COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

PREDICTING THE EFFECT OF VEGETATION CHANGES ON CATCHMENT AVERAGE WATER BALANCE

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Preface

This work was conducted under the S3 project, 'Salt Exports from Dryland Catchments'. The aim of the work was specific, to estimate the effects of afforestation or deforestation on run-off that leads to recharge to some of the alluvial catchments in the upland areas of the Murray-Darling Basin. The method proved to be more successful than expected, leading to simple robust estimators at an appropriate scale. Having done this, the method could be used much more widely than its original purpose, providing a basis for making estimates of the water yield impacts of wide-scale afforestation in the Murray-Darling Basin. This report substantiates the estimators, both from a process understanding and a statistical analysis of a large number of catchments.

Glen Walker

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Abstract

It is now well established that that forests increase catchment evapotranspiration compared to grassed catchments. This has implications for catchment water balance in terms of land use management and rehabilitation strategies. The key processes that control evapotranspiration include rainfall interception, net radiation, advection, turbulent transport, leaf area, and plant available water capacity. The relative importance of these factors varies depending on climate, soil, and vegetation conditions. Results from over 250 catchments worldwide show that for a given forest cover, there is a good relationship between long-term average evapotranspiration and rainfall. A simple two-parameter model was developed that relates mean annual evapotranspiration to rainfall, potential evapotranspiration, and plant available water capacity. The mean absolute error (MAD) in the ratio of evapotranspiration to rainfall between the model and field data is 6 %, and the root mean squared error (RMSE) is 8 %. The model showed potential for a variety of applications including water yield modelling and recharge estimation. The model is a practical tool that can be readily used for assessing the effect of vegetation changes on catchment average water balance and is scientifically justifiable.

Acknowledgments

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1 Introduction

A large number of field experiments have been conducted to quantify the impact of vegetation changes on the water balance of catchments and have shown such changes to be important. The change in water balance is dependent on a number of factors including the spatial pattern of vegetation, soils, groundwater, and rainfall pattern. It is difficult and expensive to gather such data on catchments of any significant size. Yet, knowledge of these relationships is critical for land management.

Sources of information on the water balance associated with vegetation change generally fall into two categories. The first involves the "paired-catchment experimental techniques". This method is based on two similar catchments which are studied for a calibration period; then one catchment is subject to a change (i.e. clearing), and the other remains unchanged (i.e the ‘control’). Paired catchment studies try to minimise differences between control catchments and treated catchments in terms of rainfall, soil, topography, and other factors that may influence catchment water balance. Hibbert (1967) reviewed results from 39 such experiments. Bosch and Hewlett (1982) updated Hibbert’s review to include an additional 55 catchments. Results from these experiments showed a large variation in catchment responses to changes in vegetation cover. However, a clear conclusion was that reduction of forest cover increases water yield.

The second source of information on the impact of vegetation comes from hydrological studies. These studies were not specifically designed to examine the effects of vegetation on water yield, but the fact that they represent catchments with diverse climate, vegetation, and soil can provide useful information about the role of vegetation in catchment water balance.

From these studies, it is clear that the largest hydrological impacts often arise from afforestation and deforestation (Calder, 1996), the later often leading to major environmental problems such as salinity. In southern Australia, salinity is recognised as one of the most serious environmental degradation issues, with up to 30 % of large areas being predicted to become affected by salt (CSIRO, 1999). It also affects stream water quality (Walker et al., 1998). Salinity is caused by massive clearing of native vegetation and its replacement by shallow-rooted annual crops and pastures. The removal of the forest reduces evapotranspiration and increases groundwater recharge. As groundwater levels rise, this leads to salt accumulation in the root zone in some areas. The clearing of native vegetation is also likely to lead to increased stream flow, which not only increases water supply, but also helps to dilute salt inflows.

The degree to which salt inputs are offset by ‘dilution’ flows depends on the rainfall zone. If the same amount of salt was exported from two catchments, but one had higher annual rainfall and yielded more stream flow, the concentration of salt would be lower, because of greater dilution. However a relatively small increase in stream flow will result in a significant increase in salt export due to the large absolute amount of flow. In medium rainfall zones (500-800 mm/yr), there are usually high concentrations of salt in the stream flow and groundwater system. While the absolute amount of water exported may be small, the change in concentration can increase by an order of magnitude or more, leading to a similar change in salt balance. The commercial viability of plantations also changes through these zones, and is generally sub-economic for lower rainfall zones. The ability of non-tree land uses to reverse the change in water balance also varies across these rainfall zones. With higher rainfall, it is expected that any pasture or cropping system will use much less water than trees. However, for the lower rainfall zones, some perennial systems may use approximately the same amount of water as trees.

Given the above, it can be seen that developing a sustainable land management system involves trade-offs between economic viability, environmental sustainability and water resource security. Thus, in order to determine the trade-offs, it is important to understand the water balance-vegetation relationships through the different parts of the landscape. Salinity is obviously not the only issue for which the water balance and vegetation relationship is important. Water resource security in relation to plantations is important in Australia and other parts of the world.

The purpose of this report is twofold: (1) to review the state-of-the-art on the hydrological role of vegetation, in particular the impact of vegetation changes on mean annual evapotranspiration, and (2) to develop a simple water balance model that describes the effect of vegetation change on mean annual evapotranspiration. The data used in this report came from both forestry and hydrological literatures and they represent diverse climate, soil, and vegetation conditions. There is no attempt in this report to partition between run-off and recharge, only to calculate the water available for either. We also do not attempt in this report to predict changes in flow regimes, focusing instead on mean annual water yield. In developing these relationships, it is important that we use data that are appropriate for the scale of investigation, that can be scientifically validated, and have appropriate vegetation types.

2 Vegetation and Hydrological Processes

The natural circulation of water in the soil-vegetation-atmosphere continuum is an important process and it is central to the energy, carbon, and solute balances of the system. There are many pathways that water may take in its continuous cycle of falling as rainfall and returning to the atmosphere as evapotranspiration. It may be intercepted by vegetation and evaporated directly to the atmosphere. It may infiltrate into the soil to be evaporated from the soil surface or be transpired by vegetation. It may become surface runoff and it may percolate through the soil to groundwater as recharge. Vegetation plays an important role in the hydrological cycle through the exchange of energy, water, carbon, and other substances. In what follows we will review the key hydrological processes and the impact of vegetation on catchment water balance.

2.1 Catchment water balance

The concept of the water balance provides a framework for studying the hydrological behaviour of a catchment and it can be used to identify changes in water balance components. The water balance for a catchment can be written as

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

where P is precipitation, ET is evapotranspiration, R is surface runoff measured as streamflow, D is recharge to groundwater, and ΔS is the change in soil water storage.

Precipitation is the largest term in the water balance equation and it varies both temporally and spatially. For most of the hydrological applications, the orographic effect of vegetation on precipitation can be ignored and it is appropriate to assume that precipitation is independent of vegetation types. However, some studies using General Circulation Models (GCMs) suggest that on a continental scale forests may affect precipitation (Rowntree, 1988; Institute of Hydrology, 1994; Xue, 1997). Evapotranspiration is the second or third largest term in the water balance equation and it is closely linked with vegetation characteristics. In arid and semi-arid regions, evapotranspiration is often nearly equal to precipitation. Surface runoff is also an important component of the water balance and it can be generated when the soil is saturated with water or when rainfall intensity exceeds infiltration capacity. Surface runoff is affected by the presence of vegetation through rainfall interception and evapotranspiration. On an annual basis, surface runoff will generally show good correlation with annual rainfall, particularly in areas with winter dominant rainfall (Budyko, 1974). Recharge is the amount of infiltrated water that reaches a specific groundwater system and it occurs when too much water is available to be used by vegetation or to be stored in the root zone. Recharge is generally the smallest term in the water balance and usually inferred from precipitation and evapotranspiration measurements. The last term in the water balance equation is the change in soil water storage. Over a long period of time (*i.e* 5 to 10 years), it is reasonable to assume that changes in soil water storage are zero. Recharge and change in soil water storage is often only 5 to 10 % of the annual water balance. Therefore, it is expected that a change in annual surface runoff associated with land use changes such as afforestation or deforestation should be reflected in annual evapotranspiration.

2.2 Rainfall interception and evaporation from wet canopies

Rainfall interception by vegetation is an important hydrological process, especially in forested catchments. The intercepted water may be retained on leaves, flow down the plant stems to become stemflow, or drop off the leaves to become part of the throughfall, or be evaporated from wet canopy surface during the period of storm. The sum of stemflow and throughfall is considered to be net rainfall. The difference between gross rainfall and net rainfall is called the interception loss, which is the sum of water stored on canopy surface and evaporation from a wet canopy. Initially much of the rainfall is retained on the canopy surface and there appears to be a well defined storage capacity, which is related to canopy leaf area, leaf configuration (i.e.

surface tension, leaf orientation), and rainfall intensity. Evaporation loss during the storm period may be an important component of the interception process. The relationship can be expressed as following (Horton, 1919)

$$I = S + \alpha t \tag{2}$$

where I is the total interception loss during a storm, S is the canopy storage capacity, α is the rate of evaporation during the storm period, and t is the duration of the storm. From Eq. (2) it is evident that the total interception increases as canopy storage and duration of the storm increase.

Rainfall interception is a complex process and affected by a number of factors such as canopy characteristics and rainfall regime. Detailed studies of interception processes require accurate and frequent measurements. In practice, such data are not always available. However, for most catchment water balance modelling the interception process can be approximated using a simple equation. A recent study has shown that Eq. (2) is reliable for describing interception process (Gash, 1979).

Interception processes affect redistribution of rainfall in the system and there is large variation in interception loss among different vegetation types. A number of experiments have been conducted to estimate the interception characteristics of different vegetation types and these results are summarised in Table 1

It is evident that the proportion of rainfall intercepted by vegetation varies considerably between species. On average, pine forests intercept 28 % of rainfall compared to 14 % for eucalyptus forests based on Table 1. Short grass and crops intercept 20 to 48 % of rainfall during the growing season. However, on an annual basis the percentage is much smaller compared to forests. The interception values shown in Table 1 were obtained under different climate and vegetation conditions. The absolute values may not be accurate and may vary from year to year depending on the nature of rainfall. However, these values are useful for catchment scale water balance modelling.

2.3 Evapotranspiration

Evapotranspiration is an important component of the hydrological cycle and the physics of the process is well understood. There are many equations for calculating evapotranspiration and one of the most commonly used is the Penmen-Monteith equation, which is based on energy balance and aerodynamic transport. The equation also considers the effect of water availability on evapotranspiration through canopy resistance. The Penman-Monteith equation enjoys wide application and can be used to analyse the effect of these controls on evapotranspiration from different vegetation types. For this purpose, we can write the Penman-Monteith equation in the following form

$$ET = \Omega \frac{s}{s+\gamma}(R_n - G) + (1-\Omega)\frac{\rho\, c_p D_m}{\gamma\, r_s} \tag{3}$$

$$\Omega = (\varepsilon + 1) / \left[\varepsilon + 1 + \left(r_s / r_a\right)\right] \tag{4}$$

where Ω is the decoupling coefficient, s is the slope of the saturation vapour pressure curve, γ is the psychometric constant, ε is s/γ, R_n is the net radiation, G is the ground heat flux, ρ is the air density, C_p is the specific heat of air, D_m is the vapour pressure deficit, r_s is the surface resistance, r_a is the aerodynamic resistance, which is a function of roughness length. The first term on the RHS of Eq. (3) represents the available energy for evapotranspiration and is commonly known as the energy term, while the second term represents the effect of turbulent transport on evapotranspiration, known as the aerodynamic term.

The decoupling coefficient indicates the relative importance of the energy term. Jarvis and McNaughton (1986) showed that forest generally has smaller decoupling coefficient than short grass and crops. This implies that forests are very closely coupled to the atmosphere above and that the evapotranspiration rate is thus dominated by the aerodynamic term.

For wet canopies, the rate of evaporation of intercepted rainfall can be a significant component of the catchment water balance. Studies have shown that

Table 1. Interception loss (I) as a percentage of gross annual rainfall (P) for selected vegetation types

Species	I/P (%)	Reference
Acacia aneura	13.0	Pressland (1973)
Acacia harpophylla	15.2	Tunstall (1973)
Aegle maramelos	13.1	Yadav and Mishra (1985)
Agropyron koeleria	22.3	Couturier and Ripley (1973)
Bouteloua curtipendula	18.1	Thurow et al. (1987)
Clover	40.0	Wollny (1890)
Crosotebush	12.2	Tromble (1988)
Digitaria deceumbens	15.5	Acevedo et al. (1993)
Douglas fir	34.1	Aussenac and Boulangeat (1980)
Eucalyptus	8.3	Pook et al. (1991)
Eucalyptus camadldulensis	14.3	Heth and Karschon (1963)
Eucalyptus Regnans	23.3	Langford and O’Shaughnessy (1978)
Eucalyptus Rossii	10.6	Smith (1974)
Eucalyptus Obliqua	15.0	Feller (1981)
Hilaria belangeri	10.8	Thurow et al. (1987)
Maize	29.1	Schmidt and Mueller (1991)
Maize	54.5	Wollny (1890)
Mixed conifer and hardwood	22.0	Moul and Buell (1955)
Montane rain forest	18.2	Veneklaas et al. (1990)
Notjofagus solandri	38.6	Rowe (1975)
Oats	48.3	Schmidt and Mueller (1991)
Oats	20.5	Wollny (1890)
Pinus canariensis	28.0	Kittredge et al (1941)
Pinus elliottii Engelm	38.1	Johansen (1964)
Pinus radiata	26.5	Pook et al. (1991)
Pinus rigida	19.1	Kim and Woo (1988)
Pinus roxburghii	33.5	Dabral and Subba Rao (1968)
Pinus wallichiana	21.0	Singh and Gupta (1987)
Rain forest	8.9	Lloyd et al. (1988)
Rain forest	27.0	Sollins and Drewry (1970)
Shorea robusta	35.4	Ray (1970)
Soya beans	32.0	Wollny (1890)
Sugarbeet	47.3	Schmidt and Mueller (1991)
Tarbush	6.1	Tromble (1988)
Wheat	33.2	Leuning et al. (1994)
Neopanax arboreum scrub	27.0	Wells and Blake (1972)
Cypress	26.0	Pereira (1952)
Bamboo	20.0	Pereira (1952)
Spruce	28.0	Delfs et al. (1958)

evaporation rate from wet forest canopies may be several times higher than that from dry canopies and the energy required can exceed net radiation by a large amount as a result of advection (Monteith, 1965; Rutter, 1967; Stewart, 1977, Calder, 1982). For short grass and crops, wet canopy evaporation exceeds net radiation by only a small amount (McMillan and Burgy, 1960; McIlroy and Angus, 1964; McNaughton and Jarvis, 1983). The difference in wet canopy evaporation between forests and short grass is likely to be a major factor in the water balance of forested and non-forested catchments.

The rate of transpiration from a dry canopy is controlled by net radiation, canopy resistance, vapour pressure deficit, and atmospheric turbulence. The relative transpiration rate (ET/Eo) (i.e. actual to potential) depends only on air temperature and the ratio of surface to aerodynamic resistance (Eq. (3)). Monteith (1965) showed that for short vegetation such as grass and field crops, r_s/r_a is much smaller than for tall vegetation such as forest. *Figure 1* shows the dependence of the relative transpiration rate on canopy resistance. It is clear that for short vegetation even large values of canopy resistance (i.e. 100 s/m) do not reduce the transpiration rate much below the potential evapotranspiration. In contrast, for forests small values of canopy resistance (i.e. 30 s/m) may reduce the transpiration rate well below its potential rate. In other words, forests are more sensitive to changes in canopy resistance than short grass. However, this does not necessarily mean that the transpiration rate of forest is always less than that of grass because trees can access soil moisture from greater depth and maintain a relatively constant transpiration rate even during dry seasons compared to short grass.

In what follows, we will review other factors that affect catchment evapotranspiration.

Surface albedo and Net radiation

Net radiation is the primary source of energy for evapotranspiration, but in some cases the effect of advection can be significant. Net radiation is composed of four components: downwards short-wave radiation from the sun; upward short-wave radiation reflected from the surface; downwards long-wave radiation emitted from the atmosphere; and upward long-wave radiation emitted from the surface.

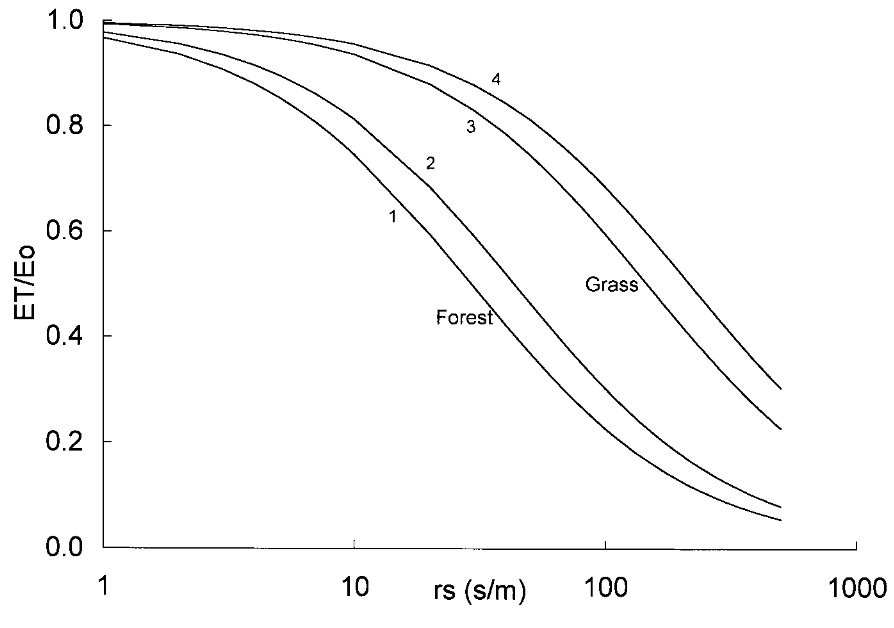

Figure 1: Dependence of the ratio of actual to potential evapotranspiration (ET/Eo) on surface resistance(r_s). Values of aerodynamic resistance r_a was set to 10 and 50 s/m for forest and grass respectively; curve 1 and 3 for air temperature of 25°C; curve 2 and 4 for air temperature of 30 °C.

The downward short-wave radiation is the radiant flux resulting directly from the solar radiation and is independent of surface conditions. The upward short-wave radiation is a significant term in the surface radiation balance and is strongly affected by the reflection coefficient or albedo of the surface. For most short pasture and agricultural crops, albedo is about 0.25. Forests tend to have lower albedo of 0.15 (Brutsaert, 1982, Monteith, and Unsworth, 1992). Representative values of albedo for various vegetation species are listed in Table 2. The difference is mainly because tall vegetation is more able to absorb short-wave radiation by multiple reflections within the canopy.

The downward long-wave radiation is a function of air temperature and water vapour content. The upward long-wave radiation is determined by surface temperature and emissivity. The net long-wave radiation is effectively a small difference between two large numbers and the errors are much less serious than errors in albedo for calculating evapotranspiration.

The foregoing discussion indicates that net radiation is generally higher for forests than for grass and crops mainly because forests have lower albedo values. For example, Moor (1976) found that average net radiation of pine (pinus radiata) forest was 24% higher than that of nearby grassland. Field measurements during the HAPEX-MOBILY experiment showed that net radiation of pine forest was 20% higher than that of crops (Noilhan et al., 1991).

Advection

There is strong evidence to suggest that advection is an important factor in controlling forest evapotranspiration (McNaughton and Black, 1973; Jarvis and Stewart, 1979; McNaughton and Jarvis, 1983; Calder, 1996). When advection occurs dry air is introduced over an area, the vapour pressure deficit will increase and it will cause enhancement of evapotranspiration. When moist air is advectively introduced, it will reduce evapotranspiration. Quantifying the effect of advection on forest evapotranspiration has not been easy because it may occur on different scales and the process is not well understood. The effect of advection on short grass and crops is much less important because they are strongly decoupled from the atmosphere and the rates

Table 2. Representative values of albedo for various vegetation species

Surface	Albedo	Reference
Rain forest	0.15	Lee (1980), Dingman (1994)
Eucaluptus	0.20	Lee (1980), Dingman (1994)
Red pine forest	0.10	Lee (1980), Dingman (1994)
Mixed hardwoods	0.18	Lee (1980), Dingman (1994)
Spruce-fir	0.10	Lee (1980), Dingman (1994)
White-red-jack pine	01.0	Lee (1980), Dingman (1994)
Loblolly-shortleaf pine	0.12	Lee (1980), Dingman (1994)
Longleaf-slash pine	0.12	Lee (1980), Dingman (1994)
Maple-beech-birch	0.19	Lee (1980), Dingman (1994)
Oak-pine	0.15	Lee (1980), Dingman (1994)
Aspen-birch	0.20	Lee (1980), Dingman (1994)
Oak-hickory	0.18	Lee (1980), Dingman (1994)
Grass	0.24	Gates (1980), Monteith and Unsworth (1992)
Barley	0.23	Gates (1980), Monteith and Unsworth (1992)
Wheat	0.26	Gates (1980), Monteith and Unsworth (1992)
Maize	0.22	Gates (1980), Monteith and Unsworth (1992)
Pasture	0.25	Gates (1980), Monteith and Unsworth (1992)
Cotton	0.15	Gates (1980), Monteith and Unsworth (1992)
Sugar cane	0.21	Gates (1980), Monteith and Unsworth (1992)
Tomato	0.23	Gates (1980), Monteith and Unsworth (1992)

of evapotranspiration are more closely controlled by available energy.

Vapour pressure deficit and canopy resistance

It has been recognised that a biological system differs from a physical system in that it can respond to changes in environment and even sense difficult conditions before they have developed (Passioura and Stirzaker, 1993). The biological control on transpiration is often represented by stomatal resistance or canopy resistance. It is known that plant stomata respond to changes in environmental variables such as light, water availability, and temperature. An increase in vapour pressure deficit would increase evapotranspiration which in turn would increase leaf water potential and cause the stomata to close. This is often called the indirect effect or a feedback response (McNaughton and Jarvis, 1983). Plants can also close the stomata at large vapour pressure deficits to prevent high rates of evapotranspiration before there has been any reduction in leaf water potential. This represents a feedforward response or direct effect of vapour pressure deficit on evapotranspiration. It is possible that both responses exist in majority of plants and the net effect of vapour pressure deficit on evapotranspiration depends on which process is dominant. Several studies have suggested that sensitivity of the response varies with plant species and environmental conditions (McNaughton and Jarivs, 1983). For example, Schultze and Kuppers (1979) showed that transpiration from hazel plants increases with increasing relative vapour pressure deficit and it starts to decrease when relative vapour pressure deficit exceeds 25 mbar/bar. In other studies, it has been reported that transpiration rate is independent of vapour pressure deficit (Tan and Black, 1976; Kaufman, 1979), arguing that trees respond more to energy than to vapor pressure deficits.

Forests are strongly coupled to the atmosphere above and are aerodynamically efficient in turbulent transport. As a result, transpiration from forests is chiefly controlled by the vapour pressure deficit and canopy resistance. For short grass and crops, evapotranspiration is determined principally by net radiation and the effect of canopy resistance is relatively small.

The forgoing discussion indicates that vapour pressure deficit and canopy resistance will have significant effects on forest evapotranspiration. It is clear that the cause of change in stomatal closure is a change in leaf water potential, but the interactions and feedback between plants and external variables is complex and there is no appropriate framework available for analysing these processes.

Roughness length and turbulent transport

Turbulent transport is the primary process responsible for the exchange of water vapour between the surface and the atmosphere. While much of the turbulence in the atmosphere is produced by the frictional retardation of wind blowing horizontally over a surface, the intensities of the turbulence are also affected by temperature gradients. The effectiveness of turbulent transport can be deduced from wind speed and a knowledge of surface roughness. One way of describing turbulent transport is to use aerodynamic resistance given by

$$r_a = \{\ln\left(\frac{z-d}{z_o}\right) - \Psi\}^2 / (k^2 u) \qquad (5)$$

where z is the reference height, d is the zero displacement height, z_o is the roughness length of the surface, Ψ is the stability function, k is the von Karman constant, and u is the wind speed. Under neutral conditions (i.e. no vertical temperature gradient), the aerodynamic resistance is a function of roughness length and wind speed. For short grass, the roughness length is about 0.01 m, while for forests it is in the order of 1.0 m. If we assume a constant wind speed of 2 m s^{-1}, the corresponding aerodynamic resistance varies between 75 to 5 s m^{-1}. For relatively wet canopies, evapotranspiration occurs freely from the surface and it is mainly controlled by the degree of turbulence in the atmosphere. Zhang and Dawes (1995) found that under this condition the aerodynamic resistance can affect evaporation significantly and increasing aerodynamic resistance from 10 to 70 s m^{-1} could lead to 40 % reduction in evaporation. However, the effect of turbulent transport on evapotranspiration becomes less important when canopies are dry. Webb (1975) studied the effect of the aerodynamic resistance on evapotranspiration under neutral and non-neutral conditions. He showed that evapotranspiration rate from forests is higher than that from grass even under unstable atmospheric conditions.

Leaf area

The amount of water that a plant transpires is related to its leaf area. Leaf area affects interception of rainfall, radiation, and defines the canopy area available for evapotranspiration. In dryland agriculture, total water use by any plants depends primarily on the temporal distribution of active green leaf area and rainfall. When active green leaf area and rainfall are in phase, plants are likely to use more water and develop larger leaf area. However, when they are out of phase, part of rainfall will be stored in the soil and the ability of the plants to explore this water is limited by rooting depth. The period of evapotranspiration from annual plants is restricted to the growing season and hence annual plants are unable to use rain that falls outside the growing season. Perennial plants generally use more water than annuals because they keep their leaves green and actively transpire for much longer.

When available water is not limiting, the ratio of actual to potential evapotranspiration for crops and pastures increases exponentially with its leaf area index until canopy closure occurs (Ritchie and Burnett, 1971; Choudhury and Monteith, 1988; Choudhury et al., 1994). The relationship resembles Beer's Law for radiation partitioning and it suggests that the available energy is the controlling factor under this condition. A number of studies also reported that total annual evapotranspiration from forests is similarly related to leaf area index (Greenwood et al. 1982; Dunin and MacKay, 1982). Specht and Specht (1989) studied relationships between evaporative coefficient and leaf area index for evergreen Eucalyptus dominated open-forest/woodland communities under different climatic zones. They found that the evaporative coefficient increases exponentially with leaf area index (Fig. 2). The evaporative coefficient indicates the rate of change of actual evapotranspiration per unit change in available water. A high value of the evaporative coefficient usually means low canopy resistance to water movement through the plant, and therefore more transpiration. Wullschleger et al (1998) reviewed 52 published studies on tree water use using different techniques and also showed that tree water use increases with leaf area. Under relatively dry conditions, the same relationships are expected, with the asymptote a result of limited water supply.

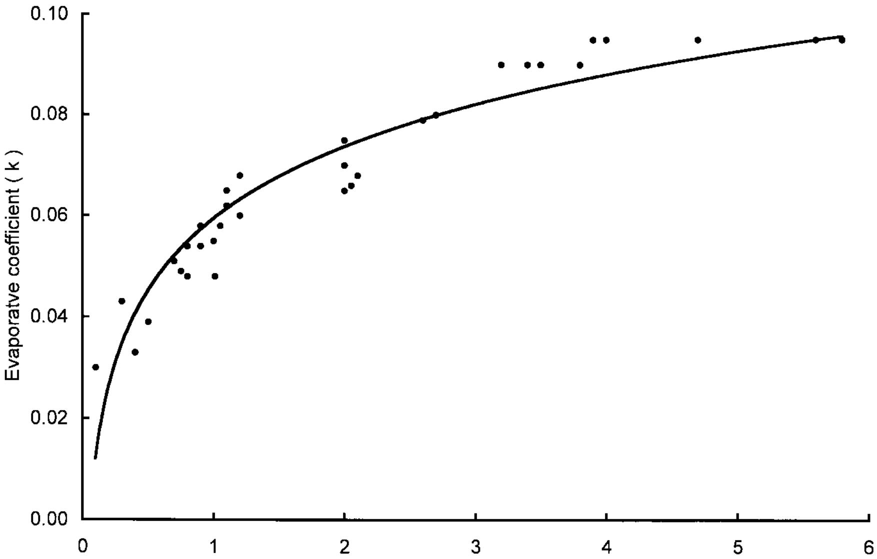

Figure. 2: Relationship between leaf area index of the overstorey of mature climax plant communities and the evaporative coefficient (adapted from Specht and Specht, 1989)

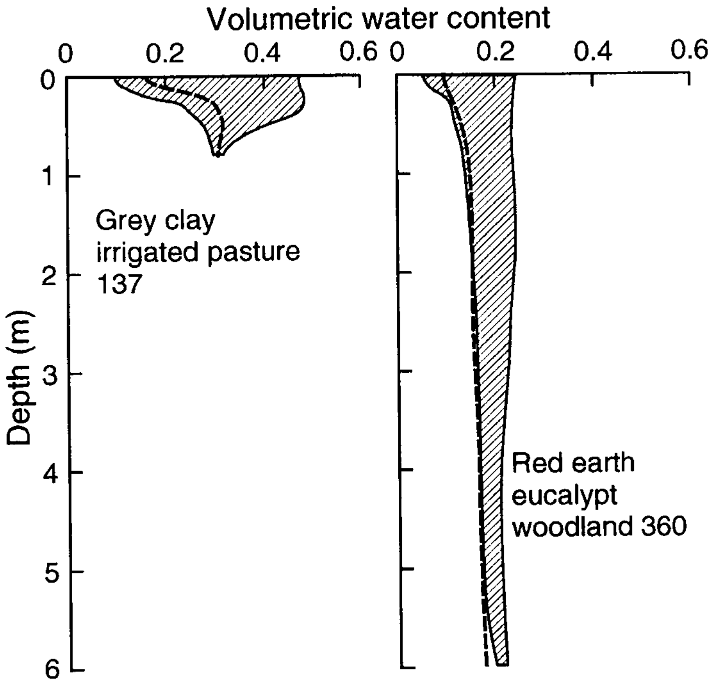

Figure. 3: Typical soil moisture profiles and plant available water capacity for two soil types under different plants (adapted from Greacen and Williams, 1983). Solid lines represent upper and lower limits of the soil water store. Numbers on figure refer to stored water expressed in mm.

Rooting depth and Plant available water capacity

Deep roots are ecologically significant in terms of water and carbon fluxes. During wet seasons, plants extract most water from shallow layers where the root density is the highest. As the soil dries progressively, more water is extracted from deeper layers to keep stomata open. Rooting depth determines the soil volume which plantsf are able to draw water from and together with soil hydraulic properties, it defines the plant available water capacity.

Tennant (1976) showed that the plant available water of wheat in five different soils depended more on the rooting depth than it did on the soil hydraulic properties. The depth and distribution of plant roots is affected by a number of factors such as physical barriers, chemical barriers, and nutrient distribution. When soil physical properties such as porosity, pore sizes, strength, and root channels are unfavourable to water and oxygen supply, plant growth can be severely limited. Canadell et al.(1996) showed that average maximum rooting depth was about 7 m for trees, and 2.6 m for herbaceous plants. Such a difference in average maximum rooting depth will translate into 540 mm difference in plant available water for sandy soils, and up to three times this amount for loamy and clayey soils. Therefore, it is expected that rooting depth will contribute to differences in evapotranspiration between forests and herbaceous plants.

Greacen and Williams (1983) reported the plant available water for some important Australian soils. For example, in a deep red earth under eucalypt woodland, the plant available water was about 360 mm, although its water holding capacity was relatively low (Fig. 3). On the other hand, for a grey clay under irrigated pasture, the profile was relatively shallow but with high water holding capacity, the plant available water was only 137 mm. As shown in Fig. 3, deep-rooted plants (i.e. trees) generally have larger storage capacity compared to shallow-rooted plants (i.e. short grass and crops). The differences in both magnitude of the plant available water and its profile water store will affect plant transpiration.

When available energy is not limiting, the amount of water plants can transpire is determined by plant available water in the soil profile. Hodnett et al. (1995) showed that during wet seasons evapotranspiration of a terra firme type forest was very similar to that of pasture (Brachiaria decumbens) in Central Amazonia and the soil moisture under the two vegetation types showed little difference. However, in the dry seasons the forest sustained a higher evapotranspiration rate compared to the pasture and the difference was attributed to the ability of the trees to access soil moisture from greater depth. Nepstad et al. (1994) found that soil water stored below 2 m provided over 75% of total water extracted from the entire soil profile. This indicates that deep roots play an important role in plant water uptake.

In summary, catchment evapotranspiration is a complex process and it is affected by rainfall interception, net radiation, advection, turbulent transport, canopy resistance, leaf area, and plant available water capacity. Under dry conditions, the principal controls on evapotranspiration are plant available water capacity and canopy resistance, and actual evapotranspiration is only a small fraction of the potential evapotranspiration. Under wet conditions, the dominant controls are advection, net radiation, leaf area, and turbulent transport. Under intermediate conditions, the relative importance of these factors is likely to vary depending on climate, soil, and vegetation. The challenge in modelling catchment scale evapotranspiration is to be able to represent these processes and factors in a simple fashion allowing practical prediction of the effect of vegetation changes on evapotranspiration.

3 Development of a Simple Water Balance Model

3.1 Data description

As stated earlier, the data used in this report were obtained from two sources: *catchment water balance studies* and *paired-catchment studies*. There are some noticeable differences between these two types of studies. The catchment water balance studies focused on relationships between rainfall, runoff, and evapotranspiration. These are generally large catchments with good quality rainfall and runoff data over a long period of time. However, information on vegetation type and cover is not ideal for our purpose, but it provides value. The paired-catchment studies generally involved small catchments (< 100 km^2) and the main objective was to detect changes in catchment water yield (i.e. precipitation minus evapotranspiration) after afforestation or deforestation. There is detailed information available on vegetation type and cover from these studies. In order to be able to draw some general conclusions about the impact of vegetation on catchment water balance from these studies, we selected catchments with the following characteristics:

- *Rainfall is the dominant form of precipitation in the catchments*
- *Slopes of the catchments are gentle*
- *Soil depth is relatively thick (> 2m)*

Given that detailed information on vegetation is not available for all the catchments concerned, especially large catchments, we will use the following terms to describe vegetation types:

- *Herbaceous plants*
- *Mixture of herbaceous plants and trees*
- *Forest (> 70 % of canopy cover)*

Most of the catchments used in this study have long records of annual rainfall and streamflow data, from which we were able to obtain average annual evapotranspiration by assuming zero soil water storage change. In a few catchments, evapotranspiration was measured directly (see Appendix A). The size of the catchments varied from less than 1 km^2 to 600,000 km^2. These catchments span a variety of climates including tropical, dry, and warm temperate. Mean annual rainfall in these catchments varied from 35 mm to 2978 mm and the seasonal distribution was variable. For examples, Calder et al. (1986) described the Janlappa catchment of Indonesia as a wet tropical rain forest catchment with mean annual rainfall of 2851 mm. Ni-Lar-Win (1994) reported some sub-tropical catchments in China with over 80% of annual rainfall occurring between April and September. This is in contrast to the catchments reported by Silberstein et al (1999) with warm Mediterranean climates in Western Australia. Jolly et al (1997) showed catchments from the Murray-Darling Basin in eastern Australia, with mainly uniform and summer-dominant rainfall patterns with mean annual rainfall of between 450 and 1150 mm. Farquharson et al (1996) studied catchments in Yemen under extremely dry climate.

The vegetation ranges from even-aged plantations to native woodlands, open forests, rainforest, eucalyptus, various species of pine trees and conifers, through to native and managed grassland and agricultural cropping. Soil descriptions were not routinely included in the reviewed papers, since for catchment studies the problem of spatial variation can make a simple descriptor misleading. The sheer variation in geographical location and climatic regime in the data however, must cover most of the spectrum of soil types, from sand, through loams to clays.

3.2 Simple water balance model

In the previous sections, we reviewed the key processes and factors associated with catchment water balance, particularly evapotranspiration. It is a common practice to combine these factors by considering their net effects. One way of approaching catchment evapotranspiration is to assume that evapotranspiration from land surfaces is controlled by water availability and the atmospheric demand. The water availability can be approximated by precipitation, the atmospheric demand represents the maximum possible evapotranspiration and is often considered as potential evapotranspiration. Under very dry conditions, potential evapotranspiration exceeds precipitation and the actual evapotranspiration will be equal to precipitation.

Under very wet conditions, water availability exceeds potential evapotranspiration and actual evapotranspiration will asymptotically approach the potential evapotranspiration. Based on these considerations, Budyko (1974) postulated that the following relationships are valid under very dry conditions

$$\frac{R}{P} \to 0 \quad or \quad \frac{ET}{P} \to 1 \quad when\, \frac{R_n}{P} \to \infty \tag{6}$$

where R is surface runoff, P is precipitation, ET is evapotranspiration, R_n is net radiation, and under very moist conditions

$$ET \to R_n \qquad when\, \frac{R_n}{P} \to 0 \tag{7}$$

These two limits are represented by BC and AB in *Fig. 4*. It should be noted that Budyko (1974) used net radiation (R_n) to represent potential evapotranspiration and in what follows we will use potential evapotranspiration (E_0) instead of net radiation (R_n).

The dimensionless function (F) that satisfies condition (6) and (7) must take the following form

$$\frac{ET}{P} = F\left(\frac{E_o}{P}\right) \tag{8}$$

As stated earlier, the plant available water capacity plays an important role in maintaining transpiration during dry seasons. A number of studies have shown that it is primarily responsible for greater transpiration rate from forests compared to pasture and crops (Tuner, 1991, Hodnett *et al.*, 1995). It is clear that the largest difference in transpiration will be in the plant available water capacity because of large differences in rooting depth. Milly (1994) hypothesized that the long-term water balance is determined by the local interaction of fluctuating water supply and demand, mediated by water storage in the soil. For the purpose of predicting the effect of vegetation changes on evapotranspiration, we introduced a second factor to represent plant available water capacity. This relationship can be expressed in dimensionless form as

$$\frac{ET}{P} = F\left(\frac{E_o}{P}, w\right) \tag{9}$$

It can be shown that the following equation satisfies conditions (6) and (7)

$$\frac{ET}{P} = \frac{1 + w\frac{E_o}{P}}{1 + w\frac{E_o}{P} + \left(\frac{E_o}{P}\right)^{-1}} \tag{10}$$

where w is the plant available water coefficient.

It should be pointed out that Eq. (10) is a semi-empirical relationship and the plant available water coefficient (w) and potential evapotranspiration (E_0) can be considered as model parameters. The plant available water coefficient represents the ability of plants to store water in the root zone for transpiration. We posit that it should vary between 0.5 to 2.0 for plants and larger values of the plant available water coefficient tend to promote evapotranspiration. For forests, the value was found to be close to 2.0, while for short grass and crops the value was close to 0.5. For bare soil, the plant available water coefficient simply represents the relative water stored in the soil that can be evaporated directly from the surface. It is expected that the value of w is close to 0.1. The sensitivity of the ratio of mean annual evapotranspiration to rainfall with respect to the plant available water coefficient is shown in *Fig. 4*. The effect of the plant available water coefficient on evapotranspiration is minimal under both very dry and very wet conditions. The reason that the plant systems become insensitive to changes in water storage is due to the fact that under these two extreme conditions evapotranspiration is dominated by rainfall and available energy. The maximum difference in the ratio of evapotranspiration to rainfall between trees and herbaceous plants occurs when annual rainfall equals to the atmospheric demand (i.e E_0/P =1.0). Under this condition, the ability of trees to exploit a greater depth in soils allows them to use water that has been stored during the times they are least active, while shallower rooted herbaceous plants may allow that water to escape their root zone.

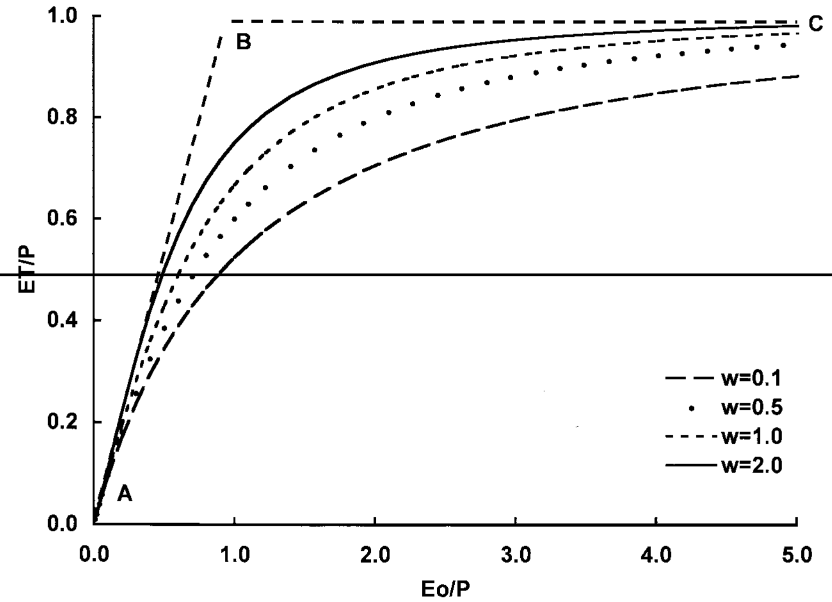

Figure. 4: Ratio of mean annual evapotranspiration to rainfall as a function of the index of dryness (E_o/P) for different values of plant available water coefficient (*w*).

A number of relationships have been developed based on the assumption that evapotranspiration is limited by available water (i.e. rainfall) under very dry conditions and available energy (i.e. potential evaporation) under very wet conditions. A list of these equations is given in Table 3. A comparison of these relationships with Eq. (10) is shown in *Fig. 5*. It is clear that Eq. (10) is in good agreement with these empirical relationships. With the plant available water coefficient set to 1.0, Eq. (10) yielded better agreements with these curves.

Despite its semi-empirical nature, the functional form of Eq. (10) was found to be in good agreement with the data listed in Appendix A and shown in *Fig. 6*. The mean absolute error (MAE) in the ratio of evapotranspiration to rainfall (ET/P) between observation and Eq. (10) is 6%, and the root mean square error (RMSE) is 8%. In this comparison, the plant available water coefficient (w) was set to 2.0 for forest, 1.0 for mixed vegetation, and 0.5 for pasture. The potential evapotranspiration (E_0) was calculated using the equation of Priestley and Taylor (1972). An attempt was made by Milly (1994) to develop a theoretical model which incorporates soil water storage, rainfall seasonality, and other factors. For a mid-latitude location and assuming an exponential distribution of soil water storage, his model yielded similar results as Eq. (10) (see *Fig. 6*).

Equation (10) is a dimensionless function and it can be used to calculate actual evapotranspiration when rainfall and potential evapotranspiration are known. A comparison of observed and calculated evapotranspiration from Eq. (10) is shown in *Fig. 7*. The mean absolute error (MAE) between the model estimates and measurements is 27 mm or 4.0 %. The correlation coefficient is 0.92 and the best-fit slope through the origin is 1.04.

Table 3. Description of different relationships for estimating annual evapotranspiration

Equation	Symbol	Reference
$ET = P[1-\exp(-E_0/P)]$	*ET* is annual evapotranspiration; *P* is annual rainfall, E_0 is potential evaporation	Schreiber (1904)
$ET = P/[1+(P/E_0)^2]^{0.5}$	As above	Pike (1964)
$ET=[P\,(1-\exp(-E_0/P))\,E_0 \tanh(P/E_0)]^{0.5}$	As above	Budyko (1974)

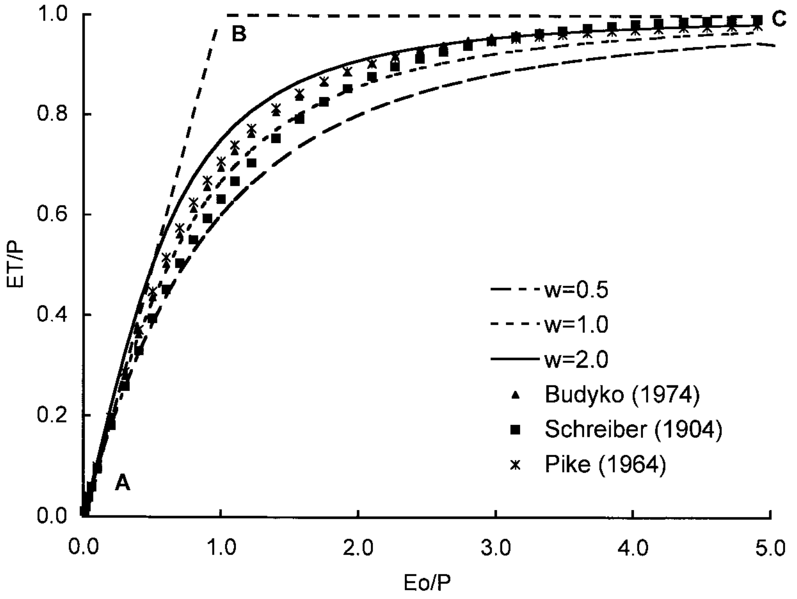

Figure. 5: Comparison of Eq. (10) with the relationships developed by Schreiber (1904), Pike (1964), and Budyko (1974).

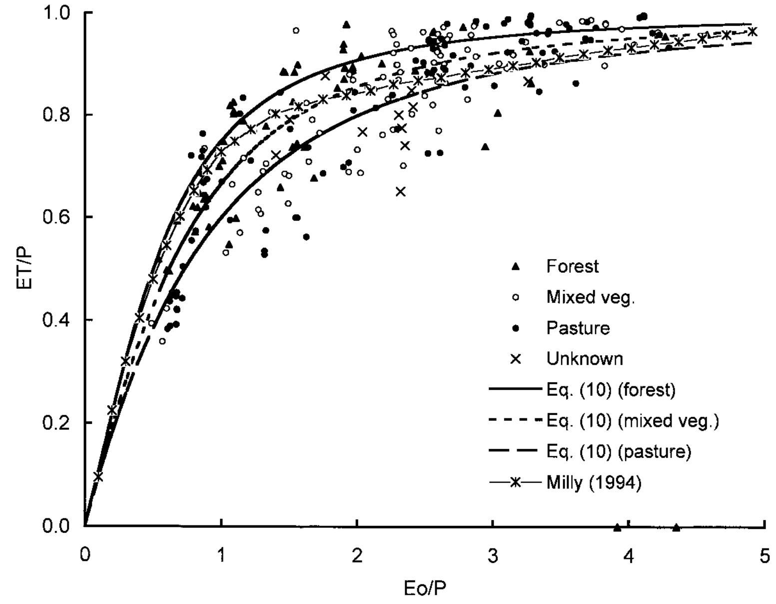

Figure. 6: Comparison of Eq. (10) with measurements for catchments with different vegetation covers. Also shown is curve of Milly (1994).

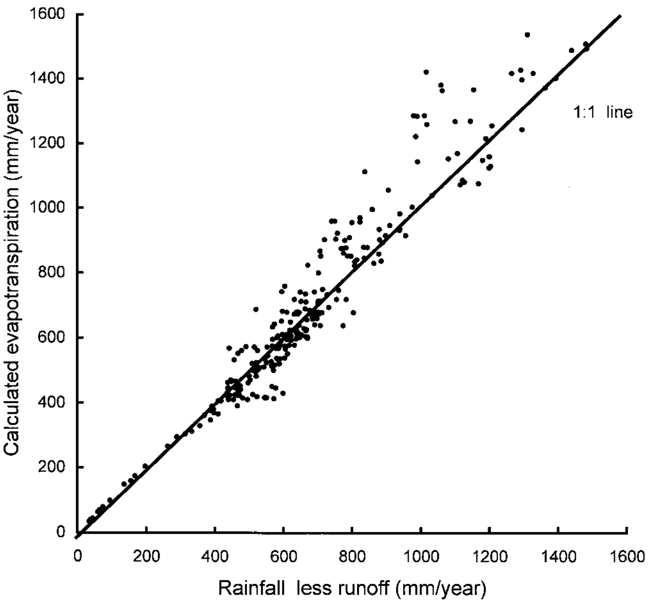

Figure. 7: Scatter plot of the observed and calculated evapotranspiration for the catchments listed in *Appendix A.*

Base on the previous discussion, a simple catchment scale water balance model is proposed. It is assumed that annual evapotranspiration from a catchment is the sum of the annual evapotranspiration from herbaceous vegetation (including soil evaporation) and that from forest weighted linearly according to their areas (Eagleson, 1982). The general equation can be expressed as

$$ET = f\,ET_f + (1 - f)ET_h \tag{11}$$

where ET is the total annual evapotranspiration in mm, f is the forest cover, ET_f is the annual evapotranspiration from forests in mm; and ET_h is the annual evapotranspiration from herbaceous plants in mm.

Holmes and Sinclair (1986) studied 103 catchments within Victoria, Australia, with varying mixture of grass and native eucalypt forest cover. They found that there were clear differences between evapotranspiration rates for forested and grassland catchments along a rainfall gradient. Turner (1991) reported similar relationships based on a study of 68 catchments in California, U. S. A. These relationships suggest that mean annual evapotranspiration rates are greater for forested than for non-forested catchments and there is a strong relationship between evapotranspiration and rainfall.

As demonstrated earlier, Eq. (10) is a useful framework for estimating annual evapotranspiration. It requires estimates of potential evaporation (E_o) and plant available water coefficient (w) for each catchment. Inspired by the work of Holmes and Sinclair (1986), and Turner (1991), we developed parameters for Eq. (10) for forested and cleared catchments, so that average evapotranspiration could be estimated from average annual rainfall. We replaced E_o in Eq. (10) with a constant (E_z), which was obtained by a least-squares fit based on the data listed in *Appendix A*. *Figure 8a* shows the fitted function for trees, which has r^2 0.93, RMSE 93 mm, E_z 1410 mm and w of 2.0. *Figure 8b* shows the fitted function for herbaceous plants, which has r^2 0.90, RMSE 75 mm, E_z 1100 mm and w of 0.5. Using fixed parameters rather than allowing them to vary by catchment greatly reduces the data requirements and facilitates automated implementation of the model within GIS and other model frameworks (e.g. Zhang *et al* 1997, Vertessy and Bessard, 1999). The simplified form of Eq. (11) can be expressed as:

$$ET = \left[f \frac{1 + 2 \times \frac{1410}{P}}{1 + 2 \times \frac{1410}{P} + \frac{P}{1410}} + (1 - f)\frac{1 + 0.5 \times \frac{1100}{P}}{1 + 0.5 \times \frac{1100}{P} + \frac{P}{1100}} \right] P \tag{12}$$

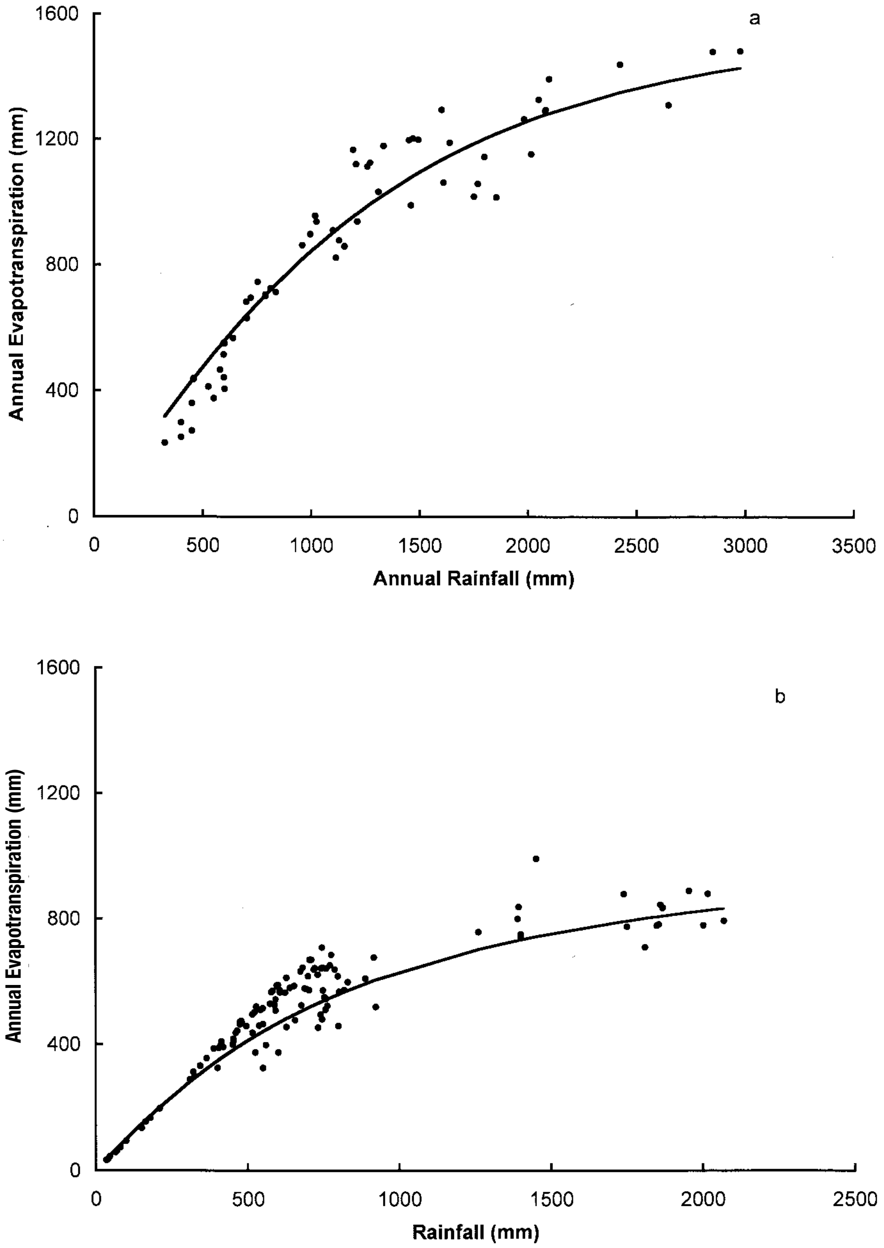

Figure. 8: Scatter plots of the least-squares fit for (a) forested and (b) grassed catchments.

A comparison of our simplified Eq. (10) with the curves described by Holmes and Sinclair (1986) and Turner (1991) is shown in *Fig. 9.* Over the range 500 to 1500 mm of annual rainfall, these curves are all very similar. As stated earlier, the data listed in *Appendix A* represent varying mixtures of grass and forest cover. A scatter plot of these data with the simplified Eq. (10) is shown in *Fig. 10.* It is clear that most of the forested catchments plotted around the upper curve and grassed catchments around the lower curve with mixed vegetation catchments in the middle.

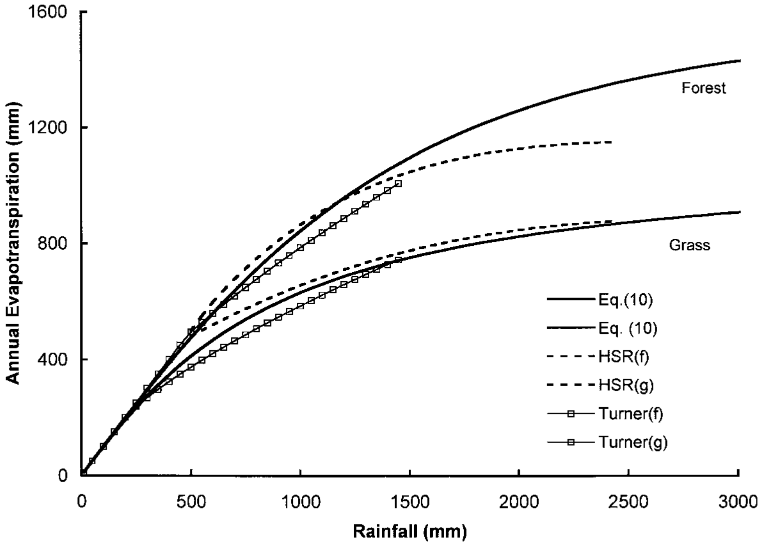

Figure. 9: Comparison of simplified Eq. (10) with the empirical relationships developed by Holmes and Sinclair (1986), Turner (1991) for forested and grassed catchments.

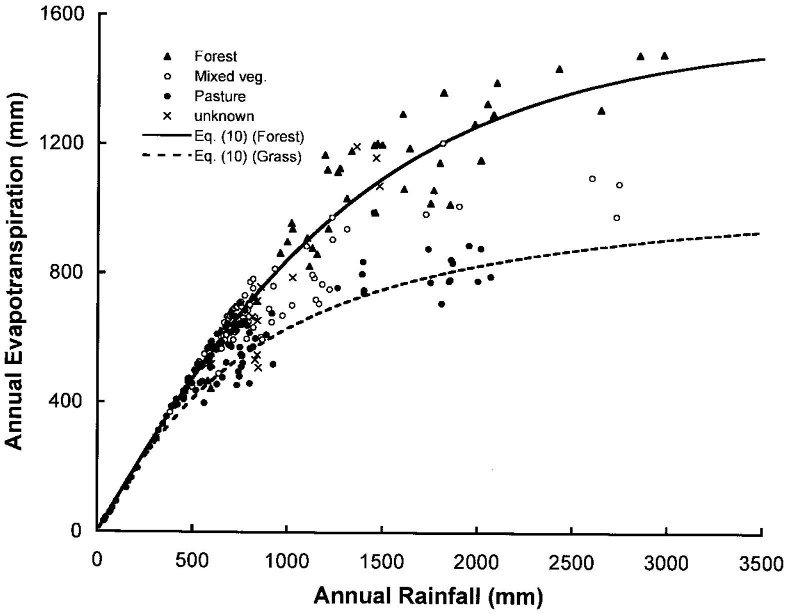

Fig. 10. Relationship between annual evapotranspiration and rainfall for different vegetation types

4 Discussion

Evapotranspiration is a complex process and is closely associated with characteristics of vegetation. It has been shown that evapotranspiration is affected by interception of rainfall and energy, advection, turbulent transport, canopy resistance, leaf area, and plant available water capacity. This list is not complete and within a catchment, the spatial distribution of these factors and topographic effects such as slope and aspect, will affect total evapotranspiration. It is fair to say that we have a good understanding of individual processes and factors involved in catchment-scale evapotranspiration. Under very dry conditions, evapotranspiration is controlled by available water (i.e. rainfall and plant available water), while under wet conditions it is controlled mainly by available energy (i.e. net radiation and advection). In most cases, actual evapotranspiration occurs between these two limits, and the relative importance of the factors varies depending on the specific climate, soil, and vegetation conditions.

Rainfall interception varies considerably between species and on average forests intercept more rainfall than grass and crops. The difference in rainfall interception between forests and short grass has important implications for catchment water balance because most of the intercepted rainfall is evaporated directly into the atmosphere. Turbulent transport above forest canopies is very efficient and the wet canopy evaporation rate may be several times higher than dry canopy transpiration rate (Monteith, 1965; Rutter, 1967; Stewart, 1977). The energy used can exceed net radiation and this additional energy is introduced by advection. Forests are generally very closely coupled to the atmosphere, and the evapotranspiration rate is dominated by turbulent transport, whereas short grass and crops are poorly coupled to the atmosphere and the evapotranspiration is controlled by net radiation. For short grass and crops, wet canopy evaporation exceeds dry canopy transpiration by only a small amount (McMillan and Burgy, 1960; McIlroy and Angus, 1964; McNaughton and Jarvis, 1983).

Plant available water capacity may have a significant impact on evapotranspiration under dry conditions. Trees generally have much larger available water capacity than herbaceous plants. As a result, trees are able to maintain relatively constant evapotranspiration rate over time, even when soil moisture in the upper part of the soil is limited. Under such conditions, shallow-rooted plants tend to close their stomata and show reduced evapotranspiration rate. In regions with dry climates, plant available water capacity is expected to be a main reason for differences in annual evapotranspiration between trees and shallow-rooted plants. Calder (1998) showed that evapotranspiration in semi-arid areas is limited principally by plant available water, whereas in the wet uplands of the UK, evapotranspiration is limited principally by radiation and advection.

Many models that incorporate all these factors and the detailed processes and feedbacks have been developed, e.g. WAVES (Dawes and Short, 1993; Zhang et al., 1996), SCAM (Raupach, 1997), SiB (Sellers et al., 1986). These model are useful in exploring sensitivity of the system. However, they may have little practical value for catchment studies because the interactions and feedbacks between processes are not yet fully understood, and the data required to calibrate and run them are not available. An alternative is to use the "top-down" approach to establish long-term equilibrium relationships for catchment water balance and this can be regarded as a preliminary step to simulating the dynamic relationships of the water balance. The advantage of this approach is that it is practical, robust and much less data intensive than a fully deterministic modelling approach.

In spite of the complexity in the soil-vegetation-atmosphere system, the most important factors controlling mean annual evapotranspiration appear to be annual rainfall and vegetation type. A number of studies have shown that mean annual evapotranspiration is strongly correlated with mean annual rainfall, proposing theoretical and empirical functions that predict the proportion of rainfall that is evaporated (Schreiber, 1904; Pike, 1964; Budyko, 1974). Holmes and Sinclair (1986) and Turner (1991) each differentiated between trees and grass as the major vegetation cover within a catchment. A simple model framework has been proposed for estimating mean annual evapotranspiration based on rainfall, potential evaporation, and a plant available water coefficient (Eq. 10). Further a simplified version for direct application has been developed where only annual rainfall and two vegetation-based constants are required (Eq. 12). The model describes long-term average behaviour of catchment water balance, and it is not designed for exploring inter- or intra-annual variability. Milly (1994) showed that the spatial distribution of soil water storage capacity and temporal rainfall pattern can affect catchment evapotranspiration, but over a wide range of climatic zones this is a second order effect.

The proposed model showed good agreement with the empirical relationships developed by Schreiber (1904), Pike (1964), and Budyko (1974). The model also compared well with observations for over 250 catchments worldwide, with different climates. The mean absolute error (MAD) in the ratio of evapotranspiration to rainfall between the model and field data was 6 %, and the root mean squared error (RMSE) was 8 %. The mean absolute error (MAE) between modelled and measured evapotranspiration was 27 mm or 4.0 %, the least-squares line through the origin had a slope of 1.04 and a correlation coefficient of 0.92. It is clear from *Fig. 6* that a single curve can not explain all the variability among the data. The uncertainties associated with rainfall and potential evapotranspiration estimates must contribute to the scatter.

For the simplified version, both the rainfall scalar and plant available water coefficient were set to constant values for each vegetation type. Theoretically, w should be estimated from rooting depth and soil water holding properties, however these values were obtained by inspection of the data and an understanding of the relativity between vegetation types. E_z was obtained by a least-squares fit to the actual data with the chosen w. For forest catchments, E_z = 1410 mm and w = 2.0, and for grassed catchments E_z = 1100 mm and w = 0.5. It should be noted that the use of a constant E_z in Eq. (12) is to simplify the model, and it cannot be interpreted as potential evaporation in the traditional sense.

For a given amount of annual rainfall, total evapotranspiration from forested catchments is greater than for non-forested catchments. The difference is larger in high rainfall areas and it diminishes in areas with annual rainfall less than 500 mm. This implies that tree plantations in low rainfall areas are not likely to alter the water balance very much and hence control the amount of non-transpired water (i.e the difference between rainfall and evapotranspiration). It should also be noted that the relative errors associated with these relationships are larger in low rainfall areas. Petheram *et al* (1999) investigated the relationship between non-transpired water and recharge in environments suffering dryland salinity, and introduced a factor for soil texture to partition non-transpired water into runoff and recharge.

From *Fig. 10* it is clear that catchments with mixed cover have annual evapotranspiration between that observed for fully forested and fully cleared catchments, therefore we can use the two curves as an envelope. It can be assumed that mean annual evapotranspiration is a linear function of tree cover (Vertessy and Bessard, 1999) and this may introduce errors in catchments with mixed cover type in high rainfall zones. Sahin and Hall (1996) showed that the effect of tree cover is likely to be a non-linear function and there exists thresholds below which no changes in evapotranspiration could be observed (Turner, 1991). Eq. (12) provides a catchment approach for estimating the order of magnitude of the changes in mean annual evapotranspiration that result from changes in catchment vegetation, although any function of forested area can replace the factor f. The advantage of this model is its simplicity and it requires only mean annual rainfall and fraction of forest cover, and can be used to evaluate the impact of vegetation changes on catchment water balance.

5 Conclusions

Annual evapotranspiration is generally greater for forested than for non-forested catchments and tree plantations will increase catchment evapotranspiration compared with pastures or crops. This has implications for catchment water balance in terms of multiple-purpose land use management and rehabilitation strategies. The amount of annual evapotranspiration in a catchment is determined by the interaction of supply of water (total rainfall) and atmospheric demand (potential evapotranspiration), balanced by plants. From both a theoretical and empirical viewpoint, the most important factors in determining annual evapotranspiration are the amount of annual rainfall, potential evapotranspiration, and the plant available water capacity. As a corollary, a model can be developed to estimate mean annual evapotranspiration with only two parameters. Since this is based on, and constrained by, observations, we expect the relationship to be both robust and scientifically justifiable. The model has advantages over more traditional process-based models, requiring little data and being very easy to apply to either an individual catchment or in a spatial modelling framework. The model developed is consistent with previous theoretical work and showed good agreement with over 250 catchment-scale measurements from around the world. This model is a practical tool that can be readily used to predict the consequences of reforestation, and has potential uses in many catchment-scale vegetation management studies.

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Appendix A: A summary of worldwide catchment water balance studies. Annual rainfall (P), runoff (Q), and evapotranspiration (ET) are average values.

Catchment	Area (km^2)	Vegetation cover	Years	P (mm)	Q (mm)	ET (mm)	References
Australia							
Adelong Creek	155	Mixed vegetation	1985-1994	913	264	649	Jolly et al (1997)
Adjungbilly Creek	411	Mixed vegetation	1985-1994	959	96	863	Jolly et al (1997)
Avoca	4740	Mixed vegetation	1985-1994	380	11	369	Jolly et al (1997)
Axe Creek	325	Mixed vegetation	1985-1994	593	48	545	Jolly et al (1997)
Axe Creek 33	100	Pasture, crops	1990-1994	588	62	526	Jolly et al (1997)
Barwon	132200	Pasture, crops	1985-1994	598	9	589	Jolly et al (1997)
Bet Bet Creek	635	Mixed vegetation	1991-1994	565	45	520	Jolly et al (1997)
Bet Bet Creek 39	225	Pasture, crops	1991-1994	606	41	565	Jolly et al (1997)
Billabong Creek26	3065	Mixed vegetation	1985-1994	661	55	606	Jolly et al (1997)
Billabong Creek27	27500	Mixed vegetation	1985-1992	451	16	435	Jolly et al (1997)
Bogan	14760	Pasture, crops	1985-1994	509	9	500	Jolly et al (1997)
Border	44070	Pasture	1985-1994	599	10	589	Jolly et al (1997)
Broken	24530	Mixed vegetation	1988-1994	798	95	701	Jolly et al (1997)
Bullock Creek	225	Pasture, crops	1991-1992	537	77	460	Jolly et al (1997)
Campaspe31	3398	Mixed vegetation	1988-1994	655	65	590	Jolly et al (1997)
Campaspe32	629	Pasture, crops	1985-1994	786	148	638	Jolly et al (1997)
Castlereagh	3600	Forests	1985-1994	701	18	683	Jolly et al (1997)
Castlereagh13	8400	Pasture, crops	1987-1994	627	15	612	Jolly et al (1997)
Coliban	225	Pasture, crops	1985-1993	922	161	761	Jolly et al (1997)
Condamine-Culgoa	156575	Pasture, crops	1985-1993	478	3	475	Jolly et al (1997)
Coxes Creek	4040	Pasture, crops	1985-1989	682	16	666	Jolly et al (1997)
Crabapple	0.147	Eucalypt	4 years	1639	449	1190	Cornish (1993)
Creswick Creek	225	Mixed vegetation	1985-1994	722	104	618	Jolly et al (1997)
Cungegong	3490	Mixed vegetation	1985-1994	687	28	659	Jolly et al (1997)
Darling28	386000	Mixed vegetation	1985-1994	524	6	518	Jolly et al (1997)
Darling29	569800	Pasture, crops	1985-1994	474	3	471	Jolly et al (1997)
Darling30	647200	Pasture, crops	1985-1994	474	2	472	Jolly et al (1997)
Dumaresq	8850	Pasture	1985-1994	746	43	703	Jolly et al (1997)
Goodradigbee	1165	Forests	1985-1994	1212	273	939	Jolly et al (1997)
Graceburn	25	Eucalyptus forest	Long term	1460	850	610	Langford (1976)
Gwyder 1	6389	Pasture	1985-1994	753	56	697	Jolly et al (1997)
Gwyder2	12300	Pasture	1985-1994	709	40	669	Jolly et al (1997)
Joyces Creek	225	Mixed vegetation	1989-1995	647	43	604	Jolly et al (1997)
Jugiong Creek	2120	Pasture	1985-1994	694	66	628	Jolly et al (1997)
Kiewa	1655	Mixed vegetation	1985-1994	1162	455	707	Jolly et al (1997)
Lachlan15	19000	Pasture, crops	1985-1994	717	79	638	Jolly et al (1997)
Lachlan14	11100	Pasture, crops	1985-1994	746	101	703	Jolly et al (1997)
Lachlan16	25200	Pasture, crops	1985-1994	673	41	632	Jolly et al (1997)
Lachlan17	54100	Pasture, crops	1985-1994	577	10	567	Jolly et al (1997)
Loddon 34	15400	Pasture, crops	1985-1993	523	20	503	Jolly et al (1997)
Loddon 35	4178	Pasture, crops	1985-1994	623	59	564	Jolly et al (1997)
Loddon 36	1750	Mixed vegetation	1985-1994	669	76	593	Jolly et al (1997)
Loddon 37	1050	Mixed vegetation	1985-1994	717	97	620	Jolly et al (1997)
Loddon38	5350	Pasture, crops	1989-1995	591	48	508	Jolly et al (1997)
Macintyre	6740	Mixed vegetation	1985-1994	732	36	696	Jolly et al (1997)
Macquarie	4580	Pasture, crops	1985-1994	774	89	685	Jolly et al (1997)
Macquarie10	13980	Pasture, crops	1985-1994	591	83	508	Jolly et al (1997)
Macquarie11	19600	Pasture, crops	1985-1994	721	79	642	Jolly et al (1997)
Macquarie12	26570	Pasture, crops	1985-1993	704	35	669	Jolly et al (1997)
Marthaguy Creek	70850	Pasture, crops	1985-1995	528	8	520	Jolly et al (1997)
McCallum Creek	525	Pasture, crops	1985-1990	605	32	573	Jolly et al (1997)
Mehi	12960	Pasture	1985-1994	694	27	667	Jolly et al (1997)
Mitta	4716	Forests	1985-1994	1128	249	879	Jolly et al (1997)
Molongolo	1957	Mixed vegetation	1985-1994	730	108	622	Jolly et al (1997)
Mooki	2540	Pasture, crops	1985-1990	727	30	697	Jolly et al (1997)
Mooki5	3630	Pasture, crops	1985-1991	816	33	783	Jolly et al (1997)
Moonie	15810	Pasture, woodland	1985-1990	533	7	526	Jolly et al (1997)
Mountain Creek	186	Mixed vegetation	1985-1994	915	239	676	Jolly et al (1997)
Mt Hope Creek	1775	Mixed vegetation	1987-1990	475	1	474	Jolly et al (1997)
Mt Lda Creek	175	Mixed vegetation	1985-1994	651	84	567	Jolly et al (1997)
Mt. Pleasant Creek	250	Pasture, crops	1985-1993	573	43	530	Jolly et al (1997)
Murray	27300	Mixed vegetation	1985-1994	1096	211	885	Jolly et al (1997)
Murray 40	86175	Pasture, crops	1986-1994	698	81	617	Jolly et al (1997)

Catchment	Area (km^2)	Vegetation cover	Years	P (mm)	Q (mm)	ET (mm)	References
Murray 41	251175	Mixed vegetation	1985-1994	586	32	554	Jolly et al (1997)
Murray 42	898375	Mixed vegetation	1985-1994	509	10	499	Jolly et al (1997)
Murrumbidgee18	3745	Forests	1985-1994	788	87	701	Jolly et al (1997)
Murrumbidgee19	5140	Mixed vegetation	1985-1994	788	82	686	Jolly et al (1997)
Murrumbidgee20	9221	Pasture, crops	1985-1994	788	102	686	Jolly et al (1997)
Murrumbidgee21	13100	Forests	1985-1994	836	122	714	Jolly et al (1997)
Murrumbidgee22	26400	Mixed vegetation	1985-1994	817	185	632	Jolly et al (1997)
Murrumbidgee23	34200	Mixed vegetation	1985-1992	770	118	652	Jolly et al (1997)
Murrumbidgee24	56800	Mixed vegetation	1985-1992	677	40	637	Jolly et al (1997)
Murrumbidgee25	165000	Mixed vegetation	1985-1992	559	9	550	Jolly et al (1997)
Muttama Creek	1025	Pasture, crops	1985-1994	652	66	586	Jolly et al (1997)
Namoi3	5180	Mixed vegetation	1985-1988	772	40	618	Jolly et al (1997)
Namoi4	5700	Mixed vegetation	1985-1989	751	39	712	Jolly et al (1997)
Namoi6	17100	Pasture, crops	1985-1993	744	36	708	Jolly et al (1997)
Namoi7	22600	Mixed vegetation	1985-1989	716	25	691	Jolly et al (1997)
Namoi8	28200	Forests	1985-1993	721	25	696	Jolly et al (1997)
Namoi9	36290	Mixed vegetation	1985-1993	679	13	666	Jolly et al (1997)
Ovens	6239	Mixed vegetation	1985-1994	1022	320	702	Jolly et al (1997)
Parwan Creek	0.81	Pasture	1956-1963	455	15	440	Dunin (1965)
Peel	4670	Mixed vegetation	1985-1990	816	62	754	Jolly et al (1997)
Piccaninny Creek	600	Mixed vegetation	1985-1994	497	50	447	Jolly et al (1997)
Salmon	1	Forests	Long term	1260	145	1115	Silbertein et al (1999)
Shoalhaven	2700	Mixed vegetation	average	900	210	690	Morton (1983)
Talbragar	3050	Mixed vegetation	1985-1994	664	17	647	Jolly et al (1997)
Tarcutta Creek	1660	Pasture, crops	1985-1994	757	116	641	Jolly et al (1997)
Tullaroop Creek	550	Mixed vegetation	1985-1994	707	87	620	Jolly et al (1997)
Tumut	3300	Pasture, crops	1985-1994	1180	412	768	Jolly et al (1997)
Umurray	15300	Mixed vegetation	1985-1994	1128	331	797	Jolly et al (1997)
Wallumburrawang Creek	452	Pasture	1985-1994	596	11	585	Jolly et al (1997)
Wights	1	Pasture	average	1260	503	757	Silbertein et al (1999)
Wild Duck Creek	200	Pasture, crops	1985-1994	702	129	573	Jolly et al (1997)
Wungong Brook	146	Forest	average	1100	190	910	Batini et al (1980)
Yass	1362	Mixed vegetation	1985-1994	674	66	608	Jolly et al (1997)
Belgium							
Leie	3190	Pasture	1951-1986	800	26	774	Xu (1992)
Molenbeek43	45	Pasture	1968-1987	731	277	454	Ni-Lar-Win (1994)
Molenbeek44	19	Pasture	1967-1987	755	245	510	Ni-Lar-Win (1994)
Mark	171	Pasture	1976-1987	829	230	598	Ni-Lar-Win (1994)
Ede	41	Pasture	1969-1985	745	264	480	Ni-Lar-Win (1994)
Gr. Molenbeek	66	Pasture	1975-1986	761	239	522	Ni-Lar-Win (1994)
Grote Nete	468	Pasture	1976-1986	798	340	459	Ni-Lar-Win (1994)
Demer	2163	Pasture	1970-1986	758	213	545	Ni-Lar-Win (1994)
Gete	810	Pasture	1970-1986	747	176	572	Ni-Lar-Win (1994)
Grote Gete	208	Pasture	1970-1987	797	180	617	Ni-Lar-Win (1994)
Mandel	243	Pasture	1968-1986	740	245	495	Ni-Lar-Win (1994)
Brazil							
Agarape Acu	NA	Rainforest		1819	æ	1363	Holscher et al., (1997)
Manaus	NA	Rainforests	1983-1985	2648	æ	1311	Shuttleworth (1988)
Cameroon							
Kallaio			1965-1970	812	148	664	Morton (1983)
Sanguere		Forests	1973-1976	1017	61	956	Morton (1983)
Canada							
Castor		Pasture	1967-1972	922	406	516	Morton (1983)
Creighton			1971-1978	309	20	289	Morton (1983)
Magnusson		Pasture	1972-1979	419	26	392	Morton (1994)
Mimico			1966-1071	828	296	532	Morton (1983)
Perch			1972-1978	844	336	508	Morton (1983)
Ruscom		Mixed vegetation	1972-1979	863	268	595	Morton (1994)
Whitemud		Pasture	1970-1974	515	78	437	Morton (1994)
China							
Hai River	264600	Crops, pasture	1968-1984	550	85	465	Xu (1992)
Pearl River	452000	Pasture, crops	1968-1984	1867	1031	835	Xu (1992)

Catchment	Area (km^2)	Vegetation cover	Years	P (mm)	Q (mm)	ET (mm)	References
Wengjiang	2000	Pasture, crops	1968-1984	1867	1031	834	Ni-Lar-Win (1994)
Andunshui	385	Pasture, crops	1970-1984	1848	1071	777	Ni-Lar-Win (1994)
Shahe	429	Pasture, crops	1972-1986	691	114	577	Ni-Lar-Win (1994)
Colombia							
Sierra Nevada	NA	Forest	Average	1983	æ	1265	Hermann (1970)
Guinea							
Niger	6280	Forest	1981-1988	1469	265	1204	Ni-Lar-Win (1994)
India							
Betwa	20600	Mixed vegetation	1926-1975	1138	351	787	Sutcliffe et al (1981)
Nilgiri	0.32	Mixed vegetation	1982-1991	1309	370	939	Sharda et al (1998)
Nilgiri	0.32	Forested (59%)	1982-1991	1309	276	1033	Sharda et al (1998)
Indonesia							
Janlappa	0.32	Rain forest	1990-1981	2851	æ	1481	Calder et al (1986)
Ivory Coast							
Baco I	1.40	Forest	3 years	1800	æ	1145	Huttel (1975)
Feredougouba	5020	Forest	1981-1988	1494	294	1200	Ni-Lar-Win (1994)
Boa	5770	Forest	1981-1988	1272	145	1127	Ni-Lar-Win (1994)
Bafing	6230	Forest	1981-1988	1451	252	1199	Ni-Lar-Win (1994)
N’zo	4300	Forest	1981-1988	1602	307	1295	Ni-Lar-Win (1994)
Japan							
Minanmitani	0.23	Pinus densiflora	1937-1943	1153	294	859	Nakano (1967)
Kitatani	0.17	Pinus densiflora	1937-1944	1113	290	823	Nakano (1967)
Kenya							
Awach Kabuon			1969-1974	1462	308	1159	Morton (1983)
Kimakia	1.61	Bamboo forest	1957-1960	2015	861	1154	Pereira (1964)
Kimakia	0.87	Maize	1957-1960	2015	1135	880	Pereira (1964)
Lagan	5.44	Forests	1957-1968	2049	721	1328	Morton (1983)
Sambret	7.02	Forests	1957-1968	2080	789	1291	Morton (1983)
Madagascar							
D3 catchment	0.39	Forests	1964-1972	2098	703	1394	Bailly et al (1974)
D4 catchment	0.13	Eucalyptus robusta	1964-1972	2081	786	1295	Bailly et al (1974)
Malawi							
Lilongwe	730	Forest	1953-1962	930	115	814	Pike (1964)
Luweya	900	Forest	1953-1962	1554	447	1107	Pike (1964)
Rivi Rivi	305	Forest	1952-1957	909	102	807	Pike (1964)
Luchila	542	Mixed vegetation	1951-1959	1092	288	804	Pike (1964)
Mali							
Faleme	5720	Forest	1981-1988	995	97	898	Ni-Lar-Win (1994)
Myanmar (Burma)							
Yin	1100	Pasture	1982-1986	741	100	641	Ni-Lar-Win (1994)
Yenwe	790	Forest	1981-1986	2978	1495	1483	Ni-Lar-Win (1994)
New Zealand							
Maimai (M7)	0.0414	Mixed beech	Long term	2600	1500	1100	Pearce et al (1976)
Maimai (M9)	0.0826	Mixed beech	average	2600	1500	1100	Pearce et al (1976)
Waikato	14000	Mixed vegetation		1750	975	775	Morton (1983)
Panama							
Agua Salud	0.1	Mixed vegetation	1981-1983	2744	1663	1081	Lettau and Hopkins
(1991)							
Barro Colorado	0.1	Forests	1981-1984	2425	æ	1440	Bruijnzeel (1990)
Senegal							
Faleme	5720	Mixed vegetation	1981-1988	1234	328	906	Ni-Lar-Win (1994)

Catchment	Area (km^2)	Vegetation cover	Years	P (mm)	Q (mm)	ET (mm)	References
South Africa							
Biesievlei	0.27	Fynbos	Long term	1400	660	800	Bosch and Hewlett (1982)
Bosboukloof	2.1	Fynbos	average	1390	590	800	Bosch and Hewlett (1982)
Cathedral	1.90	Pasture		1400	650	750	Nänni (1970)
Lambrechtsbos (A)	0.31	Fynbos		1393	556	837	Bosch and Hewlett (1982)
Lambrechtsbos (B)	0.65	Fynbos		1451	460	991	Bosch and Hewlett (1982)
Mokobulaan (A)	0.26	Eucalypts	1973-1991	1193	24.5	1168	Scott and Lesch (1997)
Mokobulaan (B)	0.35	Pines	1973-1991	1207	85.0	1122	Scott and Lesch (1997)
Tierkloof	1.57	Fynbos	Long term	1809	1100	709	Bosch and Hewlett (1982)
Westfalia	0.40	Scrub forest	average	1611	1063	548	Dye (1996)
Spain							
L'Avic	0.52	Forest	1981-1988	548	45	502	Piñol et al. (1991)
La Teula	0.39	Forest	1986-1988	596	81	515	Piñol et al. (1991)
Tanzania							
Moro			1969-1974	1482	411	1071	Morton (1983)
U.K.							
Kingston Brook	57	Pasture, crops	1969-1973	559	157	398	McGowan et al (1980)
U.S.A.							
Alum Creek (WS2)	0.01	Pine		1333	153	1180	Bosch and Hewlett (1982)
Alum Creek (WS3)	0.01	Pine		1230	256	975	Bosch and Hewlett (1982)
Ausable	865	Pasture	1960-1965	801	233	568	Morton (1971)
Beaver Creek (1)	1.24	Juniper-pinyon forest		457	20	437	Brown (1971), Clary et al
(1974)							
Beaver Creek (3)	1.46	Juniper-pinyon forest		457	18	439	Brown (1971), Clary et al
(1974)							
Big Fossil			1960-1965	858	100	758	Morton (1983)
Boyer		Mixed vegetation	1960-1964	793	127	666	Morton (1994)
Placer county	1.68	Oak woodland	1963-1966	635	145	490	Lewis (1968)
Burns	5.63	Forest		597	155	442	Helvey (1973, 1980)
Castle Creek	3.64	Conifer		639	71	568	Rich (1968)
Coshocton	0.18	Mixed vegetation		970	300	670	Harrold et al (1962)
Coweeta (1)	0.16	Mixed vegetation		1725	739	986	Swank and Miner (1968)
Coweeta (10)	0.86	Mixed vegetation		1854	1072	782	Swank and Miner (1968)
Coweeta (13)	0.16	Pasture		1900	889	1011	Swift and Swank (1980)
Coweeta (17)	0.14	Mixed hardwoods	1936-1940	1768	709	1059	Hoover (1944)
Coweeta (17)	0.14	Pasture	1940-1944	1953	1064	889	Hoover (1944)
Coweeta (18)	0.31	Forests	1936-1940	1739	861	878	Hoover (1944)
Coweeta (19)	0.28	Mixed hardwoods	20 years	2001	1222	779	Johnson and Kovner (1956)
Coweeta (22)	0.34	Mixed hardwoods		2068	1275	793	Hewlett and Hibbert (1961)
Coweeta (3)	0.09	Mixed hardwoods		1814	607	1207	Johnson and Kovner (1956)
Cowetta (6)	0.09	Mixed hardwoods		1854	838	1016	Bosch and Hewlett (1982)
Cowetta (2)	0.12	Mixed hardwoods		1750	732	1019	Hewlett and Hibbert (1961)
Etobicoke	166		1960-1965	676	152	524	Morton (1971)
Fish	150	Pasture	1960-1965	818	245	573	Morton (1971)
Fox Creek (FC1)	.59	Mixed vegetation	Long term	2730	1750	980	Harr (1976)
Fox Creek (FC3)	0.71	Mixed vegetation	average	2730	1750	980	Harr (1976)
H.J. Andrews (1)	0.96	Mixed vegetation		2388	1376	1012	Rothacher (1970)
H.J. Andrews (3)	1.01	Mixed vegetation		2388	1346	1042	Rothacher (1970)
H.J. Andrews (6)	0.13	Mixed vegetation		2150	1290	860	Rothacher (1970)
Hubbard Brook (WS2)	0.16	Mixed vegetation		1219	467	752	Hornbeck et al (1970)
James			1960-1965	1025	237	788	Morton (1983)
Little Nemaha		Mixed vegetation	1960-1964	764	101	663	Morton (1994)
Lynn	142	Pasture	1960-1965	887	277	610	Morton (1971)
McCree	5.14	Forest		579	112	467	Helvey (1973, 1980)
Monroe Canyon	3.54	Chaparral		648	64	584	Rowe (1963)
Natural Drainage (A)	0.05	Chaparral		452	34	418	Hibbert (1971)
Natural Drainage (C)	0.05	Chaparral		452	43	409	Hibbert (1971), Hibbert
(1979)							
North			1960-1965	841	188	653	Morton (1983)
North Fork, Workman	1.0	Conifer		813	86	727	Rich et al (1961)
Omaha		Mixed vegetation	1960-1964	676	67	609	Morton (1994)
Pembina	7430	Pasture	1960-1965	474	10	464	Morton (1971)
Placer county	0.39	Chaparral		638	58	580	Lewis (1968)
Ribstone	2560	Pasture	1960-1965	413	4	409	Morton (1971)
San Gabriel	43.52	Mixed vegetation	1917-1924	782	185	597	Hoyt and Troxell (1934)
San Gabriel	43.25	Pasture	1924-1930	655	178	477	Hoyt and Troxell (1934)

Catchment	Area (km^2)	Vegetation cover	Years	P (mm)	Q (mm)	ET (mm)	References
Soldier		Mixed vegetation	1960-1964	774	129	645	Morton (1994)
South Fork, Workman	1.29	Conifer		813	87	726	Rich et al (1961)
Swift Current	390	Pasture	1960-1965	342	9	333	Morton (1971)
Three Bar (B)	0.95	Pasture	1960-1969	542	32	510	Hibbert (1971)
Three Bar (C)	0.46	Pasture	1960-1969	627	170	456	Hibbert (1971)
Three Bar (D)	0.46	Forests	1960-1969	704	73	631	Hibbert (1971)
Three Bar (F)	0.28	Chaparral	1960-1969	681	36	645	Hibbert 91971)
Tucson	NA	Desert		275	æ	262	Unland et al., (1996)
Wascana	3780	Pasture	1960-1965	363	7	356	Morton (1971)
West Humber	205	Pasture	1960-1965	687	109	578	Morton (1971)
White Hollow	0.69	Douglas fir	1935-1949	1146	426	720	T.V.A. (1961)
White Spar	1.0	Chaparral		549	34	515	Hibbert (1971)
Yorkton	2460	Pasture	1960-1965	388	1	387	Morton (1971)
Uganda							
Waki II	523		1969-1974	1360	166	1194	Morton (1983)
Yemen							
Adhanah	12600	Crops	20 years	163	8	155	Farquharson et al. (1996)
Ahwar	6410	Crops		210	13	197	Farquharson et al. (1996)
Al Ain	1500	Crops		80	7	73	Farquharson et al. (1996)
Amd/Duan	6553	Crops		100	3	97	Farquharson et al. (1996)
Bana	7400	Crops		310	21	289	Farquharson et al. (1996)
Bin Ali	743	Crops		65	6	59	Farquharson et al. (1996)
Idim	5485	Crops		70	8	62	Farquharson et al. (1996)
Jawf	14000	Crops		178	11	167	Farquharson et al. (1996)
Juaymah	743	Crops		35	0	35	Farquharson et al. (1996)
Mawar	7910	Crops		405	16	389	Farquharson et al. (1996)
Mawza	1480	Crops		480	14	466	Farquharson et al. (1996)
Najran	4400	Crops		151	16	135	Farquharson et al. (1996)
Rabwa	455	Crops	20 years	320	7	313	Farquharson et al. (1996)
Rasyan	1990	Crops		595	8	587	Farquharson et al. (1996)
Rima	2250	Crops		465	22	443	Farquharson et al. (1996)
Saar	2540	Crops		45	1	44	Farquharson et al. (1996)
Siham	4900	Crops		410	15	395	Farquharson et al. (1996)
Surdud	2300	Crops		495	36	459	Farquharson et al. (1996)
Thibi	718	Crops		40	3	37	Farquharson et al. (1996)
Tuban	5340	Crops		460	23	437	Farquharson et al. (1996)
Zabid	4630	Crops		515	19	496	Farquharson et al. (1996)
Zambia							Farquharson et al. (1996)
Kafue	155000		1969-1974	1023	85	938	Morton (1983)
Zimbabwe							
Mshagashi	514	Mixed vegetation	1957-1965	661	64	597	Lørup et al (1998)
Ngei	1036	Mixed vegetation	1957-1964	718	50	668	Lørup et al (1998)
Nyatsime	500	Mixed vegetation	1957-1964	792	141	651	Lørup et al (1998)
Popotekwe	1010	Mixed vegetation	1960-1968	649	69	580	Lørup et al (1998)
Roswa	197	Mixed vegetation	1967-1975	713	119	594	Lørup et al (1998)
Turgwe	223	Mixed vegetation	1967-1975	857	254	603	Lørup et al (1998)

Note :

1 at Pinegrove station
2 at Pallamallawa station
3 at Manila Bridge
4 at Keepit station
5 at Breeza station
6 at Caroona station
7 at Gunnedah station
8 at Boggabri station
9 at Mollee station
10 at Burrndong station
11 at Dubbo station
12 at Warren station
13 at Medooran station
14 at Cowra station
15 at Forbe station
16 at Condolin station
17 at Hillston Weir
18 at Billilingra station
19 at Angle Crossing
20 at Hall’s Crossing
21 at Burrinjunck Dam
22 at Wagga wagga
23 at Narrandera
24 at Hay
25 at Blaranald station
26 at Walbundire station
27 at Darlot station
28 at Bourke station
29 at Wilcannica Main Channel
30 at Burtundy station
31 at Rochester station
32 at Redesdale station
33 at Strathfieldsaye station
34 at Kerang station
35 at Laanecoorie station
36 at Cairn Curran station
37 at Newstead station
38 at Serpentine Weir
39 at Lillicur station
40 at Wakool station
41 at Euston Weir
42 at Rufus Junction
43 at Massemen
44 at Geraardsbergen