ECOHYDROLOGY
ASIA - PACIFIC
REGION

Proceedings of
Asia-Pacific Workshop
on Ecohydrology,
Indonesia, 2001

EFFECTS OF CHANGING FOREST COVER ON COMPONENTS OF THE WATER BALANCE

William M. Putuhena
Research and Development Institute for Water Resources
Jl. Ir. H. Juanda No. 193, Bandung - 40135

ABSTRACT

A study was undertaken of the effects of clearing a native eucalypt forest, and replanting it with a Pinus radiata (P. radiata) plantation, on individual hydrological processes, on the water yield and on the catchment water balance. The objective of the study was to examine the effects of vegetation species change and growth rates on componenst of the water balance.

In this study a water balance of the two forests was undertaken for a 27-year period (1967-1993); 11 years before and 16 years after the forest conversion. Analysis of the rate of vegetative growth and development of the forest floor litter, combined with data on precipitation, canopy interception, forest floor interception and streamflow, enable investigation of the effects of forest conversion on water balance components for the whole period.

The age of a P. radiata plantation during the first 16 years of its growth greatly affected the streanflow and the other water balance components. For the first 4 years after forest conversion, the rates of evapotranspiration and streamflow changed completely. Transpiration and the evaporation of intercepted rainfall ceased after the forest floor was cleared. The changes in the first 4 years were followed by a further transformation of the whole evapotranspiration and canopy and forest floor interception losses as the plantation grew, with decreases in runoff, was followed by an equilibrium situation in which streamflow and the evapotranspiration from soil water storage were smaller for the native forest.

Keywords: Eucalypts; *Pinus radiata*; forest floor interception

1. INTRODUCTION

In a major review of vegetative change and water yield studies, Bosch & Hewlett (1982) observed decreases in the water yield following afforestation and these decreases seemed to be proportional to the growth rate of the new stand. The influence of vegetation, from the standpoint of water yield augmentation, comprises two general elements. First, some of the rainfall intercepted by the forest canopy and forest floor litter evaporates before it reaches the ground (mineral soils). The second element, transpiration, involves the draft on soil moisture by growing plants. In this study, the effects on components of the water balance especially on these two elements of clearing a native eucalypt forest, and replacing it with a *Pinus radiata* (*P. radiata*) plantation at Lidsdale State Forest (Lidsdale S.F.), Australia are investigated. A secondary objective was to observe the effects of forest growth on streamflow.

2. GENERAL DESCRIPTION OF THE STUDY CATCHMENT

The experimental catchment at Lidsdale S.F. (Fig. 1) is located between Bathurst and Lithgow of N.S.W.,

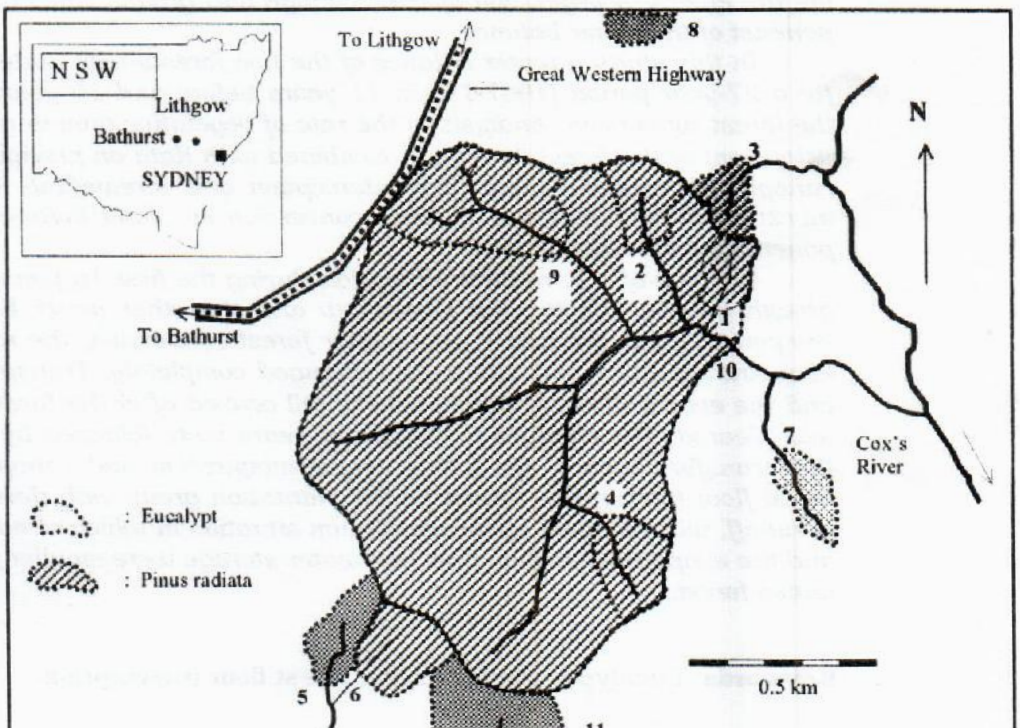


Fig. 1 Experimental catchment at Lidsdale, NSW - Australia

Australia. The study area has a subtropical climate. January has mean maximum and minimum temperatures of 23^0 C and 12^0 C, respectively. July has mean maximum and minimum temperatures of 9^0 C and -1^0 C respectively. Annual rainfall of 755 mm is fairly well distributed throughout the year with an average of 128 raindays. The area has been subdivided into a number of experimental catchments (Fig. 1).

The experimental catchments are subsequently referred to as L-1, L-2, L-3 and up to L-11. Catchment L-6 has been adopted for the present study. The area of the catchment is 0.094 km^2. Up to January 1978, L-6 was covered by eucalypt forest. During February 1978, the forest was cleared and windrowed, and then burned in April 1978. During winter of the same year the catchment was planted with *P. radiata*. In late 1986, the lower branches were pruned to a height of two metres but no trees were removed.

3. METHODS OF ANALYSIS

The analysis was restricted to a single catchment approach although data from a second (adjacent) catchment was used in a pseudo paired catchment approach to enhance the results. The study period included the period prior to (11 years: 1967-1977) and after (16 years: 1978-1993) the forest conversion. During these periods the catchment itself remained unchanged with the exception of the growth of the *P. radiata* plantation and the development of its forest floor litter during the post-conversion period.

3.1 The Water Balance Equation

Considering the components of the water balance that are of interest in this study, the water balance equation can be written as

$$R_g = I_c + I_f + E_{TS} + D_g + \Delta S_m + R_O$$

where, R_g is gross rainfall, I_c is canopy interception loss, I_f is forest floor interception loss, E_{TS} is transpiration and evaporation directly from the soil, D_g is deep seepage, ΔS_m is the change in soil moisture storage, and R_O is runoff or streamflow. The term deep seepage (D_g) refers to water that moves downward out of the bounds of the physical catchment system considered in Eq. [1]. The other terms in the equation account for all of the water within the system, which extends to about 2 m below the surface. Observations during clearing operations, as reported by Pilgrim et al. (1982) indicated that the roots of the trees are confined within this depth. The downward flux of soil water out of the system (D_g), based on regular measurements at the study catchment during the period 1968-1971, as reported by Smith et al. (1974), was small and could be ignored in the water balance.

One problem encountered here was that data on soil moisture change was unavailable. The changes in soil moisture (ΔS_m) over a lengthy period of time such as a year, however, are generally small relative to other components and thus can be ignored. As rainfall and evapotranspiration vary seasonally, it is advantageous to select a period of one year so that a complete cycle is included which will tend to minimise the value of ΔS_m. Only a small error in the annual values would result from ignoring the changes in soil moisture. Thus, with a minor degree of error, the water balance equation (Eq. [1]) for a period of one year can be rewritten as follows:

$$R_g = I_c + I_f + E_{TS} + R_O$$

For annual data, the relationship between rainfall and streamflow is then largely governed by I_c, I_f, and E_{TS}. In a catchment, these components are largely governed by the potential evapotranspiration and land use or vegetation type.

3.2 Components of the Water Balance

[a] Rainfall (R_g) and Streamflow (R_O); A long run, 1967-1993 (27 years) of rainfall and streamflow data was available. In addition, data from the eucalypt catchment L-5 were available to allow estimation of the streamflow and other water balance components that would have occurred at L-6 during the period had the forest conversion not been made.

[b] Canopy Interception (I_c); The canopy interception was calculated as the difference between the gross rainfall and the sum of throughfall and stemflow. Measurements of throughfall and stemflow were conducted in the eucalypt forest and in the *P. radiata* plantation. Throughfall and stemflow were measured continuously over a period of 2 years (January 1993 - January 1995) and 13 months (September 1993 to October 1994) respectively. Daily accumulations of these measurements show:

<u>Stemflow</u> for:

eucalypt stand at L-5:

$$S_f = 0.021 R_g \qquad [3]$$

15-year-old pine stand at L-6: [2]

$$S_f = 0.038 R_g \qquad [4]$$

<u>Throughfall</u> for:

eucalypt stand :

$$T_f = \left[1 - \left\{0.55 C_c + 0.27 \exp\left(-0.20 \frac{R_g}{C_c}\right)\right\}\right] R_g \qquad [5]$$

pine stand :

$$T_f = \left[1 - \left\{0.47 C_c + 0.48 \exp\left(-0.40 \frac{R_g}{C_c}\right)\right\}\right] R_g \qquad [6]$$

where, S_f is stemflow (mm), T_f is throughfall (mm), R_g is gross rainfall (mm), C_c is fraction of canopy cover (less than one; dimensionless) — for the eucalypt stand, C_c = 0.34 and for the 15-year-old pine, C_c = 0.71. Note that all variables in these four equations including C_c parameters were measured.

Since the forest cover of the adjacent eucalypt catchment was mature and in a reasonably steady state with regard to the biomass and leaf area, the results of throughfall and stemflow measurements for this catchment (Eq. [3] for stemflow and Eq. [5] with C_c equal to 0.34 for throughfall) were directly applicable to the study catchment. The equations were used to calculate values of the daily canopy interception during the period before forest conversion (1967-1977) and also to estimate canopy interception that would have occurred had the forest conversion not been made.

For the pine stand, after planting, the growth of vegetation was expected to lead to an increasing interception loss. These changes are the result of changes in the relationship between gross rainfall and throughfall as the plantation grows and are represented by changes in the fraction of the canopy cover (C_c in Eq. [6]) and in the relationship between gross rainfall and stemflow (Eq. 4). The growth rates of the canopy and stem diameters of the *P. radiata* plantation reported by Knights (1983) were used to quantify the changes.

In order to calculate the daily values of stemflow for the period after forest conversion (1978-1993) a new variable (growth rate index) was added to Eq. [4] as follows:

$$S_f = \left(G_p\right) 0.038 R_g \qquad [7]$$

where G_p is the growth rate index of the *P. radiata* stem. For the 15-year-old *P. radiata* plantation, G_p is equal to unity and the rate of change of stem diameter presented by Knights (1983) was used to determine the variation of G_p.

[c] Forest Floor Interception (I_{ff}); Water reaching the forest floor (throughfall plus stemflow) must pass through the litter layer to reach mineral soil. The evaporation of water absorbed by the forest floor litter was considered in this study to be forest floor interception loss. This loss was considered to be a function of

(i) the accumulated mass of litter per unit area,

(ii) the water retention characteristics of the litter (storage capacity),

(iii) the wetting frequency of the litter, and

(iv) the drying rate of the litter.

For the eucalypts and the 15-year-old *P. radiata* stands, the parameters included in the calculation have been described by Putuhena & Cordery (1996). The parameters derived from eucalypt catchment L-5 were used directly as parameters for catchment L-6 for the period under eucalypts, while those for the 15-year-old *P. radiata* stand were adjusted to allow for their variation as forest growth occurred.

[d] Transpiration Plus Evaporation Directly from the Soils (E_{TS}); E_{TS} is the water balance component that is most difficult to measure directly in the forest environment. In this study E_{TS} was calculated for each year as the residual of other values in the water balance equation (Eq. [2]). The calculation was carried out for the periods prior to and after forest conversion. For the latter period, the equation was solved both to predict the water balance components that existed after forest conversion and to determine values of the components had the forest conversion not been made.

4 RESULTS AND DISCUSSION

4.1 Canopy and Forest Floor Interception Losses

The annual values of the canopy and forest floor interception losses as a result of the partitioning of daily gross rainfall are presented in Fig. 2. For the eucalypt stands (Fig. 2[a]), the annual canopy interception losses, as percentages of annual gross rainfall were less variable than the annual forest floor interception losses. On an annual basis, differences between eucalypt canopy and forest floor interception ranged from 4% (1982) to 11% (1973) of the annual gross rainfall. For the period after forest conversion, Fig. 2[b] shows that the increase in the annual canopy interception as percentages of gross rainfall is very slow up to the third year.

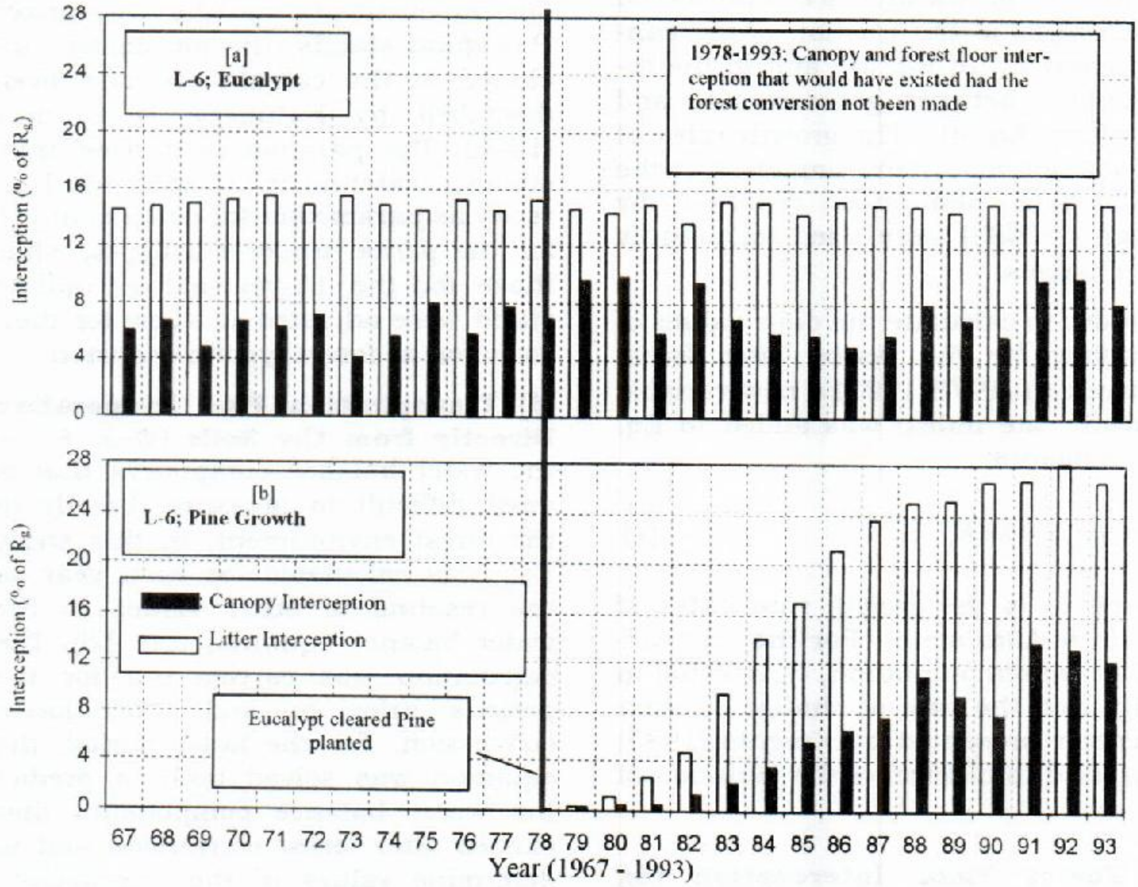


Figure 2. Annual Canopy and Forest Interception as Percentages of R_g (Gross Rainfall) at L-6 [a] Eucalypt and [b] P. radiata

The rate then increased rapidly from the fourth to the ninth year after planting (1981-1986). However, from the tenth year onwards, the rate of increase declined. The rate of increase of the forest floor interception loss, up to the fifth year after planting, was also very slow.

A significant increase in the forest floor interception occurred between the sixth and eleventh years after planting (1983-1988). From the twelfth year onwards, the forest floor interception remained constant.

The average annual values of canopy and forest floor interception losses as a percentage of the gross rainfall over consecutive four-year periods are presented in Table 1.

As can be seen in this table, the increasing trend of the interception losses (both canopy and forest floor interception) as the plantation grew was reflected particularly in the second and third four-year periods. The high percentage of canopy and forest floor interception in the fourth period (1990-1993) was probably influenced somewhat by the drought conditions during this period.

4.2 Analysis of the Results of Water Balance Component Changes

Annual estimates of the water balance components of the eucalypt and pine stands at catchment L-6 for the period 1967-1993 and 1978-1993 respectively are presented in Table 1 and Table 2. Canopy and forest floor interception (Table 1) are the important components of the water balance that were most changed by forest conversion. For the eucalypt stand these represent only about 15% and 7% of the gross rainfall respectively.

Table 1 Average annual canopy and forest floor interception losses as a percentage of the gross rainfall at catchment L-6 for various periods after planting P. radiata and for mature eucalypts.

Period	Average Annual Gross Rainfall (mm)	Average Annual Interception Loss as Percentage of the Gross Rainfall		
		Canopy	Forest Floor	Total
1978-1981 (pine, 1-4 year old)	705	1.1	0.4	1.5
1982-1985 (pine, 5-8 year old)	716	11.4	3.2	14.6
1986-1989 (pine, 9-12 year old)	838	23.7	8.6	32.3
1990-1993 (pine, 13-16 year old)	674	27.0	11.7	38.7
1978-1993 (mature eucalypt forest)	733	14.9	7.0	21.9

Table 2. Annual values of gross rainfall (R_g), streamflow (R_o) and E_{TS} at catchment L-6 for the period 1967-1993

Year	**Gross Rainfall** R_g (mm)	**1967-1993: Eucalypt stand** (1978-1993; calculated annual values of R_o and E_{TS} as if eucalypt stand remained in place)				**1978-1993: P. radiata stand**			
		in mm of depth		as % of R_g		in mm of depth		as % of R_g	
		R_o	E_{TS}	R_o	E_{TS}	R_o	E_{TS}	R_o	E_{TS}
1967	663.0	74.6	452.4	11.3	68.2				
1968	679.1	29.1	504.5	4.3	74.3				
1969	893.2	164.8	551.6	18.5	61.8				
1970	815.9	96.5	540.7	11.8	66.3				
1971	852.4	214.5	453.0	25.2	53.1				
1972	695.9	133.0	409.8	19.1	58.9				
1973	1124.2	335.5	568.1	29.8	50.5				
1974	893.3	280.6	429.7	31.4	48.1				
1975	629.8	64.2	423.5	10.2	67.2				
1976	907.7	259.8	457.8	28.6	50.4				
1977	569.7	28.8	414.1	5.1	72.7				
1978	961.1	189.3	559.7	19.7	58.2	386.2	573.3	40.2	59.6
1979	582.5	38.5	402.3	6.6	69.1	142.9	435.0	24.5	74.7
1980	494.3	16.9	357.6	3.4	72.4	45.7	439.6	9.3	88.9
1981	811.8	81.3	560.9	10.0	69.1	148.3	637.5	18.3	78.5
1982	415.7	11.5	307.9	2.8	74.1	24.3	366.0	5.8	88.0
1983	835.2	51.5	598.8	6.2	71.7	98.9	637.8	11.8	76.4
1984	900.9	133.2	578.6	14.8	64.2	154.7	587.1	17.2	65.2
1985	718.7	32.2	542.7	4.5	75.5	25.1	531.9	3.5	74.0
1986	938.1	256.7	491.5	27.4	52.4	234.5	443.0	25.0	47.2
1987	858.8	96.0	584.9	11.2	68.1	39.0	551.8	4.5	64.3
1988	786.6	64.2	542.5	8.2	69.0	16.7	487.6	2.1	62.0
1989	804.3	57.3	574.4	7.1	71.4	5.9	521.4	0.7	64.8
1990	910.1	121.2	598.6	13.3	65.8	73.7	522.8	8.1	57.4
1991	530.4	15.3	383.2	2.9	72.2	1.4	314.1	0.3	59.2
1992	649.3	30.2	456.3	4.7	70.3	4.9	375.7	0.7	57.9
1993	607.7	10.8	455.6	1.8	75.0	0.9	371.0	0.1	61.1

Note: R_o for 1967-1977 (euc. stand) and for 1978-1993 (pine stand) were observed while R_o for 1978-1993 (euc. stand) were calculated.

Nevertheless, it is evident that the elimination of interception by forest clearing causes substantial increases in the runoff from the catchment. The drop in the amount of interception losses for the first four years after the treatment, 1978-1981 (from 14.8% to 1.1% of the gross rainfall for the canopy interception and 8.1% to 0.4% of the gross rainfall for the forest floor interception) had a major impact on the increase in water yield. For the next twelve years (5-16 years after planting), the interaction of rainfall and vegetation was further demonstrated by reductions in the runoff during plantation growth. The results show that the reduction of runoff, and to a lesser extent evapotranspiration with time was due largely to the corresponding increases in both canopy and forest floor interception with plantation growth.

The effects of forest conversion on the annual water balance components are also presented in Figs. 2 and 3. The figures show that there is a systematic trend between changes in the water yield and changes in the interception (forest floor and canopy interception). As expected, the water balance components changed markedly.

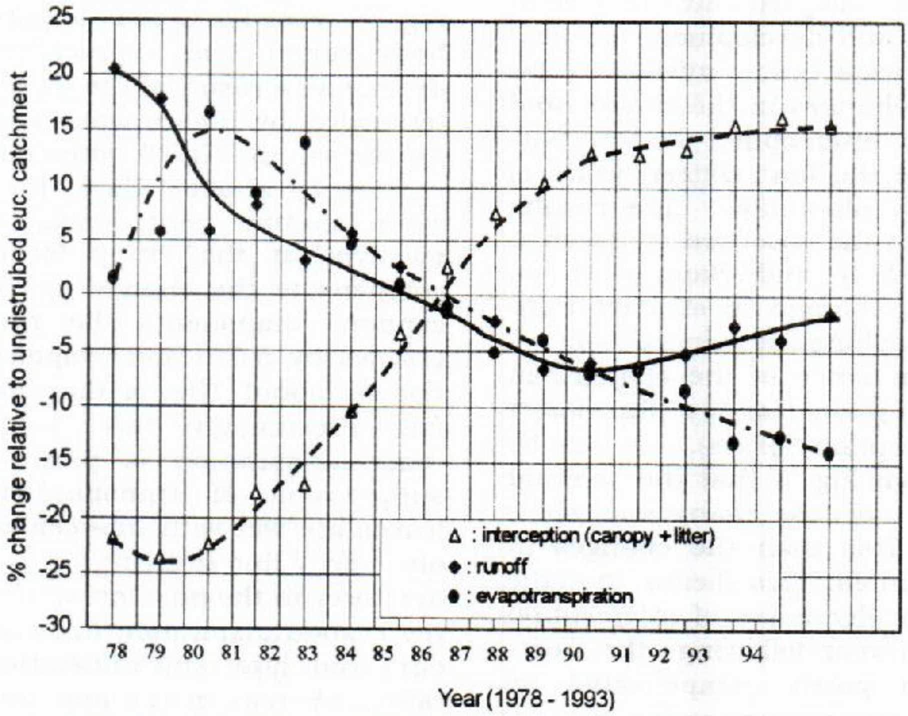
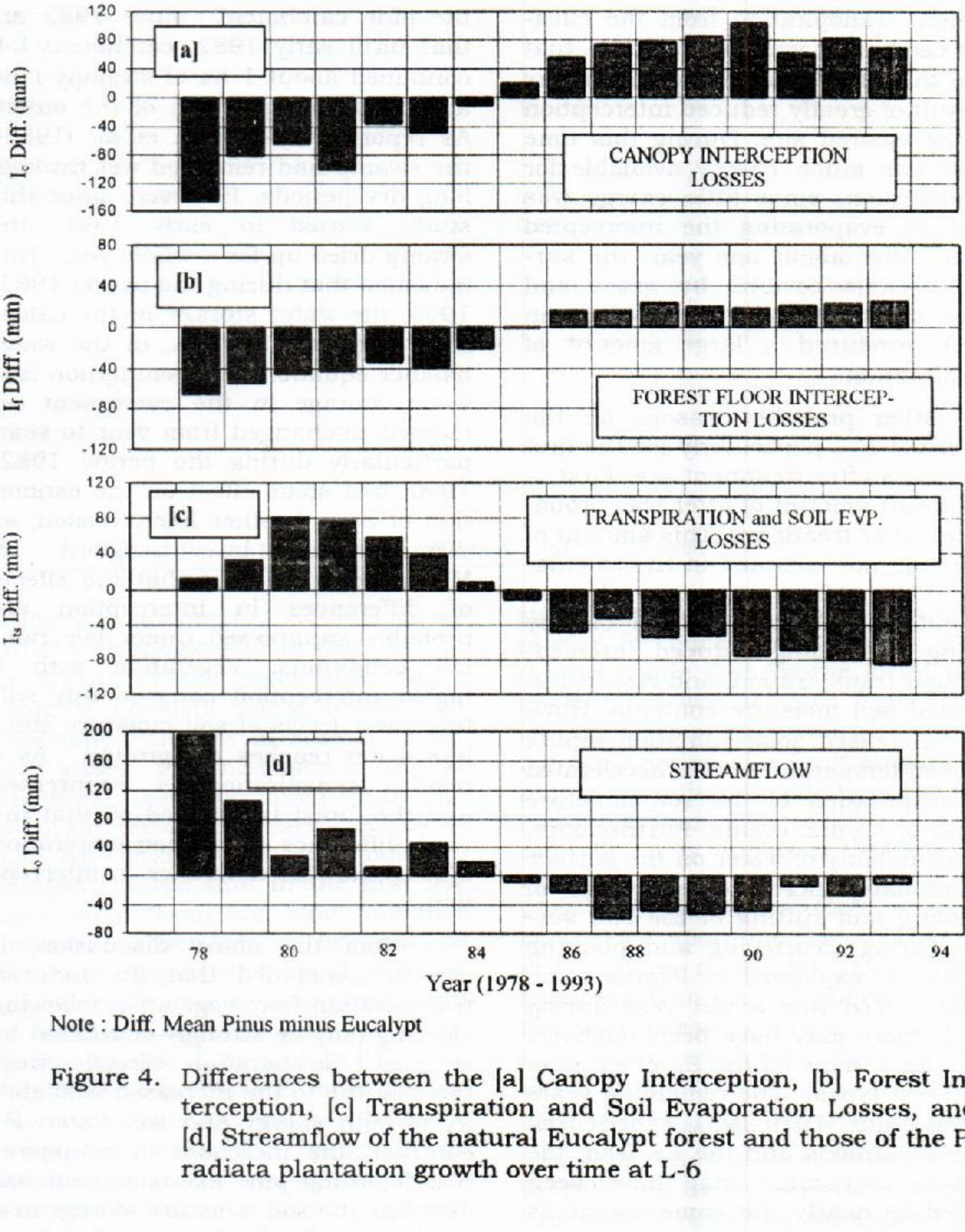


Figure 3. % change of runoff, interception (canopy + litter) and evapotranspiration relative to those in undisturbed eucalypt catchment during plantation growth

At conversion evaporation of intercepted rainfall ceased. The canopy and forest floor interception decreased by 165 mm and 65 mm respectively. These decreases diminished rapidly as the plantation grew and during the seventh and the eighth years after planting both the forest floor and canopy interception had returned to pretreatment levels. As shown in Figs. 2 and 3, increases in interception continued at a lower rate until 1988 (12 years after planting) and remained approximately constant thereafter. Similar trends in the opposite direction were evident for runoff (Figs. 3 and 4).

The results described above indicate that the adopted rates of vegetative growth and development of forest floor litter were quite satisfactory for evaluating changes in the canopy and forest floor interception losses, particularly for the first sixteen years of growth of a plantation. The results also support the assertion of Bosch & Hewlett (1982) and Samraj et al. (1988). The changes in effective rainfall (rain reaching the mineral soil) reflect the influence of the changes in total interception (canopy plus forest floor interception losses). It can be inferred from Fig. 3 that the annual magnitude of the changes in water yield were less than the changes in effective rainfall. This means that the increases or decreases of interception losses each year following the treatment were partly compensated by changes in evapotranspiration, E_{TS}.

The annual changes in E_{TS} following the treatment can be seen in Fig. 4. E_{TS} is the largest water balance component in the catchment after rainfall (Table 2). For the eucalypt catchment, the average annual E_{TS} for the period 1967-1993 was 487 mm, or 66% of the annual rainfall. The absolute annual changes in E_{TS} for the period after treatment (1978-1993) varied from 8.5 mm in 1984 to 85 mm in 1993, while the proportional increases of those changes varied from 1.5% to 19% of the corresponding annual E_{TS} from the eucalypt catchment. From Fig. 4 it can be seen that runoff from the *P. radiata* forest is less than that from the eucalypt forest, but that the difference is not as large as the change in the interception components. In spite of the errors involved in estimating E_{TS} from Eq. 2 it is apparent that both runoff and evapotranspiration decline as a result of the increased interception by the growing pine forest. As shown in Fig. 4 interception increases by about 15% of the rainfall when mature pine forest replaces eucalypt at the study location. To compensate the change in the interception components the runoff decreases by 5-7% and evapotranspiration by about 10% of the input rainfall. Presumably this decrease in evapotranspiration is partly due to suppression of transpiration while leaves are wet with intercepted water, and partly due to there being less understorey in the pine forest. Understorey evapotranspiration in eucalypt occurs from litter and understorey vegetation whereas in the pine forest it is limited to litter evaporation.



Note : Diff. Mean Pinus minus Eucalypt

Figure 4. Differences between the [a] Canopy Interception, [b] Forest Interception, [c] Transpiration and Soil Evaporation Losses, and [d] Streamflow of the natural Eucalypt forest and those of the P. radiata plantation growth over time at L-6

5. CONCLUSION

The age of a *P. radiata* plantation stand, particularly during the first 16 years after its establishment, greatly affects the streamflow and other water balance components. The water regime of a forest area changes notably

sumed that for the remaining life time of the plantation, the annual forest floor interception will be similar to that in the fourth four-year-period of this study, or 8-14% of gross rainfall. The canopy interception will be similar to the 25%-28% of gross rainfall that

During the early years after conversion, transpiration from the eucalypt catchment was greater than that from the cleared catchment mainly as a result of greatly reduced interception on the cleared site. During this time there was much energy available for transpiration, since little energy was used in evaporating the intercepted water. After about one year, the surface became covered by grass and other short ground cover vegetation which produced a large amount of transpiration.

Other probable reasons for the increased E_{TS}, particularly for the first four years after treatment are: First, a significant amount of litter was probably left after treatment. This amount of litter was not included in the calculation of forest floor interception losses. Second, the removal of the canopy during clearfelling reduced interception and transpiration, and resulted in elevated soil moisture contents. However, increased solar radiation inputs and soil temperatures also accelerated the evaporation of the soil moisture following rainfall events. Furthermore, the availability of water on the surface soil probably increased as a result of puddling and rutting of the soil surface during clearfelling and planting Thirdly, as explained by Pilgrim et al. (1982), 1978 was a wet year during which there may have been relatively small limitations on the E_{TS} of either of the forest types. The remaining years of that study (1979-1981) experienced dryer conditions and the E_{TS} from the forested catchment may have been limited to nearly the same extent as that on the cleared catchment.

Reasons for the decreased E_{TS} in the pine catchment since 1982 are that until early 1982, catchment L-6 contained about 1 ha of swampy land about 100 m upstream of the outlet. As reported by Pilgrim et al. (1982), the swamp had remained wet through long dry periods. However, since this study started in early 1991, the swamp dried up for a whole year. This indicates that during the period 1982-1990, the water storage in the catchment decreased. Thus, in the water balance equation, the assumption that water storage in the catchment remained unchanged from year to year, particularly during the period 1982-1990, had some effect on the estimation of E_{TS}. Another likely reason, as demonstrated by Langford & McGuiness (1974), is that the effects of differences in interception are probably suppressed under low rainfall conditions. Vegetation with a higher interception consequently suffers lower levels of soil moisture since less water reaches the ground. As a result, transpiration is suppressed and the forest is stressed so that the total difference in evapotranspiration is less than the difference in interception.

From the above discussion, it can be concluded that the reduced transpiration from vegetation following clearing may be strongly countered by increased evaporation directly from the soil due to the increased availability of both energy and soil water. By contrast, the increases in transpiration following pine establishment will decrease the soil moisture storage in a catchment. In the Stewarts Creek ex-

REFERENCES

Bosch J.M. & Hewlett J.D., 1982, A review of catchment experiments to determine the effects of vegetation changes on water yield and evapotranspiration, *J. Hydrol., 55*: 3-23.

Feller M.C., 1981, Water balances in Eucalypt regnans, E. obliqua and *P. radiata* forests in Victoria, *Aust. For., 44*: 153-161.

Forest W.G. & Ovington, J.D., 1970, Organic matter changes in an age series of *P. radiata* plantations, *J. Appl. Ecol., 7*: 177-186.

Knights P.C., 1983, The hydrologic significance of pine forest development at Lidsdale, NSW., PhD thesis, University of New South Wales.

Langford K.J. & McGuinness J.L., 1974, *The use of mathematical models in assessing the hydrological effects of land use change,* U.S. Dept. Agri. Tech. Bull.

Nandakumar N. & Mein R.G., 1993, Analysis of paired catchment data for some of the hydrologic effects of land-use change, *Hydrology and Water Resources Symposium, Newcastle, June 30 - July 2 1993*, Inst. Eng. Aust., National Conf. Publ. No. 93/14: 87-92.

Pilgrim D.H., Doran D.G., Rowbottom I.A., Mackay S.M. & Tjendana J., 1982, Water balance and runoff characteristics of mature and cleared pine and eucalypt catchments at Lidsdale, New South Wales, In: Preprints of Papers: The First National Symposium on Forest Hydrology, Melbourne, 11-13 May, 1982, O'Loughlin, E.M. & Bren, L.J. (eds), *The Inst. Eng. Aust., National Conference Publication No. 82/6*: 103-110.

Putuhena W.M. & Cordery I., 1996, Estimation of interception capacity of the forest floor, *J. Hydrol., 180*: 283-299.

Samraj P., Sharda V.N., Chinnamani S., Lakshmanan V. & Haldorai B., 1988, Hydrological behaviour of the Nilgiri Sub-Watersheds as affected by bluegum plantations, Part I. The annual water balance, *J. Hydrol., 103*: 335-345.

Smith M.K., Watson K.K. & Pilgrim D.H., 1974, A comparative study of the hydrology of Radiata pine and eucalypt forests at Lidsdale, New South Wales, *Inst. Eng. Aust., Civ. Eng. Trans., CE16(1)*: 82-86.