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THE HYDROLOGY OF EUCALYPT FORESTS IN AUSTRALIA - A REVIEW

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RESUMO - O presente trabalho de revisão contém as informações disponíveis a respeito da hidrologia de florestas de eucalipto na Austrália. Estas informações não são de interesse apenas para a Austrália, mas também são úteis para mais de 52 outros países, os quais desenvolvem programas extensivos de reflorestamento com espécies de eucalipto. A revisão inclui Informações sobre os processos hidro1ógicos de precipitação oculta, interceptação, precipitação interna, escoamento pelo tronco, água do solo, evapotranspiração, balanço hídrico de bacias hidrográficas, qualidade da água e ciclagem de nutrientes em florestas de eucaliptos. Também é incluída a avaliação dos efeitos das atividades florestais relacionadas com o uso do fogo controlado, corte seletivo, corte raso, desbaste e exploração florestal sobre os recursos hídricos, bem como Informações sobre os efeitos hidro1ógicos da substituição de florestas naturais de eucalipto por plantações de pinheiros. Incluem-se, ainda, sugestões de novas pesquisas em hidrologia de eucalipto.

ABSTRACT - The present review brings together available information in the hydrology of eucalypt forests in Australia. Interest in this information is not only related to Australia, but also to over 52 countries In the world which are carrying on extensive reforestation programs using eucalypt species. The hydrology processes of fog drip, interception, throughfall, stemflow, soil water, evapotranspiration, water balance in catchments, water quality, and nutrient cycling in eucalypt forests are reviewed. Also an appraisal of the effects of eucalypt forest activities of prescribed burning, logging, cleafelling, selective cutting, and thinning on water values 15 included, as well as information on the hydrology effect5 of replacing eucalypt forests by pine plantations. Suggestions on research needs in eucalypt forest hydrology are finally included.

INTRODUCTION

Eucalypt forests are one of the singular characteristics of the Australian landscape. Only two out of the almost 600 known eucalypt species do not occur in Australia, and it is assumed that in its evolutionary past the progenitors of the Eucalyptus have had Australia as their centre of development, giving rise, in time, to the great diversity of species now existing (PRYOR, 1976).

Including the open woodland formation, which is usually dominated by eucalypt trees SPECHT(1970) , the total area covered with eucalypt forest in Australia is around 106 million hectares, which is equivalent to 13,6% of the country's total land area. As a forest resource, that is, considering only the area suitable for timber production, the total area of eucalypt forests is in the vicinity of 35 million hectares (Australia, Dept. of Primary

Industry, 1981). About half of this area is of very difficult utilization because of accessibility problems (JACOBS 1970).

The eucalypt forests are widespread in Australia, although they are mostly confined to the moister parts of the continent, the coastal fringe of the East, Southeast, and Southwest, where nearly all the 15 million Australian people are also confined. Within this limited part, they represent about 25% of the land surface (JACOBS, 1970). In the dry interior (about 75% of the continent) eucalypts are only found along watercourses. Therefore, Australia is not well endowed with forest resources. It has to be further considered that most of the high quality forests are located on water catchments areas, and that some of them are locked up for water production, as it is claimed that multiple use of these forests could damage water quality (BROOKS and TURNER, 1964), (JACOBS, 1970), (MOUlOS,1980).

Having an annual runoff in the order of 250 million cubic meters, Australia is not well endowed with water resources either. This fact Is not only a serious challenge, but does represent a real limit to further development. For example, RAGGATT (1963) state that It is estimated that by the year 2000-2050 population growth in Australia would be limited by water shortage. The understanding of the hydrology of eucalypt forests, thus, is essential if Australians decide to overcome this challenge. As RAGGATT (1963) put It: "The key to the future lies in water management, but this must be backed by good resource data and the scientific and technological advances which we are coming to expect as a matter of course".

In 1964,BROOKES and TURNER(1964) stated: "... Meanwhile our understanding of the water economy in eucalypt forests remains meagre". More recently, FLORENCE(1981) writes: "... there has been little research on the water relations of the genus (Eucalyptus), no really adequate review of strategies by which the eucalypts cope with water stress, and only a handful of papers dealing with water relations of individual species..."

The understanding of the hydrology of eucalypt forests is not relevant to Australia only. By the beginning of this century, growing world population and increasing demand for wood resulted In the Introduction of eucalypt species In several countries in the world for shade, shelter, firewood, and railway sleepers. By about 1945, a growing demand for pulp and paper, as well as some reconstituted uses of wood, further increased the introduction of eucalypts as exotic species, so that eucalypt plantations have become one of the world's major plantations crops for wood products. The energy crisis of the seventies represented a new additional demand for eucalypt plantations in many countries. A recent book by FAO(1981) reports that more than 58 countries in the world are now developing extensive plantations of eucalypt forests among them: Algeria, Angola, Argentina, Brazil, Chile, China, Colombia, Congo, Cuba, Equator, Ethiopia, India, Israel, Italy, Kenya, Libya, Madagascar, Malawi, Morocco, Mozambique, New Zealand, Nigeria, Paraguay, Peru, Portugal, South Africa, Spain, Tanzania, Tunisia, Turkey, Uganda, United States, Uruguay, Zimbabwe, and, for that matter, also Australia. The total area planted in these and other countries amounts to approximately 4 million hectares, although the figures in the FAO report are for up to 1973 only. In Brazil, for instance, the total area planted up to 1980 has more than double that which appears in the FAO report.

In many of these countries, there appears to exist a widespread concern about the possible hydrologic effects of these plantations, particularly in regards to the water use by the eucalypts, and the effects of the plantations on the quality of water (LIMA, 1975). (NSHUBEMUKI and SOMI, 1979).

With this background, the present paper attempts to review the factual information about the hydrology of eucalypt forests in their native environment. The review is comprehensive, and over one hundred papers have been included. By putting together small pieces of information in one single frame of ideas, we hope to contribute to a better understanding of the hydrologic functioning of the eucalypt forest, as well as to stimulate further research in one aspect or another. It is also hoped that this information could be of help to several countries in the world where the potential use of eucalypts has been threatened by misunderstandings and the controversy about their hydrologic side effects.

HYDROLOGIC PROCESSES IN EUCALYPT FORESTS

Precipitation and Interception

The presence of a forest cover in certain fog prone environmental conditi0ns such as humid mountain ranges and coastlines, can sometimes result in the entrapment of fog particles, which could eventually drip from the canopy, thus representing an additional source of precipitation to the site.

Only a few attempts have been made to estimate the effect of eucalypt forests in the possible increase of precipitation to the site through the process of fog drip. (COSTIN and WIMBUSH, 1961) report results from a study conducted in upper mountain sclerophyll eucalypt forest in the Kosciusko area in 1958-1960. By placing 3,4m diameter collecting trays around selected trees and also in the open, they concluded that fog drip would amount to at least 25 to 50 mm per annum in catchments located at elevations of 1200-1500m.

In the Dividing Range near Melbourne, in a lower elevation in comparison with the previous study, and in a mature **Eucalyptus regnans** forest, BROOKES and TURNER (1964) determined that fog drip could amount to approximately 180 mm per year, based on estimation from regression analysis of total rainfall against throughfall. Their estimate is undoubtedly an important indication of the effect of fog drip in that forest type, but the actual magnitude of the effect is open to criticism, mainly because of insufficient replication.

Some years later, O'CONNELL and O'SHAUGHNESSY(1975) carried out a more thorough experiment in the same location, using two adjacent, even-aged stands of **E. regnans**: one 80 to 90 years old, and the other well over 200-year old The site has an elevation of 670m, an average annual rainfall in the vicinity of 1200 mm, and is characterized by dry summer and wet winter. The measurement of fog drip was made by placing two removable, recording rain gauges in each plot, thus permitting the determination of the exact timing of the precipitation under the canopies of the two forests and in gauges in the open. The experiment was conducted over a four-year period, and the results showed the annual average fog drip to be in the order or 9,2 mm in the younger stand, and 12,9 mm in the older stand, the difference between the two stands being not statistically significant.

By measuring fog drip in open areas through the difference in catch between a standard rain gauge and a fog gauge (a vertical cylinder of wire gauze mounted above a standard rain gauge) in 9 sites with elevations ranging from 100 to 830m, in the Mt. Beenak State Forest, Victoria, ELLIS (1971)concluded that the increase in fog drip is one of the environmental factors that can account for the sequence of forest types, from dry sclerophyll (**Eucalyptus sieberi-Eucalyptus obliqua**) forest on the lowest ridge, to wet sclerophyll (**E. regnans**) rainforest, on the highest ridge.

A more significant hydrologic effect or the presence of a forest cover in any particular site is the process of interception, through which the rainfall is redistributed by the forest canopy, end part of it is lost through direct evaporation from the canopy. Considering the species diversity and the many different forest types of eucalypt, there is not sufficient data on interception to give an overall picture of this important process of the hydrologic cycle in eucalypt forests.

The results found in this review are summarized in Table 1.

The data on Table 1 are derived from different approaches and forest conditions. For instance, data on canopy storage by ASTON (1979) was obtained in laboratory conditions, through applying simulated rainfall in small trees cut from the field. The works by WESTMAN (1978) and PREBBLE and STIRK (1980) consisted in measuring interception under isolated trees.

An interesting point in the results shown in Table 1 is the similarity of interception values between wet sclerophyll **E. regnans** forest and mixed, dry sclerophyll forest found in DUNCAN et alii (1978) study, although the work by SMITH (1974) showed a lower interception value for a mixed, dry sclerophyll eucalypt forest in a region of lower precipitation.

Although meagre, the data in Table 1 could be compared with the wealth of interception data available from different forest types all over the world, in order to have an assessment of the effect of eucalypt forests in this hydrologic process.

Soil Water

The effects of eucalypt forests on soil and groundwater have been one important aspect of the controversy mentioned in the beginning of the present review.

How intensively will eucalypt forests draw on water stored in the soil? A recent review by HOLMES and WRONSKI (1971) reports that unfortunately there is not much information of this kind in Australia. They suggest that in the climatic regions of southern Australia, for example, with average annual rainfall of 700 mm or more, eucalypt forests would create a soil water deficit of 250 mm each year, whereas annual crops would create a soil water deficit of 180 mm each year. These estimates would imply, ceteris paribus, that forested land would yield approximately 70 mm less-runoff, or recharge of groundwater, each year, in comparison with annual crops.

BROKES and TURNER (1964) compared soil moisture between **E. regnans** and an adjacent area covered with bracken (fern), in the Dividing Range, near Melbourne. During the summer season soil moisture remained higher in the bracken plot.

TABLE 1. Interception loss (I), throughfall (T), Stemflow (Sf), Canopy storage (S), and regression equations relating interception, throughfall, and stemflow to gross precipitation (GR) in different eucalypt species.

Species	I (%)	T (%)	Sf (%)	S (mm)	Regression	Ref.
E. regnans	22 - 26	-	2 -3	-	-	(1)
E. regnans (mature)	23,2	72 - 76	4.3	-	I = 0.176 GR + 1.51 T = 0.775 GR - 1.36 Sf = 0.05 GR - 0.15	(2)
E. regnans (40-yr old)	18.7	72 - 76	5.3		I = 0.150 GR + 1.09 T = 0.790 GR - 0.88 Sf = 0.06 GR - 0.21	(2)
Mixed dry sclerophyll (A)	23.3	72 - 76	1.3	-	I = 0.176 GR + 1.36 T = 0.809 GR - 1.31 Sf = 0.015 GR - 0.05	(2)
E. melanophloia	11	88	0.6	2	(T + Sf) = 0.96 GR - 1.4	(3)
Mixed dry sclerophyll (B)	10.6	89	< 3	-	T = 0.837 GR - 0.057 Sf = 0.019 GR + 0.00	(4)
E. signata	22	65	13	-	-	(5)
E. umbra	22	75	3	-	-	(5)
E. viminalis	-	-	-	0.2	-	(6)
E. dives	-	-	-	0.3	-	(6)
E. mannifera	-	-	-	0.3	-	(6)
E. cinerea	-	-	-	0.4	-	(6)
E. maculata	-	-	-	0.5	-	(6)
E. pauciflora	-	-	-	0.8	-	(6)

(1) BROOKES and TURNER, 1964
(2) DUNCAN et alii, 1978
(3) PREBBLE and STIRK, 1980
(4) SMITH, 1974, and SMITH et alii, 1974
(5) WESTMAN, 1978
(6) ASTON, 1979
(A) **E. obliqua - E. cypellocarpa - E. viminalis - E. baxteri - E. goniocalix - E. dives**
(B) **E. rossi - E. maculosa - E. dives**

COSTIN et alii (1964) compared soil moisture at different depths, using gypsum blocks under grass and alpine herb field in the Kosciusko area. They concluded that the eucalypt forests located at elevations of about 1800 and 2000 mare not undesirable for water yield purposes due to the fact that they restricted water use during the summer, dry months. Further they found that in the study area thinning or replacement of deep-rooted by shallow-rooted species will not substantially affect water yield.

In semi-arid conditions similar to large areas of open eucalypt forests in Australia, WILLIAMS and COVENTRY (1979) have shown that the study of soil water regime will give a good insight into the hydrology of the area. They monitored soil moisture by neutron technique in two soil types in northern Queensland (mean annual precipitation around 550 mm): an area of deep red yellow earth supporting woodland association of **E. similis**, **E.**

dichromophloia, E. whitei, E. crebra; and an adjacent shallow yellow earth supporting open woodland and shrubland dominated by **E. similis**, acacias and grassland. During the two dry seasons (April-October) of 1976 and 1977, they found soil water deficits of 218 mm and 116 mm, respectively in the deep red earth profile, and of 166 mm and 16 mm, respectively, in the shallow yellow earth soil profile.

In wetter eucalypt forests in Tasmania, with average annual precipitation of 900-1400 mm, NICOLLS et alii (1982) also found interesting results of the soil water regime, by measuring soil water during 4 years in 8 sites of **E. obliqua / E. regnans**, including recently planted seedlings of **E. obliqua**, in one of the sites, regrowth of **E. regnans / E. obliqua**, and 80 year old forest. On the planted site, the small seedlings did not deplete soil moisture during the first summer after planting. In the second year, soil water deficit was 80 mm at the 2 m depth of the profile, while the deficit reached a value of 230 mm under the mature forest, for the same 2-m soil depth. As the planted seedlings grew older, soil water deficit also increased, being similar to that observed under mature trees when the seedlings were 4-year old, and about five metres in height. In a 70-year old forest, soil water deficit in the 1978/79 dry season in the top 3 m of soil was 250m.

More information on the soil water regime in **E. regnans** forests comes from near Melbourne. In a 40-year old regrowth forest, the soil moisture regime was studied in regard to different stand densities and also to the distance of the trees from the borehole (LANGFORD and O'SHAUGHNESSY, Ed. 1977), (MORAN and RONA, 1978), (LANGFORD and O'SHAUGHNESSY, Ed., 1979). The measurements were done monthly by neutron technique, down to a depth of 5.2 m, from June 1973 to the end of 1975, over 33 boreholes in the Black Spur Catchments. For each borehole, an inventory of vegetation characteristics was carried out for plots of 15 m radius from the borehole. The stand density was found to be the major single influence on the drying rate of the soil water. The highest correlation between drying rates and vegetation characteristics was achieved with the basal area of the eucalypt weighted for the cube of the distance of the tree from the borehole.

In the same region, LANGFORD et alii (1982) measured soil water after clearfelling and selective cutting of mature **E. regnans** forest in two experimental catchments. During the first year after clearfelling, soil moisture in the top 3.1 m of soil increased by 120 mm. As the regrowth forest developed, soil moisture levels declined, reaching the pre-treatment level 6 years after the clearfelling. No significant change in soil moisture was detected after selective cutting in the other catchment. The work by NICOLLS et alii (1982) also revealed that in the study area summer rainfall is insufficient to meet the forest needs. The authors suggested that this finding is at least consistent with the incidence of regrowth dieback in the area, even though their measurements did not give direct evidence of water stress in the eucalypt trees.

In a more general overview, this availability of soil water seems to be one of the key factors that regulate the pattern of eucalypt forest associations in Australia, which is characterized by a changing mosaic of species associations, sometimes with an abrupt change from wet sclerophyll, high quality, eucalypt forest, to dry sclerophyll eucalypt forest of no commercial value(McCOLL, 1969), (ELLIS, 1971), (ASHTON, 1981).

This distribution pattern of different forest association, in this sense, is related with the possibility of using available soil water, or for that matter, with the root systems of eucalypt species. JACOBS (1955) and ASHTON (1975) give some information on the variation of root systems of eucalypts. Lateral spread may go from 36 m from the tree trunk, in sandy soils, to 18-20 m from the trunk, in heavy soils. In 8 29-year old **E. regnans** forest in Melbourne, INCOLL (1979) found a maximum lateral spread of the roots of 0,17 cm/cm of d.b.h.o.b. As to the depth of root penetration, JACOBS (1955) cites reports claiming penetration of well over 30 m. Some eucalypt species are characterized by developing shallow root system (**E. pilularis**, **E. grandis**), whereas some species have inherently deep-going main roots (**E. microcorys, E. propinqua, E. paniculata**, etc.). Other species will present a root system that may even penetrate the gley layer of a flood plain, like **E. camaldulensis**, and **E. multiflora**.

NAMBIAR (1981) explains that about half of the relatively large underground biomass reported for some eucalypt forests in Australia (42-75% of the total biomass) is made up of "butts" and "roots crowns", which are unimportant for water uptake.

CARBON et alii (1980) studied the root distribution and the theoretical limits of flow of soil water to the roots of the jarrah (**E. marginata- E. calophylla**) forest in Western Australia. The approach used by the authors was that the flow of soil water to roots is related to the distribution of root length per unit soil volume. The model calculates radial flow of water to roots as a function of water potential gradient from soil to root, through an average soil hydraulic conductivity and at a given soil water content. They tried to sample different sites to cover the variation of landform and rainfall zones in the area.
Results show that:
a) most of the roots was contained in the surface (0-1 m) sandy soil horizon (in the **E. regnans** forest INCOLL (1979) also found that 98% of the oven-dry root weight occurred in the top 60 cm of soil profile);
b) roots were found down to 18 m depth, but no roots were found below the water table;
c) as soil water potential decreases, the rate of water flow to roots also decreases. In the surface, sandy horizon there is no flow to meet the transpirational demand when water potential falls below-400 cm of water. In the clay horizon (4-15m) the limit is not affected even at potentials of -50.000 cm of water;
d) therefore, most or the root system of the jarrah forest is on the surface (0 - lm) sandy soil horizon, which provides the best conditions of water availability, as long as the soil is in a moist condition. As this horizon dries, water soon becomes unavailable, and the trees have to depend on water extracted from deeper parts of the soil. For a species to survive in such a condition, it has to be capable of growing some small amounts of roots down to the deeper, clay horizon.

Evapotranspiration

A recent paper by STEWART (1981) gives a most useful discussion of the process of evapotranspiration in forests. Some highlights of Stewart's discussion which are relevant to the present review on water use by eucalypt forest are the following:
a) the concept of potential evapotranspiration does not apply to forests. Measurements have shown that when the canopies are wet (interception) the latent heat flux (evaporation) is frequently greater than the net input of radiational energy;
b) the surface resistance(the resistance offered by the stomata to the evaporation of water) of forest is strongly related to the evaporation from that forest
c) the surface resistance varies with different species;
d) the stomata resistance of many species increases as atmospheric humidity deficits increase;

e) the stomata resistance may be similar for different species, but if total leaf area is different, then difference in evapotranspiration can be expected;
f) as a form of compensating mechanism, sometimes the lower value of total leaf area could lead to luxuriant understorey growth, which will add to the total evapotranspiration from the site;
g) because of Its complexity, and Its greater dependence on physiological and surface factors, evaporation estimates from forests require the measurements of meteorological parameters at greater frequency than is usually done from routine meteorological observations. Even so, the models used to estimate forest evapotranspiration should take into account the physiological control exerted by the forests, particularly in regard to how the stomata resistance is related to the states of soil, tree and atmosphere.

There is some, but not enough, information on eucalypt forests evaporation in Australia (GREENWOOD, 1979), particularly those derived from the measurements of transpiration of excised leaves (WOOD, 1934), (CONNOR et alii, 1977), (KREEB, 1966), (DOLEY, 1967), soil water balance (BROOKES and TURNER, 1964), (COSTIN et alii,1964), (MARTIN and SPECHT, 1962), catchment water balance (LANGFORD et alii, 1980), ventilated chamber technique (GREENWOOD and BERESFORD, 1979), leaf water potential (CONNOR et alii, 1977), (SHEA et alii,1978), (SINCLAIR, 1980), (DOLEY,1967), and weighing seedlings in containers (LADIGES, 1974), (WITHERS, 1978), (LEGGE, 1979). However the only approach on line with STEWART'S (1981) discussion is the experiment being carried out on the south coast of New South Wales by DUNIN (1981), who has constructed a weighing lysimeter. In an undisturbed soil on a 10 - year old regeneration growth of mixed dry sclerophyll eucalypt forest, and is conducting parallel estimations of forest evapotranspiration by both lysimeter and the measurements of micrometeorological parameters. Besides, soil water and streamflow from the catchments are also being monitored.

The pioneer studies of transpiration in eucalypt forests in Australia were, perhaps, those carried out by Wood in South Australia as far back as 1923 WOOD (1934). Wood mentions great variation in transpiration from individual species, as measured by the transpiration rate of excised leaves, but no significant difference in relative transpiration by different types.

In regards to the first aspect, several other works have also shown different rates of transpiration by different eucalypt species (GRIEVE, 1956), (SHEA et alii, 1978), (BIDDESCOMBE et alii, 1979), (GREENWOOD and BERESFORD, 1979), (PEREIRA and KOSLOWSKY, 1976). When It comes to total transpiration by forest in field conditions, however, the differences in environmental conditions play an important role (GREENWOOD, 1979), (ASTON and DUNIN, 1980). In the alpine conditions of the Kosciusko area in New South Wales, (COSTIN et alii, 1964) did not find any significant difference in evapotranspiration between natural, alpine sclerohyll eucalypt forest, and adjacent dense regrowth of eucalypt, and a grassland plot. The authors concluded that ordinary methods of manipulating vegetation, such as thinning, and replacemente of deep-rooted by shallow-rooted communities would not substantially affect water yield in those alpine conditions.

On the Diving Range near Melbourne, on the other hand, BROOKES and TURNER (1964) found significant differences in evapotranspiration between mature, light stocking regrowth, and dense stocking regrowth **E. regnans** forests.

In discussing the rate of water use by eucalypt, the great species diversity, the many environmental conditions in which they grow, and the interaction of these two features shown by the characteristic pattern of species associations in their native environment should be considered. In all climates in Australia, except that which permits the development of rain forest, the trees and associated perennial vegetation are generally of the sclerophyll type WOOD (1934) As thoroughly discussed by ATTIWILL (1980), FLORENCE, (1981), and ATTIWILL (1981), these sclerophyllous characteristics of eucalypt forests represent an adaptation to conditions of low nutrient content in the soil, rather than to a dry climate. There is no evidence that eucalypts can be classed as having truly xerophytic characteristics, but rather it would appear that they should be classed as drought tolerant mesophytes POOK et alii (1966) FLORENCE (1981).

The tolerance to drought, or to conditions of water stress, varies within different eucalypt species. Some species just do not present any ability, or only a limited ability to control high rates of water use, and therefore have limited capacity to tolerate stress. This characteristics possibly restricts the range of habitats in which such species can survive or maintain competitive ability (WITHERS, 1978). The best example in this group is probably that of **E. regnans**, which is restricted to a very narrow set of environmental conditions (ASHTON, 1958) and can have a significant influence on streamflow (LANGFORD, 1976), (CONNOR et alii, 1977), (LANGFORD and O'SHAUGHNESSY, 1979).

Other example is the **E. marginata** of Eastern Australia. SHEA et alii (1975), state that the "jarrah (**E. marginata**) is able to transpire at a high rate during the dry, hot summer months, and forested catchments yield less than 10% of rainfall". They also say that the roots can penetrate through laterite down to the water table. GRIEVE (1956) compared transpiration rates of **E. marginata** and its associated species **E. calophylla** during a summer period, and found that **E. marginata**, transpired at a higher rate (7.2 mg g^{-1} min^{-1}). maintaining the stomata wide open, whereas **E. calophylla** presented a lower rate (4.2 mg g^{-1} min^{-1}), closing its stomata during the hotter part of the day, when transpiration declined to as low as 0.3 mg g^{-1} min^{-1}. Grieve also verified that both species presented an extensive root system. **E. calophylla**, therefore, is more sparing of water in summer.

E. camaldulenis and **E. robusta** are probably other examples, being restricted to specific sites such as along the seasonal water courses, and flood plains and swampy areas JACOBS (1955), PRYOR (1976).

Comparing transpiration rates of **E. obliqua, E. fasciculosa,** and **E. leucoxylon** in Mount Lofty Range, east of Adelaide, SINCLAIR (1980) observed that **E. obliqua**, being restricted to sites where rainfall is over 875 mm per annum, never completely closed its stomata, even though presenting a low water potential. He argues that **E. obliqua** either has not developed the mechanism of rapidly closing the stomata when water potential falls below a critical level, or the critical level of water potential for this species is below -5MPa, which seems to be too low to prevent leaf damage. In fact, he has observed leaf damage in **E. obliqua**, whereas the other two species have shown no foliage damage. MARTIN and SPECHT (1962), comparing evapotranspiration through the soil water balance method, had found that **E. obliqua** forest in the same location depleted soil moisture early in the summer, and had to survive a drought period every year.

This group of profligate water user eucalypt species characteristically presents either a deep root system that permits continuous access to ground water, or a very restricted set of favorable environmental conditions. Only relatively few eucalypt species fall into this situation. For most of the other eucalypt species, mechanisms exist for coping with varying periods of soil water deficit. Among these mechanisms are (JACOBS, 1955), (PRYOR, 1976), (FLORENCE, 1981):

a) development of a hard leaf tissue;
b) vertical alignment of the leaves;
c) the lignotuber habit;
d) better efficiency of stomatal closure in response to increasing water stress;
e) lower rate of transpiration at high soil moisture
f) the photosynthetic efficiency of the species when water is available;
g) greater root-shoot ratio.

Within one single species, the variation in drought tolerance may be correlated with the average rainfall of the habitats. By measuring transpiration of potted seedlings of **E. viminalis** of three different rainfall regimes (1040, 1000, and 635 mm/year), LADIGES (1974) found that, at the age of 6 months, seedlings from low rainfall areas were more resistant to drought, suggesting that the drought resistance of the lower rainfall population appears to be related to some physiological mechanism which would allow the plants to transpire and grow under moderate water stress.

For **E. regnans**, however, ELDRIDGE (1969) did not find any evidence of variation drought resistance in seedlings of populations from different altitudes (and rainfall regimes).

TABLE 2. Summary of data on transpiration and evapotranspiration on eucalypt forests

Species or Forest Type	Data on Water Consumption	Ref.
E. saligna trees, 2.5 - 3.5-yr old	23 litre tree^{-1} day^{-1}, summer	(1)
E. globulus trees, 2.5 - 3.5-yr old	37 litre tree^{-1} day^{-1}, summer	(1)
E. cladocalix trees, 2.5 - 3.5-yr old	30 litre tree^{-1} day^{-1}, summer	(1)
E. regnans, mature forest	1.9 mm day^{-1}, summer	(2)
E. regnans, dense regrowth	2.7 mm day^{-1}, summer	(2)
E. regnans, light dense regrowth	3.5 mm day^{-1}, summer	(2)
E. camaldulensis, 1-2-yr old tree	29 litres tree^{-1} day^{-1}, summer	(3)
E. globulus 1-2-yr old tree	37 litres tree^{-1} day^{-1}, summer	(3)
E. leucoxilon 1-2-yr old tree	23 litres tree^{-1} day^{-1}, summer	(3)
E. robusta 1-2-yr old tree	19 litres tree^{-1} day^{-1}, summer	(3)
E. sargentii 1-2-yr old tree	28 litres tree^{-1} day^{-1}, summer	(3)
E. wandoo 1-2-yr old tree	26 litres tree^{-1} day^{-1}, summer	(3)
E. saligna 1-2-yr old tree	23 litres tree^{-1} day^{-1}, summer	(3)
E. cladocalix 1-2-yr old tree	30 litres tree^{-1} day^{-1}, summer	(3)
Mixed dry sclerophyll eucalypts	4.5-6.0 mm day^{-1}, summer	(4)
Mixed dry sclerophyll eucalypts	1.5 mm day^{-1}, winter	(4)
E. marginata trees (Adult)	7.2 mg g^{-1} min^{-1}, summer	(5)
E. calophylla trees (Adult)	4.2 mg g^{-1} min^{-1}, summer	(5)
E. marginata trees (Adult)	2.5 g dm^{-2} day^{-1}, (ave. Oct-Jan)	(6)
E. regnans / E. obliqua, 70-yr old	4.6 mm day^{-1}, (ave. 6-mo.summer)	(7)

(1) BIDDESCOMBE et alii, 1979: no details of methods given
(2) BROOKES and TURNER, 1964: soil water balance
(3) GREENWOOD and BERESFORD, 1979: ventilated chamber
(4) DUNIN, 1981: lysimeter
(5) GRIEVE, 1976: excised leaves
(6) DOLEY, 1967: excised leaves
(7) NICOLLS et alii, 1982: soil water balance

An interesting point to conclude this discussion on evapotranspiration is in regard to the question of just how much water do eucalypt forests use. There are some figures available, (table 2), but of course it has to be born in mind that they come from different research approaches and, therefore, are difficult to compare directly The results from South Africa reported recently by VAN LILL et alii (1980) are interesting to be included in the present discussion because they represent the first experiment in the world, on catchment basis, to measure the effect of a eucalypt plantation on water yield. After planting **E. grandis** on an approximately 30-ha catchment originally covered with natural, seasonally dry grassland, they found out an average reduction of 340 mm in the annual stream-flow of the catchment. They reported the observable influence on water yield started at about the third year after planting, reaching a maximum at the fifth year after planting, this level remaining constant for about four years. The soils in the catchment are shallow. The planting was carried out on a 2.7 m retangular pattern, and the average precipitation in the area is around 1200mm yr^{-1}.

Other relevant data on catchment water yield in eucalypt forest is given by LANGFORD (1976). After a wildfire swept through **E. regnans** forest in the Melbourne region in 1939, young, vigorous regeneration of **E. regnans** took place. At the age of 21 years, this regrowth was using about 200 mm yr^{-1} more water than the old growth, approximately 200-year old **E. regnans** forest. The author also noticed the commencement of a gradual return of streamflow to the pre-fire levels, but could not establish the significance of this return because of insufficient streamflow records.

Catchment Water Balance

A summary of catchment water balance values is given in Table 3.

Table 3 shows a relationship between rainfall and catchment loss in eucalypt forests, the loss reaching a constant value of approximately 1000 mm yr^{-1} once rainfall exceeds a little over 1200 mm yr^{-1}. Therefore, this value of 1000mm per year can well be a representative average figure of evapotranspiration of a well stocked eucalypt forest growing in temperate zones of rainfall above 1200 mm per annum. with decreasing rainfall, soil moisture becomes limiting and evapotranspiration decreases, reaching eventually a value of 450 mm yr^{-1} at rainfall around 1500mm per year (MCARTHUR, 1964), (MCARTHUR and CHENEY, 1965). As one progresses toward the equator, evapotranspiration tends to increase, probably reaching a figure of around 1500 mm per year. Compare for this purpose, the data on water balance obtained by GILMOUR (1975) in a tropical forest in the wet, tropical coast of northern Queensland, as an average value for 4 years:

Precipitation = 3900 mm yr^{-1}
Streamflow = 2350 mm yr^{-1}

Evapotranspiration = 1500 mm yr^{-1}

TABLE 3. Average water balance of selected eucalypt forested catchments in Australia. P = precipitation, Q = streamflow, Loss = evapotranspiration + interception + change in soil water storage

Catchment	Location	P	Q	Loss	Vegetation	Ref.
Cotter	ACT	500	54	446	Dry-wet sclerophyll (A)	(1)
Lidsdallye	NSW	877	125	752	Dry sclerophyll (B)	(2)
Cropper Creek	Vic	1006	149	857	Dry sclerophyll ©	(3)
Stewart Creek	Vic	1093	186	907	**E. obliqua**	(4)
Picaninny	Vic	1156	256	900	**E. regnans**, mature	(5)
Bancells	WA	1160	240	920	**E. marginata**	(6)
Dwellingup	WA	1160	240	920	**E. marginata**	(6)
Dandalup	WA	1160	190	970	**E. marginata**	(6)
Clem	Vic	1200	165	1035	Dry sclerophyll (C)	(7)
Ella	Vic	1200	115	1085	Dry sclerophyll (C)	(7)
Betsy	Vic	1200	84	1116	Dry sclerophyll (C)	(7)
Cotter	ACT	1270	300	970	Dry sclerophyll (A)	(1)
Blue Jacket	Vic	1335	414	971	**E. regnans**, mature	(5)
Stewart Creek	Vic	1359	369	990	**E. obliqua**	(4)
Myrtle	Vic	1606	765	841	**E. regnans**, mature	(8)
Black Spur	Vic	1660	532	1095	**E. regnans**, regrowth	(8)
Ettercon	Vic	1757	690	1067	**E. regnans**, regrowth	(8)
Monda	Vic	1759	605	1190	**E. regnans**, regrowth	(8)
Cotter	ACT	2030	1030	1000	Dry sclerophyll (A)	(1)

(1) MCARTHUR, 1964
(2) SMITH et alii, 1974
(3) BRENS and TURNER, 1979 and 1980
(4) GUTHRIE et alii, 1978
(5) LANGFORD and O'SHAUGHNESSY, Ed., 1980
(6) MCARTHUR, 1964
(7) FLINN et alii, 1979
(8) LANGFORD and O'SHAUGHNESSY, Ed., 1977; LANGFORD and O'SHAUGHNESSY ed., 1980a.

(A) E. delegatensis - E. dives - E. dalrympleana
(B) E. rossi - E. dives - E. dalrympleana
(C) **E. radiata - E. viminalis - E. mannifera**

For the **E. regnans** forest, on an average site having an annual rainfall of 1600 mm, the forest consumes around 1100 mm per annum, leaving approximately 500mm per annum of available stream flow (LENGFORO and O'SHAUGHNESSEY, 1979), MMBW (1980). As given by LANGFORD et alii 1980) and LANGFORD and O'SHAUGHNESSY, Ed. (1977), the average catchment loss in **E. regnans** forest is related to the radiation index (RI) and to the eucalypt basal area (SA), according to the following equation:

$$\text{Loss(mm)} = 1116{,}6 + 99.3RI + 75.7BA$$

Water Quality and Nutrient Cycling

The stream flow which drains catchments containing natural eucalypt forests is of high quality. This has been tested in a number of water quality studies in several regions in Australia.

In the ACT, TALSMA and HALLAM (1982) analyzed water samples from 16 experimental catchments in the Cotter Valley, comprising data from 1973 to 1977, and including weekly values of electrical conductivity, pH, and mean weekly concentrations of calcium, potassium, magnesium, sodium, chloride, and iron. Vegetation on the catchments varied from dry sclerophyll (**E. dives - E. dalrympleena - E. radiata**) to wet sclerophyll (**E. delgatensis - E. pauciflora**) forests. Some of the catchments contained also plantation of **Pinus radiata**. Results showed that water quality depended strongly on geological arid soil properties, rather than on vegetation types. In catchments characterized by well permeable soils, they found water quality to vary little with discharge; in less permeable catchments, water quality varied with discharge, a condition which reflects the differential effects of base flow, interflow and surface runoff in the composition of the discharge hydrograph. Some insights into this catchment behavior had been verified and discussed in earlier specific studies (TALSMA et alii, 1980), (TALSMA, 1981), (CORNISH, 1991), (JAKOBSEN and TALSMA, 1981).

In the same catchments in the Cotter Valley, THISTLETHWAITE (1970) suggested that areas covered with low grade, dry sclerophyll eucalypt forest, and having discontinuous or bare soil areas, are potentially associated with sheet erosion, which could influence stream turbidity. This potential of soil loss with reduced forest cover was also shown in the alpine conditions of Kosciusko area (COSTIN et alii, 1960).

In Western Australia, HATCH (1976) also observed, similarly to the results in the Cotter Valley, that the main factor influencing the chemical composition of forest stream is the nature of the soil. He also found the stream water to be of high quality (HATCH and SHEA, 1977). In a later study, though, HATCH et alii (1978) found some evidence of different eucalypt species affecting differently the quality of streamflow water. Comparing the water quality in catchments containing **E. marginata**, and **E. wandoo**, they observed that pH in the water from the **E. diversicolor** catchment was significantly higher than the other two species. They attributed the difference to the leaching of the heavy **E. diversicolor** litter, which is higher in total base, in comparison with the other two eucalypt species.

Some of the water quality studies in eucalypt forests were aimed at determining the nutrient balance in catchments. The results found in the present review are summarized in Table 4. Such measurements are, of course, very important in assessing the influence of forest cover on the quality of stream water, on the maintenance of site productivity, and on the balanced functioning of the catchment. Substantial increases in the losses of nutrients from the catchment can affect all these aspects.

TABLE 4. Catchment nutrient input in precipitation (R) and output streamflow (Q), in some eucalypt forest (Kg ha^{-1} yr^{-1})

SPECIES	Ca		Mg		K		P		Na		Ref.
	R	Q	R	Q	R	Q	R	Q	R	Q	
E. obliqua	2.6	0.2	5.4	3.6	2.0	2.0	0.01	0.02	-	-	(1)
Dry scler. (A)	3.2	0.4	1.1	1.1	1.8	0.3	0.01	0.01	2.8	2.7	(2)
E. obliqua	1.3	0.2	1.4	3.6	4.2	2.1	-	-	17.9	19.8	(3)
Wet-dry sclerop. (B)	7.0	7.1	1.5	4.5	-	-	0.33	0.26	2.5	15.9	(4)
E. regnans (C)	6.6	10.3	2.6	4.9	2.9	7.5	0.15	0.12	12.4	20.4	(5)
E. regnans (D)	6.6	16.8	2.6	7.4	2.9	8.7	0.15	0.15	12.4	32.8	(5)

A) E. radiata, E. viminalis, E. mannifera
B) E. radiata, E. dives, E. delegatensis, E. pauciflora, E. dalrympleana
C) 60% old growth, 16% regrowth
D) old growth

1) ATTIWILL, 1981
2) BREN et alii, 1979; FLINN et alii, 1979; BREN and TURNER, 1979; BREN and TURNER, 1980.
3) GUTHRIE et alii, 1978
4) LIKENS et alii, 1977
5) FELLER, 1981

As may be inferred from Table 4, there is not much data on catchment nutrient balance in eucalypt forests, and apparently it seems difficult to find any consistency in the figures that could be worth discussing. FELLER (1981) gives a summary of catchment nutrient balance (input minus output) data for some eucalypt catchments, and states that, for a given nutrient, they are comparable to and lie within the range of variation of nutrient balance found in other temperate forest catchments in the world. GUTHRIE et alii (1978), on the other hand, present a similar table for different parts of the world, stating that there is considerable variation in the balance of nutrients in the different catchments. In general, output of nutrients exceeds the input, but the balance varies from caption to caption. Variation in input is related to the geographical location of the catchment. Variation in the output will reflect catchment characteristics and vegetation cover. For one Individual catchment, the balance for some nutrients will also vary from year to year. By comparison with world data presented by GUTHRIE et alii (1978), the nutrient balances in eucalypt catchments of Table 4 shows a conservative balance, which reflects a stable condition being exerted by the undisturbed eucalypt ecosystem.

Another aspect related both with water quality and with nutrient cycling is the interaction of rainfall with the forest canopy. The few data available in this respect in eucalypt forests is presented in Table 5. The first aspect for attention in this table is the data on nutrient input in bulk precipitation in Australia. CHARLEY (1981) gives a little higher average for calcium and magnesium, based on data from several sources. WETSELAAR and HUTTON (1963) argue that this soluble material contained in rain water is part of a terrestrial cycle and, thus, can not be regarded as a true accession to the site.

A second aspect of Table 5 is the consistent enrichment of the rainfall water after its interaction with eucalypt canopy, particularly in regards to potassium and sodium, and mainly through the process of throughfall. ATTIWILL (1966) suggested that the contribution of stemflow to the nutrient cycling in eucalypt forest would be small, which can be seen in two of the results shown in Table 5. This leaching of nutrients from the canopy by rain has also been observed in other studies in Australia, such as COSTIN and WIMBUSH, (1961) and FERGUS (1981), but their data could not be fitted into the form used in Table 5. Overall, the process is an important part of the cycling of nutrients within the ecosystem. It represents around 2 times the amount of sodium contained in the litter fall and around 1.3 times the amount of potassium contained in the litter (GUTHRIE et alii, 1978), (ATTIWILL, 1980).

The leaching can also be seen as an important influence of eucalypt forest in the alteration of the quality of rain water, although the efficiency of this process can be significant only above ground and perhaps in the upper soil profile. Most of the increase in cation concentrations that occur as a result of the interaction of rainfall with the forest canopy is buffered out in the soil profile, and therefore will not greatly affect the quality of the streamflow (TALSMA et alii, 1980), (CHARLEY, 1981).

EFFECTS OF EUCALYPT FOREST ACTIVITIES ON WATER VALUES

In the previous paragraphs, an attempt has been made to give an overall picture of the hydrologic functioning of the eucalypt forest ecosystem. The manipulation of this forest will undoubtedly affect water resources, and it is thus necessary to complete this picture with an analysis of published results of the effects of eucalypt forest activities on water values.

What are the effects of forestry operations such as logging, road construction, clearing, planting, etc., on water quality and yield? Will there be any significant difference in water yield and quality of changing eucalypt forest by another type of vegetatio? How intensively will thinning, selective cutting and clearfelling of eucalypt forests affect catchment yield? What are the hydrologic effects of prescribed burning of eucalypt forests? The reports by BOUGHTON (1970a and 19070b) and by LANGFORD and O'SHAUGHNESSY (1977) have covered most of these aspects on a world wide basis, including data from different forest types.

Prescribed Burning

The occurrence of forest fire since long past has played an important role in shaping the present Australian forest vegetation. Most eucalypt species developed features which help them survive a wild fire, and some eucalypt forests depend on periodic fire for their regeneration. In the present time, prescribed burning has become a useful management tool in many eucalypt forests, and over a million hectares are prescribed burned annually, either for enhancing regeneration, or for removing the eucalypt forest litter, which is considered one of the world's most flammable forest fuels (FLORENCE, 1981).

BROWN (1972) reported the hydrologic effects of a wildfire that swept through an area of about 700 km^2 in NSW, in 1965, in eucalypt forests ranging from wet sclerophylls, in most of the burned area, to dry sclerophyll, at the lower elevations, and to alpine open woodland, at the higher elevations. The results of the analysis showed a greater peak discharge, an increase in runoff, and an increase in sediment load in streams after the fire. BROWN stated that it took about five years for the catchment to recover from the effects of the fire.

TABLE 5. Leaching of nutrients from the canopy of forests by rainfall (P = rainfall, T = throughflall, S = stemflow)

Species	Process	K	Ca	Mg	Na	SO4	P	Ref.
				Kg ha^{-1} yr^{-1}				
E. signata - E. umbra	P	3.4	3.2	5.9	5.0	9.6	-	
	T	8.5	14.0	7.2	44.0	17.0	-	(1)
	S	0.9	0.8	1.1	8.1	0.7	-	
E. melanophloia	P	2.6	1.9	0.7	3.7	-	0.1	
	T	22.1	9.3	8.1	6.4	-	0.5	(2)
	S	0.7	0.5	0.5	0.2	-	0.01	
E. obliqua	P	4.2	1.3	1.4	17.9	-	-	(3)
	T	15.4	6.3	6.0	27.2	-	-	
E. obliqua	P	2.0	2.7	5.4	16.8	-	-	(4)
	T	13.4	8.0	7.3	25.4	-	-	

(1) WESTMAN, 1978 (2) PREBBLE and STIRK, 1980
(3) GUTHRIE et alii, 1978 (4) ATTIWILL, 1966

In the wet, **E. regnans** forest of Melbourne, the effects of the disastrous 1939 wildfire on the water yield of selected experimental catchments were analyzed by LANGFORD (1976). After the fire, regeneration was rapid, and a vigorous regrowth of **E. regnans** forest developed. Langford's analysis covered the period of 1944-1964, that is ending at the 25th year after the fire. He reported no detectable change in yield during the immediate 5 years after the fire, which contrasts with the previous results by BROWN (1972). In the subsequent years, however, a significant decline in catchment yield as a result of the regrowth of the forest was observed.

MACKAY et alii (1980) analyzed the hydrographs of small, eucalypt forested catchments near Eden, after a severe wildlife, and compared with hydrographs from a similar unburned catchment. The effects of the fire by this type of analysis were summarized as follows:

a) diurnal fluctuations in streamflow ceased;
b) baseflow, runoff and peakflow increased;
c) the differences persisted for at least a year after the fire.

O'LOUGHlIN et alii (1982) have also noticed a cessation of diurnal fluctuation in streamflow, and an increase of 32 mm in the mean, summer baseflow, after a hot fire was set in na experimental, small, dry-wet sclerophyll (**E. radiata - E. dives - E. delegatensis - E. pauciflora - E. dalrympleana**) catchment in the Cotter Valley, A.C.T. The authors analyzed the effects of the catchment fire through its indirect influence on the proportion of the catchment area which generates rapid surface runoff during a storm (O'LOUGHlIN, 1981). This approach permits an insight into the mechanisms of base flow generation and the catchment factors that determine it. The runoff ratios (ratio of quick stormflow volume to net rainfall volume) has not been changed by the fire, but tended to increase as the pre-storm baseflow discharge increased. The increase in the ratio is shown not to be attributed to an increase in overland flow, but rather, to the occurrence of inter flow of perched saturation near the wet areas of the catchment.

The effects of forest fire on water quality and nutrient cycling have not been much studied (RAISON,1980). MACKAY and PERRENS (1979) reported that the effects of controlled burning on stream water quality are minimal, unless sufficient overland flow occurs to wash significant quantity of ash into the channel system. The analysis by O'LOUGHLIN et alii (1982) shows that burned catchment does not necessarily becomes more subject to the occurrence of overland flow.

KHANA and RAISON (1981) studied the chemical composition of soil percolates, at 10-cm depth, in burnt and unburnt **E. pauciflora** forest 1 day, 2 months, one year and two years after the fire. They reported that burning increased the concentration of all water soluble cations, except Al and H, which were significantly reduced. The availability of nutrients, thus, is likely to be increased during the period of one to two years after a forest fire.

Logging, Clearfelling, Thinning

In the **E. regnans** environment, several hydrologic studies are being carried out in the Maroondah and Coranderrk experimental catchments of the Melbourne and Metropolitan Board of Works: LANGFORD and O'SHAUGHNESSY (1977), LANGFORD and O'SHAUGHNESSY, Ed. (1977), LANGFORD and O'SHAUGHNESSY, Ed. (1979), LANGFORD and O'SHAUNESSY, E. (1980a and. 1980b), LANGFORD, and O'SHAUGHNESSY (1979), LANGFORD et alii (1980), RONAN (1981). A summary of the studies, and also of that by BROOKES and TURNER(1964) is given below with regard to the effects of logging, clearfelling, and thinning of **E. regnans** forests on the catchment yield and stream water quality:

a) thinning reduces water consumption and increases streamflow;
b) Clearfelling mature **E. regnans** increases streamflow from 256mm y up to a maximum of 564 mm yr^{-1}
c) the effect of clearfelling on streamflow yield appears to achieve a maximum in the second year after felling;
d) after clearfelling, a regrowth forest develops rapidly, and streamflow level starts to decline, reaching the pre-treatment level at about 7 years after the felling;
e) selective cutting which reduced the forest cover by 28% resulted in a smaller streamflow increase. which passed from an average of 429 mm yr^{-1} to 558 mm yr^{-1};
f) clearfelling of a 40-year old regrowth **E. regnans** forest has produced an average 435 mm of streamflow increase in the first year after clearfelling, and of 461 mm in the second year;
g) logging and road construction have produced an increase in sediment load measured in the weir, which increased from 40 kg ha^{-1} yr^{-1} ,to 90 kg , ha^{-1} yr^{-1}, immediately after logging activities, but returned soon to the pre-treatment level;
h) clearfelling temporarily increased total dissolved solids and nitrate concentrations in streamflow, but had no effects on stream temperature, dissolved oxygen, BOD, pH, and phosphorous concentrations;
i) selective cutting has had no detectable effect on water quality.

In the region of mixed species, dry and wet sclerophyll eucalypt forests, results available are mainly related to water quality effects of logging operations, which seems to be an issue of public concern and interest (McKAY, 1981), (RIEGER et alli, 1979) In the Eden area, studies are being conducted in five small catchments in a dry-sclerophyll (**E.**

sieberi - E. obliqua - E. gummifera - E. agglomerata) association. Preliminary results are given by OLIVE et alii (1978) and RIEGER et alii (1979), who observed an increase in sediment load after the begining of logging, mainly as a result of poorly located roads.

In an association of **E. pilularis - E. campanulata - E. grandis** near Lismore, CORNISH (1980a) studied the effect of logging, tractor clearing, slash burning, and planting seedlings of **E. pilularis** on turbidity and electrical conductivity of stream water, through the analysis of weekly grab samples from the weir. Results show that electrical conductivity appears to be unaffected by the forestry activities, and that turbidity on the treated catchment rose only when logging coincided with periods of high rainfall.

In an association of **E. sieberi - E. maculata - E. boliqua - Ecypellocarpa** near Bega, NSW, CORNICH(1980b) analyzed the effects on turbidity and electrical conductivity of logging operations developed on a coupe basis and snigging by crawler tractors. A stream-side buffer 40-m wide was retained on both sides of the stream. No detectable effects were found.

In the semi-arid region of southern Queensland, with an average annual rainfall of 500 mm, the effects of killing the trees on an open woodland (**E. populnea**) on the availability of soil water were studied by TUNSTALL and WALKER (1975). By measuring soil water with neutron probe, with 6 replications, to a depth of 1.6m, at fortnight interval, during 6 months following the killing of 300-500 trees per hectare, they determined that soil water storage and availability were only slightly increased.

In a more tropical area of northern Queensland, GILMOUR (1971) studied the effect of commercial logging operations on water quality and quantity. Average precipitation for the area is 2500 mm per year, and vegetation is a rain-forest, with **E. grandis** dominating on the ridges. Sediment load in stream water increased only after heavy reins, and sediments were mostly derived from poorly located roads. Double-mass analysis indicated a trend toward increased annual stream flow since logging began in 1960.

In Western Australia, the clearing of the jarrah forest (**E. marginata - E. calophylla**) has been associated with a serious problem of increased stream salinity (PECK and HURLE, 1973), (PECK, 1976), (WARO, 1977), (BATINI, 1979), (RITSON and SHEA, 1979), (SHARMA et alii, 1982). LOH (1979) estimates that stream salinity has increased from about 240 mg/1 of total dissolved solids (TDS) in 1940, when 5% of the forest had been cleared, to approximately 750 mg/1 of TDS in the seventies, when clearing has reached 23%.

WHITELEY (1978) reports results of a preliminary study of the effects of woodchip logging of **E. marginata** forest on stream water quality, in which increase in sediment load in some of the streams sampled has been found.

Regarding catchment yield in the **E. marginata** forest, SHEA et alii (1978), based on the plotting of long streamflow records for several different forest conditions, estimated that na increase of about 10% in water yield can be expected for each 30% reduction in the canopy density of the **E. marginata** forest.

In the Collie River Basin, near Perth, a region of 1150 mm of average annual precipitation, STOKES(1979) reported an increase in streamflow after clear felling **E. marginata - E. calophylla** forest.

Replacing Eucalypt Forest with a Different Forest Type

GILMOUR(1968 a) studied surface runoff and soil loss from runoff plots established under dry sclerophyll eucalypt and under pine plantations of varying ages, in the Cotter Valley, resulted from natural rainfall during one-year period. He found variation in the degree of soil protection offered by different forest cover depending on non-capillary porosity of the soil and also on the weight of ground cover. In general, though, he concluded that native eucalypt forest as well established pine plantation provided excellent catchment protection on all studied soil types. In analyzing the mechanisms of water repellence, the same author (GILMOUR, 1968b) again found no difference between native eucalypt and pine plantation.

HOPMANS et alii (1979) made a comparison of soil chemical properties under native eucalypt (**E. baxteri - E.viminalis**) forest and a 27-year old **Pinus radiata** plantation, in Victoria. The main conclusion was that no substantial deterioration in the nutrient status of the studied soil has occurred after one rotation of the pine plantation.

A comparison (of water balance between dry sclerophyll (**E. rossi - E. maculosa - E. dives - E. dalrympleana**) forest and a 35-year old **Pinus radiata** plantation was conducted in Lidsdale, NSW (BELL and GATENBY, 1969), (SMITH et alii, 1974). The study was carried out in two adjacent, small catchments and measurements included rainfall, streamflow, soil moisture, throughfall and stemflow. Evapotranspiration was estimated by the water balance method, although deep seepage was not measured. For a 31-month period, evapotranspiration from the eucalypt catchment was 1615 mm, and for the pine catchment was 1587 mm. Interception in the pine was higher, which accounted for a reduction in streamflow in the pine catchment. They used the neutron technique and measured soil water weekly to a depth of 2.2 m, from October 1968 to 1971. They found no significant difference in the total mean soil moisture content, on individual measurement dates, between the eucalypt forest and the pine plantation. For some individual soil depths, a tendency was noticed for soil moisture in eucalypt forest to become wetter than in pine, following heavy precipitation, and relatively drier during periods without precipitation.

In Western Australia, diseased **E. marginata** forests are being replaced by **Pinus radiata** plantations. RICHMOND (1980) gives descriptions and preliminary results of an experimental network of five catchments installed with the purpose of measuring the hydrologic consequences of this vegetation replacement. Although no calibration has been made so far, Richmond report an increase in streamflow after clearing and during the first two years after planting pine, and no degradation of the quality of stream water, concluding that the replacement of **E. marginata** by pine plantation is likely to have no effects on stream salinity.

In the Stewarts Creek catchments of Victoria, hydrologic data have been collected since 1960 on four small catchments, in an experiment aimed at assessing the hydrologic effects of replacing eucalypt forest by pine plantations (TSYKIN et alii, 1963). The data were analyzed by a conceptual statistical modeling method. Monthly runoff more than doubled during the first four years of pine planting, but tended to reduce as the pine trees developed. Annual runoff, as an average for the first 8 years of the experiment, during which the catchment was under eucalypt forest, was 283 mm. After clearing and planting pine, the average annual runoff for the first 7 years of the pine development was 452mm, but a strong tendency for this increase to dwindle as the pine plantation develops was also noticed.

HOLMES and WRONSKI(1981) have stated that eucalypt forested land would yield approximately 70 mm less runoff or recharge of groundwater, in comparison with annual pasture or crop land. In a karstic region of southern Australia, HOLMES and COLVILLE (1968) determined that groundwater recharge under pasture was 63mm, in comparison with no recharge observed under a pine plantation in a similar soil

SUMMARY AND CDNCLUSIONS

In Australia the best eucalypt forest are located on water catchment areas, and are considered the best vegetation cover for the purpose of water production. Some cities, such as Brisbane and Sydney, do not have control over the entire catchment area that produces their water supply, but in general many water supply authorities are vested with some form of statutory control over the land use activities in the city water supply catchments.

One outstanding example of this situation is that of the city of Melbourne, whose water supply catchments are located in the Central Highlands of Victoria, about 80 km of Melbourne. The catchments comprise an area of 121000 ha, almost entirely covered with eucalypt forests. Over 50% of the forest is composed by the **E. regnans** the second tallest tree species in the world, and this forest type alone provides an estimated 70-80% of Melbourne's water consumption. The entire catchment area is under control of the Melbourne and Metropolitan Board of Works, which maintains a policy of closed catchment and manages the area solely for water supply purposes. The quality of the water produced in the forested catchments is such that no treatment is required before it is distributed to the Melbourne's population of over three million people.

Similarly, over 3/4 of Perth's water supply is obtained in catchments covered by **E. marginata** forest, and Canberra obtains its water from the Cotter Valley, a catchment of about 48000 ha covered with mixed species, wet and dry sclerophyll eucalypt forests, mainly composed by **E. delegatensis, E. pauciflora, E. dives, E. dalrympleana, E. fastigata, E. viminalis, E. mannifera,** and **E. macrorryncha** species.

One of the purposes of the present review was to compose an overall Hydrologic image from the many isolated studies which have been developed in eucalypt forests in Australia. We have seen that this image, although built upon relatively meagre available data, is clear enough to allay some local concerns about the hydrologic side effects of the eucalypts as it is summarized below:

- Interception losses in eucalypt forests range from about 11 to 26%.
- Lateral spreading and depth of penetration or the root systems or the eucalypts vary with species, and this has to do with the variable intensity of soil water uptake. Withdrawing of soil moisture also depends on stand density and soil and environmental conditions. In alpine dry sclerophyll conditions, the soil water regime does not differ between eucalypt forests, grassland, and herbfield. In regions of deeper soils and higher rainfall regimes, soil water deficit created by eucalypt forests seems to be in the vicinity of 250 mm yr^{-1}. In comparison with crop or pastureland, this means that eucalypt-forested lands would yield approximately 70 mm yr^{-1} less streamflow or groundwater recharge. Comparative studies have shown that the overall soil water regime of eucalypt forests does not differ from that observed in pine plantations. The effects on soil moisture reserves of eucalypt plantations apparently start to appear at the age of a approximately 4-6 years, b,y which time the soil water deficit created by the plantation during the year is greater than the one observed in mature forest.
- Transpiration rates per tree vary among eucalypt species, between about 20 litres $tree^{-1}$ day^{-1} to 40 litres $tree^{-1}$ day^{-1}. Evaporation rate from eucalypt forests in field conditions is

more difficult to be detected, but it appears to vary from 1.5 mm day, in winter, to 6.0 mm day, in summer. Some eucalypt species have not developed mechanisms for controlling higher rates of transpiration, and are likely to suffer from drought stress, which limits their range of habitats. The majority of eucalypt species, however, do have some control of the rate of transpiration, which help them to survive drought stress during part of every year, and which is apparently related to the rainfall regimes of their natural habitats. Average catchment evapotranspiration of a well stocked eucalypt forest is probably around 1000 mm yr^{-1} for rainfall regimes in excess of 1200 mm yr^{-1}. For dryer regions, evapotranspiration also declines, perhaps reaching a value of approximately 450 mm yr^{-1}, when the rainfall regime is in the order of 500 mm yr^{-1}. For wetter regions, evapotranspiration increases, eventually reaching a value of 1500 mm yr^{-1} for tropical eucalypt forests of lower latitudes. Comparative studies have shown average annual evapotranspiration in pine plantations to be in the same order of magnitude of that observed in eucalypt forests. Young, vigorous, dense regrowth of **E. regnans** forest was found to yield less water in comparison with mature forest. At the age of 21 years, the difference in water yield was found to be around 200 mm per annum, but catchments yields tend to equalize as the regrowth matures.

- Very high quality water drains from catchments containing eucalypt forests. There is apparently no difference in the quality of streamflow from catchments containing different eucalypt species, although there may be some differences in the quality of the rain water collected beneath the canopy of different species. This is due to a differential intensity in the leaching process, but it apparently does not affect stream water quality because of the buffering effect in the soil profile. This enrichment of rain water in nutrients as it interacts with the canopy of eucalypt forests is mainly noticeable in the process of throughfall, and is mostly conspicuous for potassium and sodium. Comparison of catchment nutrient budgets of different eucalypt forests with data from other forest types in the world shows a conservative balance for the eucalypt forest catchments, which is a reflection of the stable condition of these ecosystems.
- Hot fires in eucalypt forests can increase peak discharge, runoff, and summer baseflow, but apparently have no effects on stream water quality, although there may be an increase in the concentration of some water soluble cations in the soil solution.
- Thinning and selective cutting in mature eucalypt forest can reduce water consumption and increase streamflow. Clearfelling mature, wet eucalypt forest increases stremaflow by an average value of approximately 400 mm per annum. The effect of clearfelling on catchment yield is maximum during the second year after the cut. Clearfelling can also cause some temporary increase in streamflow nitrate and TDS concentrations, but selective cutting appears to have no effect on water quality. Clearfelling of **E. marginata** forest in Western Australia is related to an increase in streanflow salinity.

As demand for water increases, one of the options available is to increase catchments water yields through sound forest management. The use of these forests will also attend the Country's growing demand for timber resources. To achieve this dual objective, we feel that more information is needed in the hydrology of eucalypt forests. Take interception, for instance, with just a few results summarized in Table 1. Enough evidence and some experimental results have shown that the rate of evaporation of intercepted water is greater than the transpiration rate in the same environmental conditions. Therefore, part of the intercepted water is in fact a loss to the site, but part of it will contribute to a reduction in soil moisture draft. This sort of study is being developed for pine plantation in Mount Gambler, South Australia HOLMES and COLVILLE, 1968)

(DUNIN, 1976), (HOLMES and WRONSKY, 1981), but there is no information regarding eucalypt forests.

In view of the diversity of eucalypt forests, there is also need for additional data on soil moisture regimes, and catchment nutrient budgets.

Finally, research on evapotranspiration from eucalypt forests will also have to be intensified, for this will not only assist the management of mature forested catchments, but also the reforestation schemes with eucalypt species in different situations. Estimation of evapotranspiration through measurements of micrometeorological parameters and the incorporation of a canopy resistance factor will be of extreme value for evaluating the effects of land use changes on catchment hydrology (SEDGLEY, 1979). This canopy resistance is strongly related to the evaporation from a forest, but it varies with the species. Even for different species having similar stomatal resistance, differences in leaf area index could account for difference in evapotranspiration. This micrometerological approach is being used for the estimation of evapotranspiration in pine plantations at Mount Gambier (HOLMES and COLVILLE, 1968), (DUNIN, 1976), and is now being also applied in a dry sclerophyll eucalypt forest in the South Coast of NSW (DUNIN, 1981).

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