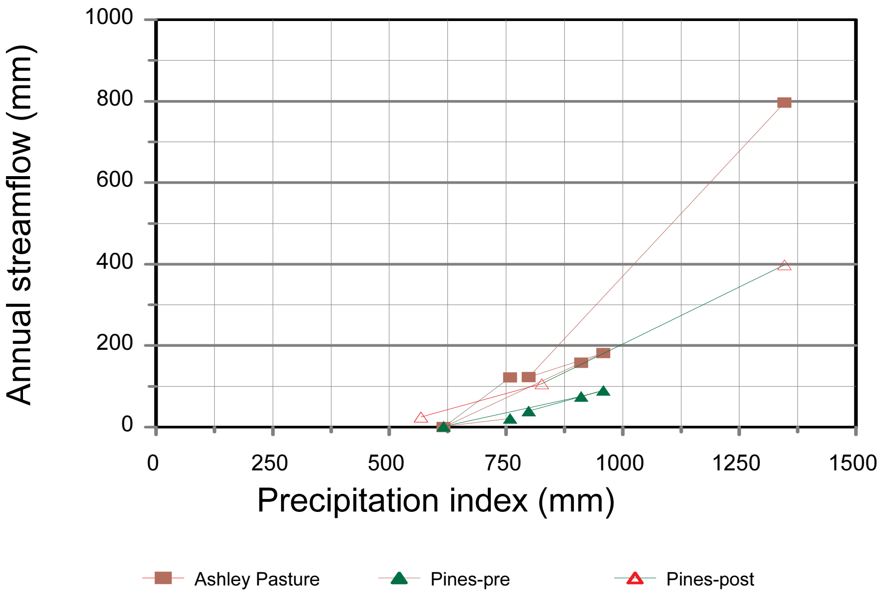

Fig. 13.1 Annual streamflow for the Ashley Pasture catchment and for the Pines catchment before and after harvest as a function of annual precipitation.

Low flows

All catchments in this suite run dry in the summer, the longest spell in 1981–1982 at Ashley Pasture being 10 months. There was no consistency in the patterns between the Pines and Pastures sites with the Pines site, contrary to the usual situation, often beginning to flow again earlier than the Pasture catchment.

Quickflow and baseflow

Because the record from Pasture stopped shortly after Pines was harvested, there is little information to be able to say with surety what the effects of harvesting have been on the change in proportion of quickflow and baseflow in the flow regime at Pines. The 5 years of data including the year of harvest indicate that both the Pasture and Pines catchments have quickflow and baseflow in equal proportions, on average.

13.2 Kakahu Suite

Four catchments have been monitored about 15 km west of Geraldine for various periods since 1980 (Table 13.3). These catchments are located either in the Timaru Downlands or the Canterbury Foothills hydrological regions (Toebes & Palmer 1969). Some plantations, about 4.5 km^2, had been established in Kakahu Forest above the Kakahu River gauging station at Mulvihills by 1971 (NZMS-1 S102 3rd Edn 1971). The late 1970s saw the area of plantations here expand so that by the early 1980s there was over 17 km^2 (40%) including all of the sub-catchment above Mitchell's weir 9 (NZMS-260 J38 1st Edn 1983). At Mitchell's, the original cover was pasture and the trees were planted about the time the weir was established (ECAN comment file accompanying data for Kakahu @ Mitchell's weir 9, site 69633). About 14% of the Te Moana River catchment was also in plantations probably established about the same time. Rainfall is approximately 900 mm/year as interpolated between Geraldine Forest (ECAN site 41000) data and the 1961–1970 normals of Pussey (NZMetS site H40091), Beautiful Valley (NZMetS site H41101), Woodbury (NZMetS site H41011), Wynward (NZMetS site H41022), and Kakahu Bush (NZMetS site H41111) (NZMetS 1973).

Table 13.3 Canterbury Region: Kakahu Suite catchments with land cover in 2000.

Site	Start of gauging	Area (km^2)	Land cover
Kakahu @ Mitchell's weir 9	Nov 1980	2.75	Exotic
Kakahu @ Turnbull's weir 10	Nov 1980	4.55	Pasture
Kakahu @ Mulvihills	Dec 1983	43.7	Pasture + exotics
Te Moana @ Glentohi	Dec 1983	77.8	Pasture + exotics

Mitchell's & Turnbull's weirs

The records from Mitchell's weir 9 and Turnbull's weir 10 can be considered a paired study. From mid-1985 there is a gap of 10 years in the records for both sites. Thus, there are about 4½ years of data as the plantations were establishing and about another 6 years when the trees could be considered mature, although many periods of missing data make comparisons at the annual scale difficult.

Comparable annual streamflow data indicate that the established plantation reduced streamflow by about 145 mm/year compared to the calibration state (when the trees are 1–4 years-old) (Table 13.4, Fig 13.2). Although there are very limited data, it appears that the reduction will be smaller in very dry years, about 100 mm as for 1998, than in a year of near average rainfall, about 190 mm as for 1999.

Table 13.4 Measured annual streamflow (mm) at a plantation forest catchment (Mitchell's) and pasture catchment (Turnbull's) and rainfall (mm) for Geraldine Forest and Kakahu Bush, Mid-Canterbury.

Period	Mitchell's weir 9	Turnbull's weir 10	Kakahu Bush rainfall	Geraldine Forest rainfall
1981–1984	365	345	620	N/A
1998	100	185	510	610
1999	250	420	710	920

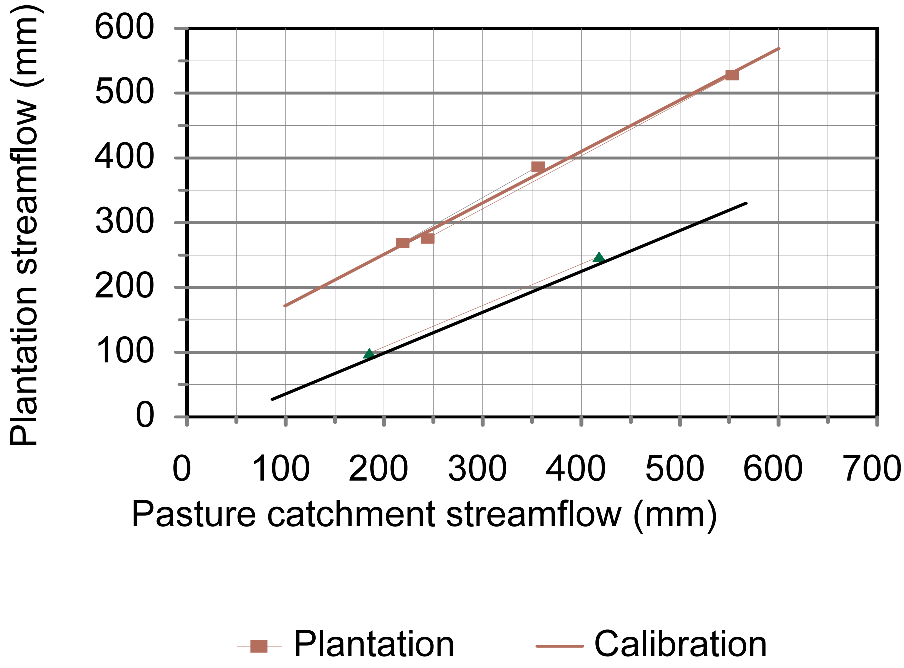

Fig. 13.2 Relationship between streamflow at the plantation catchment (Mitchell's) and at the pasture catchment (Turnbull's). The calibration state line is a calculated regression line (Mitchells = 90 + 0.8×Turnbulls); the line for the plantation state is fitted by eye through the two available data points.

There are a few more data points available to make comparisons of annual minimum 7-day low flows (Fig. 13.3). There is a difference between the values for each time period (Table 13.5). While it is tempting to attribute the smaller increase at Mitchell's to greater water use by the trees that have matured, the difference may be due to some factor such as changed characteristics at the low-flow stage of the Crump weirs; there was no maintenance over a 10-year period when recordings were not taken and Turnbull's was noted as being damaged with water flowing under it prior to the 1985 closure (ECAN comment file accompanying data for Kakahu @ Turnbull's weir 10, site 69634). Without the benefit of continuous flow records we cannot attribute the change in low flows to afforestation.

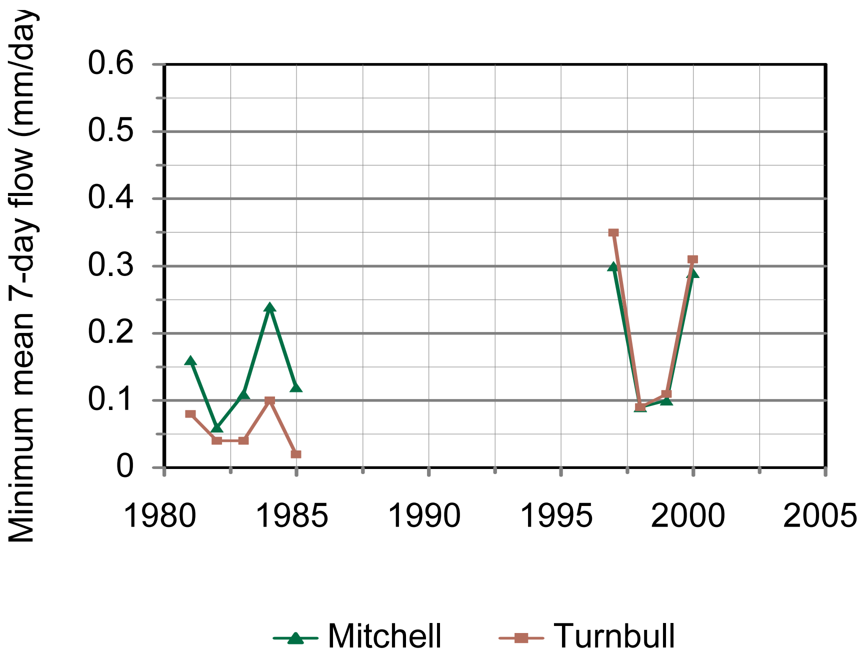

Fig. 13.3 Measured annual minimum 7-day low flow (mm/day) at a plantation forest catchment (Mitchell's) and an adjacent pasture catchment (Turnbull's).

Table 13.5 Measured annual minimum 7-day low flow (mm/day) at a plantation forest catchment (Mitchell's) and an adjacent pasture catchment (Turnbull's).

Period	Mitchell's weir 9	Turnbull's weir 10
1981–1983	0.14	0.07
1997–2000	0.2	0.22

Te Moana River and Kakahu River @ Mulvihills

These gauging stations were installed after some plantations had already been established by 1983, about 14% of Te Moana River and 40% of Kakahu River above their gauging stations. Any trend is likely, therefore, to reflect the growth of more trees in the Kakahu River catchment, about 30% of the catchment, beyond 1983. There are differences in yields from the two catchments as shown for the 1984–1992 period (Table 13.6). These are likely to reflect rainfall differences as there is an increasing gradient from about 800 mm near the Mulvihills gauging station through Kakahu River where there is about 900 mm at Mitchell's and up to 1100 mm or more at the northern extreme of the Te Moana River catchment.

Table 13.6 Measured annual streamflow (mm) from Te Moana and Kakahu rivers and mean annual rainfall (mm) at Kakahu Bush.

Period	Te Moana	Kakahu	Kakahu Bush rainfall
1984–1992	440	280	730

1997–1999	390	290	690

Differences between the two time periods, 1984–1992 and 1996–1998, seem to indicate increased yields at Kakahu River relative to Te Moana River, or decreased yields at Te Moana River relative to Kakahu River (Table 13.6). Plotting data for the two periods against Kakahu Bush as a rainfall index showed that there was no distinction between plots for the two periods of Kakahu River data, but there was a separation for Te Moana with only one point from the 1984–1992 data set overlapping with the later period, which had lower streamflow yields for some unclear reason. Not much difference was expected for Kakahu River as the trees would have been approaching canopy closure towards the end of the period when water use would be similar to the older trees in the later period.

Annual minimum 7-day low-flow values are lower for Kakahu River than for Te Moana River. Means for 1984–1992 and 1995–1999 showed increased flows at both sites in the later period but ratios between the two sites were similar for each period indicating no relative change: Kakahu 0.07 mm/day and 0.10 mm/day; Te Moana 0.19 mm/day and 0.26 mm/day; ratios Te Moana:Kakahu 1.36 and 1.40. Again, this is not unexpected because there would be very little difference of a hydrological nature between the two periods.

14. Otago Region

14.1 Berwick Suite

Four catchments in east Otago, two in plantations in Berwick Forest and two in pasture south of Berwick Forest and to the west of Lake Waihola, were monitored for nine years (Table 14.1). The plantation forests were established in 1964, and limited management took place in Storm Creek in 1979 and 1980 (Smith 1987). Effectively, this study is a comparison of two land uses. There are, however, no data to indicate whether the hydrology of the four catchments was similar in the pasture state and, therefore, a more definitive discussion on afforestation effects on water yields of the two vegetation types is not possible. Nevertheless, for the purposes of this study we have to assume they are the same, as the geology is similar and there are only small rainfall differences between catchments.

Table 14.1 Otago Region: Berwick Suite catchments with land cover in 2001.

Site	Start of gauging	End of gauging	Area (km^2)	Land cover
Storm Creek @ Storm Road	Jul 1978	Jul 1987	1.14	Exotic
Jura Creek @ Jura Road	Jun 1978	May 1987	1.92	Exotic
Vollweillerburn @ Berridale	May 1980	May 1987	1.63	Pasture
Kintore Creek @ Berridale	Sep 1979	Jan 1994	2.92	Pasture

The raingauge sited at the Kintore Creek streamgauging station had an average for 1980–1987 of 980 mm/year. This period was wetter than usual with the next 5 years, 1988–1993, averaging 890 mm/year leading to a 1980–1993 average of 940 mm/year.

Precipitation averaged for the two forested catchment is about 70 mm/year more than that averaged for the two pasture catchments, but streamflow is considerably less (Fig. 14.1, Table 14.2). The regression relationships between annual streamflow (Sf) yield and precipitation for the two cover types (Eqns 14.1 and 14.2, Fig. 14.1) had similar slopes (comparison of regression test (Freese 1967): test for common slopes F_{test} = 4.3 cf. F_{tab} = 5.0) but levels were different (test for single regression F_{test} = 187 cf. F_{tab} = 4.8).

Pasture	Sf = −40 ± 90 + 0.52 ± 0.10 × PTTN	r^2 = 0.98, SE = 12; n = 6	(14.1)
Plantation	Sf = −90 ± 215 + 0.29 ± 0.20 × PTTN	r^2 = 0.67; SE = 40; n = 8	(14.2)

Also shown are the relationships between evaporation (= precipitation less streamflow):

Pasture	Evp = 460 ± 270 + 0.13 ± 0.29 × PTTN	r^2 = 0.29; SE = 40; n = 6	(14.3)
Plantation	Evp = 90 ± 400 + 0.71 ± 0.19 × PTTN	r^2 = 0.92; SE = 40; n = 8	(14.4)

which have significantly different slopes (test for common slopes F_{test} = 18 cf. F_{tab} = 5.0).

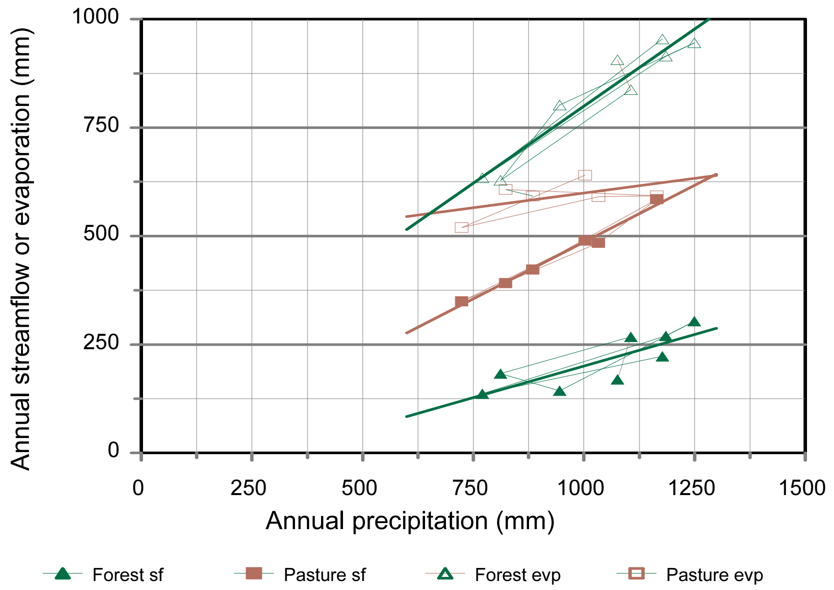

Fig. 14.1 Annual streamflow and evaporation (rainfall less streamflow) for means of two pasture and two plantation forest catchments in east Otago. The lines are based on Equations 14.1 to 14.4.

Data for the two sets of catchments have been rescaled here to a common annual precipitation of 1000 mm/year by retaining the same percentages for streamflow and evaporation as a function of precipitation for the measured data (Table 14.2). This indicates that for the forested catchments there is about 180 mm/year less streamflow than for the forested catchments. This is also shown as higher evaporation (precipitation less streamflow) (Figs 14.1 and 14.2, Table 14.2). While evaporation from the pasture catchments is similar in all years, that from the forested catchments is influenced by rainfall, being similar to the pasture catchments in dry years but higher in wetter years (Fig. 14.2).

Table 14.2 Average water balances for east Otago pasture and plantation-forested catchments calculated from data in Smith (1987), and rescaled for a common annual precipitation regime of 1000 mm.

	Pasture	Forest	Pasture less forest	Pasture	Forest	Pasture less forest
Precipitation	940	1110		1000	1000	
Evaporation	590	900	−310	630	810	−180
Streamflow	350	210	140	370	190	180
Quickflow	100	25	75	110	23	87
% qf/PTTN	11	2.3		11	2.3	
Delayed flow	240	185	65	260	167	93
% df/PTTN	26	17		26	17	

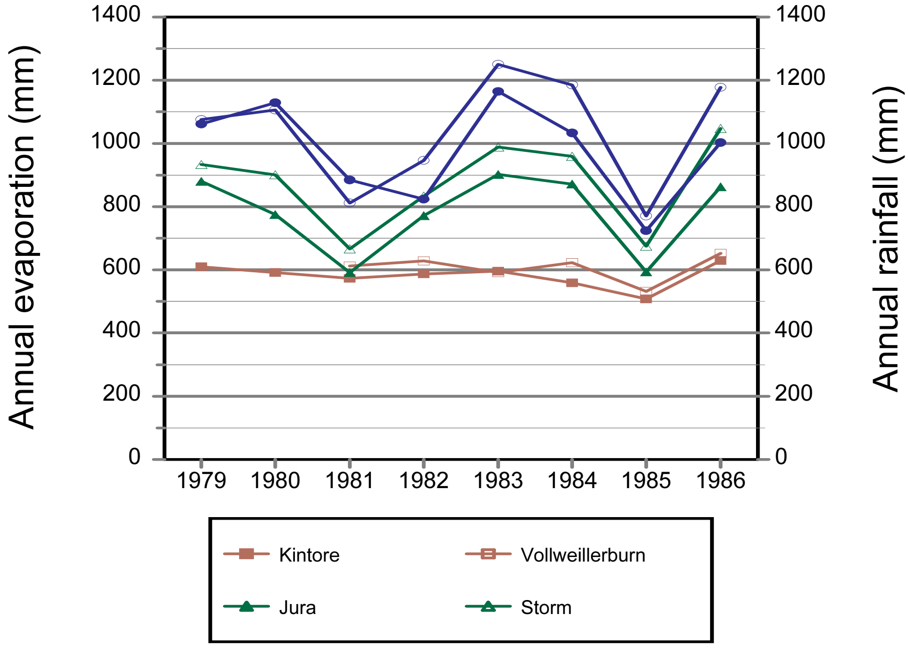

Fig. 14.2 Evaporation (as precipitation less streamflow) for grassland and plantation-forested catchments in East Otago (data for year ending 31 August extracted from Table 2 in Smith (1987)).

Low flows

Annual minimum 7-day low flows for the Berwick Suite catchments are given in Table 14.3. No differences could be attributed to land-use differences.

Table 14.3 Annual minimum 7-day low flows (mm/day) for catchments in East Otago.

	Plantation		Pasture	
	Jura Creek	Storm Creek	Vollweillerburn	Kintore Creek
1979	0.15	0.1		
1980	0.21	0.13		0.36
1981	0.2	0.15	0.12	0.21
1982	0.21	0.12	0.16	0.25
1983	0.28	0.23	0.23	0.33
1984	0.39	0.27	0.34	0.44
1985	0.26	0.14	0.11	0.23
1986	0.19	0.05	0.06	0.08
1987	0.42	0.16	0.16	0.31
Mean 1981–1987	0.28	0.17	0.17	0.26

Storm peaks

A simple analysis of annual storm peaks from the catchments shows variation between vegetation types but the two pasture catchments had peaks three times higher than under plantation. Thus, the effect of increased water use by the plantations leading to increased interception and lower soils moisture storage compared to pasture catchments has a considerable effect on storm flows. Although there are only 8 years of data used in Table 14.4, an extended set for Kintore Creek to 13 years has the same range of values but a lower mean, 5.4 ± 1.9 L/s/ha, and showed that the 1979–1986 data had five of the 13 highest annual events.

Table 14.4 Mean annual storm peaks (L/s/ha) for catchments in East Otago.

	Plantation		Pasture	
	Jura Creek	Storm Creek	Vollweillerburn	Kintore Creek
Storm peaks	3.2 ± 1.3	2.5 ± 0.8	9.7 ± 4.1	6.9 ± 2.7
Range	1.44–7.33	0.31–4.18	1.45–18.44	0.89–12.78

Quickflow and baseflow

Streamflow has been separated into baseflow and quickflow by Smith (1987) using the Hewlett & Hibbert (1967) method and adjusted to a common rainfall regime by the author (Table 14.2). The streamflow difference between the two land-use classes is about 180 mm/year, the plantations having the lower yield. About half of the difference occurs as diminished quickflow and half as diminished delayed flow. The reduction in quickflow may not be that important as this generally occurs in storms, and, unless there is constructed storage, is water not able to be used by downstream users. Thus, the comparison of the two land uses indicates there is, on average each year, a loss of about 90 mm of potentially useable water, which is the reduction in baseflow. However, there is no pre-afforestation streamflow information to verify this level of reduction, which we are basing on the supposition that the catchments were hydrologically similar before planting.

14.2 Glendhu experimental catchments

Two catchments (Table 14.5) at Glendhu Forest near Lawrence have been monitored since 1979, initially by the New Zealand Forest Research Institute and latterly by Landcare Research. Originally in tussock grassland, 67% of GH2 was ripped in winter 1981 and planted with *P. radiata* in winter 1982 (Fahey & Watson 1991). About 40 papers and reports have presented information on the hydrology and related aspects of these catchments.

Table 14.5 Glendhu experimental catchments with land cover in 2001.

	Start year	Area (km^2)	Land cover
Glendhu 1	1979	2.18	Tussock
Glendhu 2	1979	3.07	Exotics

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 & Watson (1991); Fahey & Jackson (1997), Fahey et al. (1998). About 7 years after planting 67% of catchment GH2 (1989) annual streamflow yields began to show a definite decline compared with GH1 still in tussock grassland (Fig. 14.3).

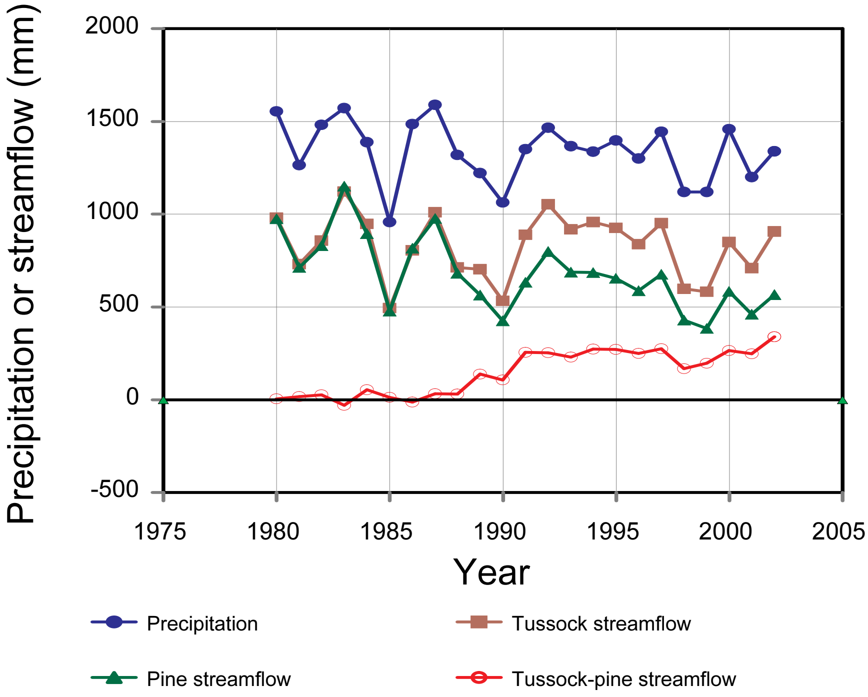

Fig. 14.3 Streamflow at Glendhu catchments GH1 (tussock) and GH2 (67% radiata pine) and the difference in flow with time. Planting was carried out in 1982.

These differences are further highlighted in Fig. 14.4 where yields from GH2 are plotted against GH1 for four different periods throughout the study to date. Yields from the two earlier periods, up to 2 years after planting and from 3 to 6 years after, were similar as were yields in the periods from 7 to 13 years and 14 to 20 years after planting, although there was a tendency for yields from the oldest group to be slightly lower than the middle group, which was still undergoing canopy expansion. Because of the similar relationships, regression equations were calculated for combined groups with the results shown as Eqns 14.5 and 14.6 and in Fig. 14.4. These relationships were statistically different (test for common slopes F_{test} 13.3 cf. $F_{tab} = 4.4$).

Up to 6 years	$GH2 = -40 \pm 100 + 1.03 \pm 0.12 \times GH1$	$r^2 = 0.98$; SE = 26; $n = 9$	(14.5)
7–20 years	$GH2 = 20 \pm 130 + 0.69 \pm 0.15 \times GH1$	$r^2 = 0.89$; SE = 41; $n = 14$	(14.6)

For a year of average streamflow from GH1, about 830 mm/year, the difference in yields at GH2 for the two periods represents a reduction of 220 mm/year. Measured streamflow yields for the two periods are given in Table 14.6 and, again, show that the reduction in streamflow as a consequence of 67% afforestation of GH2 averages of the order of 220 mm/year making an allowance for the difference in yields in the early period. The change is equivalent to a reduction of 330 mm/year for afforestation of the full catchment.

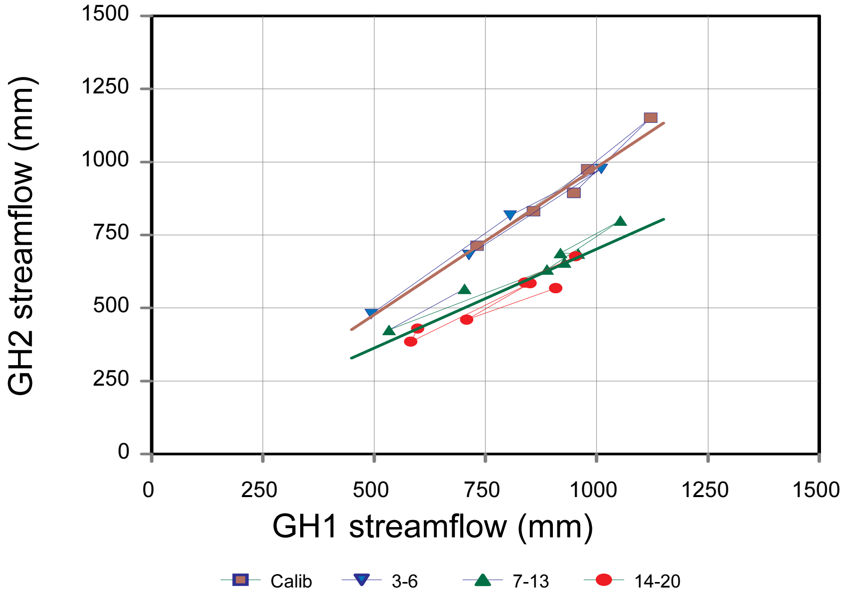

Fig. 14.4 Rrelationship between annual streamflow at Glendhu catchments GH1 and GH2 for differing time periods.

Table 14.6 Streamflow yields at Glendhu tussock catchment GH1 and for GH2 before and for 6 years after planting 67% of the catchment and for the period when the trees were aged 7–20 years.

Age class (years)	Precipitation (mm)	GH1 streamflow (mm)	GH2 streamflow (mm)
−2 to +6	1400	850	835
7–20	1300	815	580

For a year of average streamflow from GH1, about 830 mm/year, the difference in yields at GH2 for the two periods represents a reduction of 220 mm/year. Measured streamflow yields for the two periods are given in Table 14.6 and, again, show that the reduction in streamflow as a consequence of 67% afforestation of GH2 averages of the order of 220 mm/year making an allowance for the difference in yields in the early period. The change is equivalent to a reduction of 330 mm/year for afforestation of the full catchment.

Low flow

At the Glendhu tussock catchment, GH1, the minimum 7-day low flows are of the order of 0.5–1.0 mm/day in most years. Prior to planting and in the 6 years after planting at GH2, MALF7 values averaged 0.06 mm/day higher than GH1 (0.89 mm/day cf. 0.83 mm/day). Afforestation of 67% of GH2 appears to have taken effect about 6 years after planting (Fig. 14.5), and at ages 7–20 years the average LF7 was 0.21 mm/day lower than predicted from GH1. Assuming a proportionate change for area converted, this flow decrease is equivalent to about 0.3 mm/day for planting the whole catchment.

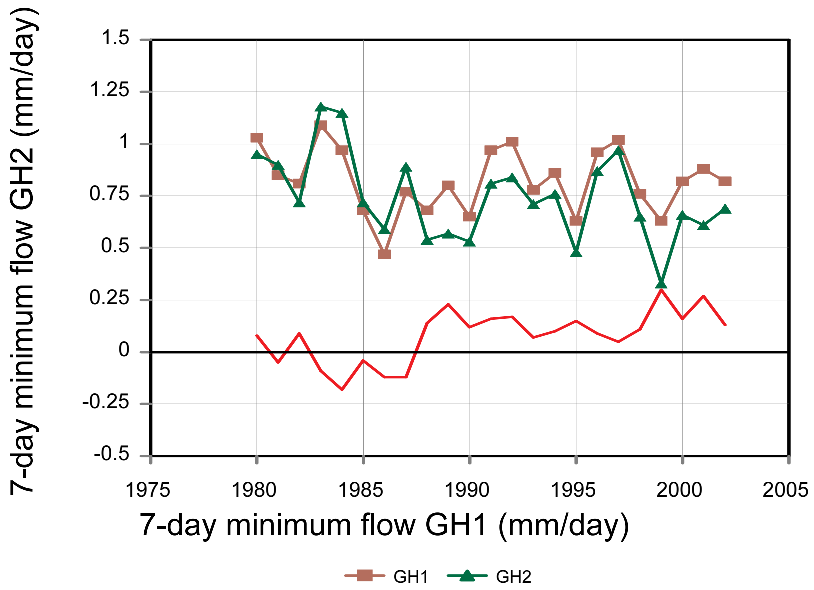

Fig. 14.5 Low-flow changes at Glendhu as a result of 67% afforestation of catchment GH2 in 1982. The solid line without markers is the difference (GH1 less GH2).

Storm peaks

Afforestation of 67% of the tussock-covered GH2 catchment at Glendhu has resulted in decreased annual flood peaks when compared to the GH1 control catchment as shown by a mass-curve plot of accumulated annual maximum peaks (Fig. 14.6). For the period up until 1989, 8 years after planting, GH2 annual floods averaged 91% of those at GH1. This average more than halved to 42% of GH1 from age 9 to 21 years. Fahey & Watson (1991) and Fahey & Jackson (1997) showed that for storms divided into a number of flow classes there were reductions over 50% in all classes above 5 L/s/ha with over 70% reductions in the 2–5 L/s/ha class.

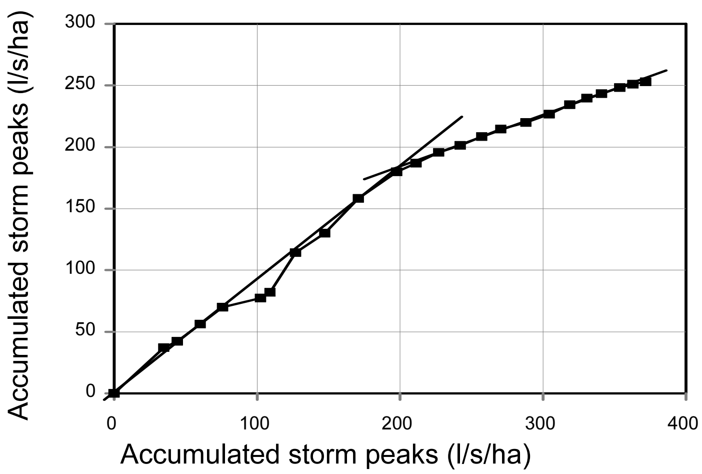

Fig. 14.6 A mass curve of annual flood peaks showing some variability between sites in the early years after planting and a definite reduction at GH2 after 1989, the point 198,180.

Quickflow and baseflow

Flow separation using the Hewlett & Hibbert (1967) method partitioned streamflow from the Glendhu catchments into quickflow and baseflow. At GH1, the control catchment, the proportion of quickflow to delayed flow remained consistent for the two sample phases (Fig 14.7) although there was a slight reduction as a result of a slightly drier second phase (Table 14.7). However, at GH2 there was a considerable reduction as a result of 67% afforestation (Fig. 14.7) with the reduction more or less evenly divided between the two flow components, 100 mm for quickflow and 110 mm for baseflow; for 100% afforestation these translate to 150 and 165 mm, respectively (Table 14.7). If the reduction in quickflow is not considered a loss of useable water to the stream because it would pass quickly through the system out to sea unless captured by storage, the loss of useable water by planting trees at GH2 would be about 165 mm/year.

Table 14.7 Average annual quickflow and delayed flow yields (in mm) at the Glendhu tussock catchment (GH1) and for GH2 before and for 6 years after planting 67% of the catchment, and for the period when the trees were aged 7–20 years.

Age class (years)	Precipitation (mm)	GH1 tussock		GH2 plantation	
		Quickflow	Delayed flow	Quickflow	Delayed flow
−2 to +6	1400	295	555	235	600
7–20	1300	280	535	120	460

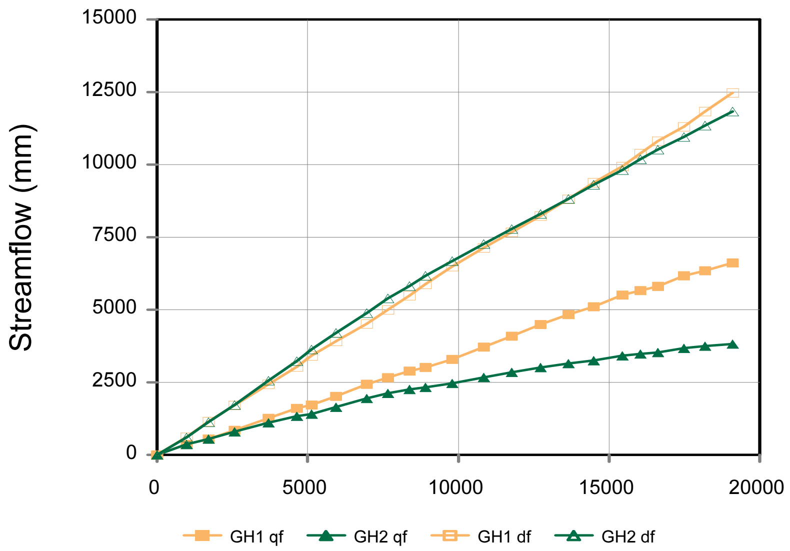

Fig 14.7 Mass curves of streamflow components, quickflow and baseflow, for Glendhu catchments GH1 and GH2 plotted against accumulated GH1 streamflow.

15. Summary

15.1 Perspectives on the project

In the previous sections, I have reported simple analyses carried out on streamflow data from catchments where there have been changes in land use, mainly afforestation of pasture or scrub, the felling of native forest and its replacement by plantation forests, and the harvesting and replanting of plantations. Information from a number of other land-use-change studies have been reported from the hydrological literature; for example, scrub to crops, scrub to pasture, drainage of pakihi.

We know that change in streamflow happens as a consequence of land-use change and is easily seen in many published studies, but usually at a catchment scale of less than 1000 ha (see for example: Hibbert 1967; Bosch & Hewlett 1982; Reports 1, 2, 3 & 5 in this series, Rowe et al. 2001a, 2001b, 2001c, 2002). In their summary of worldwide experimental catchment literature pertaining to afforestation and harvesting on water yields, one of the conclusions reached by Bosch & Hewlett (1982) was that for a 10% change in forest cover the change in annual streamflow yield was about 40 mm.

Hydrological variability has been an issue when trying to detect trends for this work. In many instances, the land use change has been planting of the order of 10–15% of a catchment's area over a period of 10 years or more. If the Bosch & Hewlett rule applies to these catchments, I have been trying to detect an effect in a streamflow record that varies considerably from year to year and also over a longer time period as the rainfall regime varies. For example, the 254-ha Esk River @ Waipunga had about 18% of its area planted between the mid-1960s and late 1990s with a potential change from pasture (with some scrub) of less than about 80 mm. The yield figures show there was a decrease in flow between the two periods of 60 mm/year but rainfall decreased 150 mm (12%) at the same time. Annual flows ranged from 370 to 1100 mm, and the 95% confidence limits on the period mean flows was about 100 mm (Table 15.1). Thus, any change that did take place as a result of the plantation establishment is submerged within the natural variation in the data.

Table 15.1 Flow parameters for the Esk River @ Waipunga, and Rukumoana rainfall.

Period	Mean yield (mm)	Standard Deviation (mm)	95% Confidence limits (mm)	Maximum yield (mm)	Minimum yield (mm)	Rukumoana rainfall (mm)
1964–1997	680	210	70	1160	370	1540
1964–1980	710	210	100	1160	370	1610
1980–1997	650	200	100	1050	370	1460

Catchment scale is really the issue here. As noted above, many small-catchment studies have shown change in streamflow yield as a change of cover occurs. In these, we are usually dealing with catchments of the order of a few to a few hundred hectares with a significant proportion of the catchment transformed in a short time frame thus making the degree of change readily detectable. In larger catchments (over a few square kilometres) we have, over an extended time frame, a number of small catchments where change occurs and many where there has been no change, so the effect of the change has been diluted at the recording site, the catchment outlet.

Another factor that had a big influence on the work is the length and timing of available records. There are many instances where there have been significant land- use changes over a short period, but flow records have begun after the change has occurred. This negates the most efficient form of analysis, the use of split records where flows over two periods (a calibration period before and a treatment period after the land-use change) are compared with that from a stable control record. The preferred control is another streamflow record from a nearby catchment where land cover has not changed as this record will reflect climate variability in a manner similar to the changed catchment. We can, therefore, adjust for differences in the two periods by proportion without introducing large errors.

Where streamflow is not available as a control parameter against which to assess change, rainfall has to be used. This is not the preferred option because we are now looking at the catchment output vs the catchment input less evaporation, which varies according to the amount of rainfall. Making adjustments between periods by simple proportion could introduce significant errors if the rainfall differences are large.

When comparisons were made between catchments with different land covers but with no pre-change data for the two catchments available, e.g., the Berwick Suite (Section 14.1), I had to assume that there were initially no differences between the catchments. Therefore, any differences seen were attributable to catchment cover. This is not always true as has been shown for small catchments at Maimai (Rowe & Pearce 1994), and for larger catchments at Purukohukohu where two pasture catchments had annual yields of 250 and 530 mm with similar catchment rainfalls (Table 5.10). Geology and/or rainfall will be two of the major factors contributing to these differences in yield from catchments that are often adjacent.

Many of the comments above also apply in varying degrees to low flows, peak flows, and flow components – quickflow and baseflow.

15.2 Final remarks

One aim of this work has been to use simple analytical tools such as mass curves, linear regression, and trend tests in the belief that if more sophisticated methods are needed to find trends and changes then the effect is going to be small and will be not significant in practical terms. A second aim was to provide, together with earlier reports in the series, a resource that land managers can use to find information relevant to their needs and for them to use as an aid when resolving water resource conflicts.

Information given in this report is my interpretation of the data I had available. I had hoped that I would be able to find a significant amount of suitable material additional to that already published or presented (but unpublished) at New Zealand Hydrological Society Symposia. This has not been the case, however. While there are many catchments being monitored that have undergone an extensive land-cover change, there have been many difficulties associated with the data: records began after the major change took place; records stopped too soon after a change to assess the full effect of the change; there was no suitable control catchment covering the full period of the record being analysed; there was no suitable rainfall record available to be used as a surrogate for control catchment streamflow; and last, but not least, missing records, which in many cases required more than a simple, proportional adjustment from another station to fill the gap without introducing a significant error into the annual total yield.

In many cases I have concluded that no trends were evident and this was often because hydrologic and climatic variability masked the relatively small changes that might (should) have occurred, i.e., the problem of detecting small effects often at the larger catchment scale. What I have endeavoured to do is bring to the forefront sources of information that may be valuable and find trends if possible using simple techniques. With time, some of the sites with short records that are currently being monitored may be extended long enough to be suitable for further analysis. Some of the data I have looked at may also need to be revisited, possibly using more sophisticated techniques to fill in missing records and for analyses. As additional areas are planted, further data will become available but the records need to be long enough to pick up trends and, most importantly, need an appropriate control catchment to be monitored at the same time, and an adequate number of raingauges to assess catchment inputs.

And, what is the effect of land-cover change on usable water? For only a limited number of data sets where changes have been evident, usually at the small catchment scale, streamflow yield and yield changes have been broken down into flow components – quickflow and baseflow. These have usually been separated using the procedure of Hewlett & Hibbert (1967), which has been illustrated by Pearce et al. (1976) and Fahey & Rowe (1992). Quickflow can be regarded as a loss of useable water to a stream or river system as it is water that flows out to sea as a flood event. Generally, it does not have an impact on water usage by man, unless it is stored in some reservoir for later use, but it may benefit the habitat for stream biota. Any change in quickflow volume, therefore, may not be important, although changes to peaks flows that accompany the change may be.

Any change to baseflow is another matter and is reflected in minimum flows. Baseflow is a gain or loss to the low-flow regime downstream and can affect habitat or the potential for abstraction from streams. Hence, the impact of a land-use change should be related to the change in baseflow, not to the change in total flow.

If charges for water use and tradeable water permits are introduced in the future, there will need to be more work done on streamflow separation into quickflow and baseflow components, and to the definition of loss to a system and water use by crops (defined as growing vegetation: trees, grass, etc.). Should the change in baseflow be a considered as a cost or gain to producing a crop? Does a change in quickflow need to be costed into the equation as well?

Another factor identified here is the change in water yield with age of a plantation. Cornish (1989), for example, has quoted instances where mature plantations require less water for growth than younger plantations. The data from Moumoukai (Section 5.2) and Puruki (Section 5.4) seem to confirm this observation. Thus, care needs to be taken when making an assessment of how much of a difference to the stream system there will be over a full plantation rotation, and the next, and so on. Predicted changes from short-term data sets (up to 15 years) may not produce a reliable estimate of the effect of a full 25-30-year-rotation. More research needs to be carried out to identify the magnitude of such an effect.

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