Journal of Hydrology 499 (2013) 210–223

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evaluation of forest interception estimation in the continental scale Australian Water Resources Assessment – Landscape (AWRA-L) model ☆

Jim Wallace [a,b,*], Craig Macfarlane [c], Dave McJannet [d], Tim Ellis [d], Andrew Grigg [e], Albert van Dijk [f,g]

[a] Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville, QLD 4811, Australia
[b] CSIRO Land and Water, Australian Tropical Science and Innovation Precinct, Townsville, QLD 4814, Australia
[c] CSIRO Ecosystem Sciences, Private Bag No. 5, Wembley, WA 6913, Australia
[d] CSIRO Land and Water, EcoSciences Precinct, Dutton Park, QLD 4120, Australia
[e] Alcoa World Alumina Australia, PO Box 172, Pinjarra, WA 6208, Australia
[f] Fenner School of Environment & Society, ANU College of Medicine, Biology and Environment, Canberra, ACT 0200, Australia
[g] CSIRO Land and Water, Christian Laboratory, Clunies Ross Street, Black Mountain, ACT 2601, Australia

ARTICLE INFO

Article history:
Received 5 December 2012
Received in revised form 9 April 2013
Accepted 19 June 2013
Available online 5 July 2013
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Matthew McCabe, Associate Editor

Keywords:
Interception
Wet canopy evaporation
Rainfall rate
Continental model

SUMMARY

The AWRA-L model is a core component of the joint Bureau of Meteorology (BOM) and CSIRO Australian Water Resources Assessment (AWRA) system which integrates hydrological models and a variety of observations and satellite products to produce a National Water Accounting system for Australia. AWRA-L is a continental scale sub-model which provides surface water balance component estimates for all landscape types, including forests ranging from sparse woody vegetation in dry climates to dense tropical rainforest in wet climates. This paper describes the AWRA-L interception sub-routine, which is based on the widely used Gash model, and considers how its predictions compare with measurements of interception in tropical rainforests in north Queensland and sparse jarrah forests in Western Australia. The results demonstrate the importance of having accurate estimates of the three parameters which dominate the interception loss (as a fraction of rainfall), i.e. canopy water holding capacity, *S*, the average wet canopy evaporation rate, *E*, and the average rainfall rate, *R*. The current 'default' values of these parameters used in AWRA-L lead to significant errors in interception, which will also be reflected in the AWRA stream flow estimates. Analysis of how *E* and *R* values vary across the Australian continent have led to recommendations for how the interception calculations made by the AWRA-L model can be improved using values of *E* and *R* calculated from forest height and latitude. Revisions of the canopy storage parameters based on regressions derived from measured values at the rainforest and jarrah sites are also evaluated. Overall, the adoption of both updated canopy storage and *E*/*R* ratios outlined in this paper does provide a measurable improvement to the performance of the AWRA-L interception model. The approach developed in this study also has direct relevance to other applications of interception models for water balance modelling at large spatial scales.

1. Introduction

Large scale water balance models have been developed for a number of reasons including the realistic representation of the land surface in general circulation models of the atmosphere (e.g. see Wood et al., 1997), large scale modelling of vegetation (Neilson, 1995) and continental scale modelling of the landscape water balance (Arnold et al., 1999; Arnell, 1999; Wood et al., 1997; Miralles et al., 2010). Many of these models include grid based process descriptions of the land surface energy and water balance that are driven by climate data; hence they are often used to simulate river flow in large catchments (e.g. Arnell, 1999) and/or the impacts of climate change on water resources (e.g. Leavesley, 1994). Such a continental model has recently been developed in Australia (the Australian Water Resource Assessment – AWRA) as part of the National Water Account currently being developed to comply with the Australian Water Act (2007). The AWRA system aims to operationally provide up-to-date, comprehensive and accurate information about the history, current state and future trajectory of the landscape water balance across the entire Australian continent. This information will be central to a wide variety of water resource planning and management applications. The core landscape model

* Corresponding author at: Centre for Tropical Water & Aquatic Ecosystem Research (TropWATER), James Cook University, Townsville, QLD 4811, Australia. Tel.: +61 1635 770 634.
E-mail address: jim.wallace@mail.com (J. Wallace).

0022-1694/$ - see front matter © 2013 The Authors. Published by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jhydrol.2013.06.036

(AWRA-L) is a 0.05° grid based biophysical model that simulates daily water stores and flows in soil, vegetation and local catchment groundwater systems; further details of which are given by van Dijk (2010).

The AWRA-L model provides surface water balance component estimates for all landscape types, including forests ranging from sparse woody vegetation in dry climates to dense tropical rainforest in wet climates. A major evaporative loss from these forest types is interception; rainfall that is caught on the canopy and evaporated during and after rainfall. For example, recent studies of interception in Australia have reported annual losses of between 25% and 40% of rainfall in dense tropical rainforests Wallace and McJannet (2008) and 14–16% in sparse jarrah forests (Macfarlane et al., 2011). Interception is therefore a large fraction of the surface water balance and is also the component which has the greatest impact on stream flow when forest are removed; for example, van Dijk et al. (2011) have shown thatthe interception contribution to stream flow increase after forest removal is two to three times that due to the associated change in transpiration.

It is clearly important therefore that the AWRA-L model makes an accurate estimate of forest interception, without which other components of the surface water balance (including stream flow) may have significant errors. This paper compares the values of interception currently estimated by AWRA-L model in its current 'default' mode (see van Dijk, 2010) with data from several rainforest and jarrah forest sites. Further comparison with an optimised version of the Gash et al. (1995) interception model allows us to identify which parameters in the AWRA-L interception model need to be improved. We also explore simple empirical methods that could be used to improve the AWRA-L model parameters based on readily available meteorological data.

2. Methods

2.1. The AWRA-L interception model

AWRA-L uses the rainfall interception model of Gash (1979), revised by Gash et al. (1995) for sparse canopies and adapted by Van Dijk and Bruijnzeel (2001a,b) who used time variant canopy storage and evaporation functions dependent on the leaf area index. The revised Gash model assumes that rainfall is intercepted in a series of discrete storms, with sufficient time between each storm for the canopy to dry. Each storm can have up to three sequential phases: (i) a wetting phase during which rainfall, P_g, is less than that required to saturate the canopy, P'_g; (ii) a saturation phase; and (iii) a drying phase after rainfall has ceased. The storage of water on the canopy is described using the canopy capacity S, the minimum depth of water required to saturate the canopy, which is given by the product of the canopy capacity per unit area of cover, S_c, and the canopy cover, c. The free throughfall coefficient, p, is the amount of rain which falls directly to the forest floor without touching the canopy (assumed to be $1 - c$). In the Gash model, evaporation of water from the trunks is specified using the trunk storage capacity, S_t, and the proportion of rain that is diverted to stemflow, p_t. The value of S_t, is often considered small compared with the canopy capacity, S (Lloyd et al., 1988; Wallace and McJannet, 2006, 2008) and therefore should not usually have a major effect on interception modelling results. However, the effect of varying S_t on modelled interception is further examined in this paper. In the AWRA-L model trunk evaporation is accounted for by increasing the canopy storage capacity by the trunk storage capacity S_t. Finally, two of the most critical parameters in both the Gash and AWRA-L models are the mean rainfall rate, R, and the mean evaporation rate per unit canopy area during rainfall, E_c, both assumed constant for all storms.

Table 1 summarises the five terms in the Gash et al. (1995) and AWRA-L models. The AWRA-L model is designed to allow cover c_j, wet canopy evaporation rate per unit ground area, E_j (=c_j E_c), and canopy capacity, $S_{v,j}$ to vary in time (e.g. to cope with vegetation with significant seasonal variation such as annual crops). In the current application to tropical rainforests and sparse jarrah forests these three parameters are held constant in the Gash model, but are allowed to vary in the AWRA-L model, when it is used in its 'default' mode.

Both of the above models require the estimation of the amount of rainfall needed to saturate the canopy, P'_g, which is given by;

$$P'_g = -(RS_c/E_c)\ln\{1 - E_c/R\} \quad (1)$$

in the Gash model and by

$$P'_{g,j} = -(RS_{v,j}/E_j)\ln\{1 - E_j/c_jR\} \quad (2)$$

in the AWRA-L model. The key difference is again that the AWRA-L model allows for seasonal changes in S_v and E_j and when these are the same as in the Gash model the two formulae give identical values of P'_g.

It is important to discriminate between the wet canopy evaporation rate per unit ground area, E_j and per unit canopy area, E_c. In the Gash model E_j is assumed to be given by $c\ E_c$ and in the AWRA-L model the cover fraction c is derived using a Beers law expression, i.e.

$$c = (1 - e^{-\kappa L_j}) \quad (3)$$

where L_j is a time variant leaf area index and κ the light extinction coefficient. Similarly canopy capacity per unit ground area, S, is given by cS_c in the Gash model, whereas the AWRA-L model estimates the total canopy capacity from the water holding capacity per unit leaf area, S_L, and leaf area index L_j as;

$$S_{v,j} = L_jS_L + S_{t,j} \quad (4)$$

where the additional term $S_{t,j}$ allows for water storage on the tree stems and branches, again with the option to be time variant. This is why there is no separate 5th term in the AWRA-L model, see Table 1 above. When the AWRA-L model is run in its current 'default' mode, it produces a seasonally varying leaf area index, and so canopy capacity for this model will also vary in time.

Although there are some differences in the interception formulations in the two models, we shall see later that the main difference in the interception values produced by the two models is

Table 1
The interception terms in the revised Gash and AWRA-L models.

Component of interception loss	Revised Gash et al. (1995) model	AWRA-L model
1. m small storms insufficient to saturate the canopy	$c\sum_{j=1}^{m}P_{g,j}$	$\sum_{j=1}^{m}c_jP_{g,j}$
2. Wetting up the canopy; n storms > P'_g which saturate the canopy	$ncP'_g - ncS_c$	$\sum_{j=1}^{n}\{c_jP'_{g,j} - S_{v,j}\}$
3. Evaporation from saturation until rainfall ceases	$(cE_c/R)\sum_{j=1}^{n}(P_{g,j} - P_g)$	$\sum_{j=1}^{n}(E_j/R)(P_{g,j} - P'_g)$
4. Evaporation after rainfall ceases	ncS_c	$\sum_{j=1}^{n}S_{v,j}$
5. Evaporation from trunks; q storms > S_t/p_t, which saturate the trunks	$qS_t + p_t\sum_{j=1}^{n-q}P_{g,j}$	Included in $S_{v,j}$ terms 2 and 4 above

Table 2
A summary of measured and optimised parameters from the Gash model for the two rainforest and two jarrah sites. Also shown are the equivalent parameters used by the AWRA-L model in 'default' mode.

	Units	Oliver Creek, QLD		Upper Barron, QLD		Huntly, WA		Bates, WA	
		Gash	AWRA-L	Gash	AWRA-L	Gash	AWRA-L	Gash	AWRA-L
Canopy leaf area index (L_j)		4.2	2.5–5.9	4.1	1.3–6.3	2.1	2.5–3.2	1.8	3.6–4.6
Tree foliage cover (c)		0.97	0.64–0.91	0.96	0.41–0.92	0.49	0.64–0.73	0.42	0.76–0.84
Canopy storage capacity per unit ground area (S)	(mm)	3.44	0.25–0.59	2.7	0.13–0.63	0.14	0.25–0.32	0.11	0.36–0.46
Canopy storage capacity per unit canopy area (S_c)	(mm)	3.56	0.40–0.65	2.81	0.32–0.68	0.29	0.39–0.44	0.26	0.48–0.55
Canopy storage capacity per unit leaf area (S_v)	(mm)	0.85	0.1	0.66	0.1	0.07	0.1	0.06	0.1
Free throughfall coefficient (p)		0.035	0.36–0.09	0.04	0.59–0.08	0.51	0.36–0.27	0.58	0.24–0.16
Stemflow partitioning coefficient (p_t)		0.032	None	0.075	None	0.081	None	0.053	None
Trunk storage capacity (S_t)	(mm)	0.15	None	0.15	None	0.11	None	0.11	None
Average rainfall intensity (R)	(mm h^{-1})	4.61		3.9[a]		1.37		1.31	–
Average wet canopy evaporation rate per unit canopy (E_c)	(mm h^{-1})	0.35		0.81		0.41		0.38	–
Ratio of E_c/R		0.07	0.2	0.21	0.2	0.30	0.2	0.29	0.20
Period		September 2001–January 2004		December 2000–March 2004		January 2008–December 2008			January 2008–December 2009
Total rain	(mm)	4077		1252		1081			2207
Total measured interception	(mm)	1039		418		173			317
Interception loss (% of rainfall)		25.5		33.4		16.0			14.4

[a] Rainfall only, cloud interception not included.

due to different values of the key controlling variables, canopy capacity (S) and the ratio of E/R. In the Gash model we use optimised values for these parameters derived from interception measurements at specific rainforest locations (see Wallace and McJannet, 2008). In contrast, the AWRA-L model, in common with other continental scale models, has to select or derive *a priori* values of these parameters from vegetation classifications, published literature and growth models (van Dijk, 2010). Further details of the differences in the interception model parameters are given below.

2.2. Forest sites and associated interception data

Comparison of the AWRA-L and Gash models was made with interception measurements made at two rainforest locations in Queensland and two jarrah (*Eucalyptus marginata*) forests in Western Australia. The first rainforest site, Oliver Creek (OC), is a lowland (30 m altitude) coastal rainforest located in the Daintree National Park about 100 km north of Cairns. The average annual rainfall at this site is 3068 mm and the forest is 27 m tall with a leaf area index of 4.2 (Wallace and McJannet, 2008). The second rainforest site, Upper Barron (UB), is a lower montane rainforest located at an altitude of 1050 m on the Atherton Tablelands (~70 km from the coast) in the Longlands Gap State Forest. This site is much drier, with an average annual rainfall of 1831 mm, but of similar height (25 m) and leaf area index (4.1) as Oliver Creek. A full description of these rainforest sites and the interception measurements and modelling already made at them is given by McJannet et al. (2007a, 2007b) and Wallace and McJannet, 2006, 2008). The two jarrah forest sites were located within 10 km north of Dwellingup, Western Australia, approximately 40 km from the coast and at an altitude of 290 m. The climate is Mediterranean, characterised by hot dry summers and cool wet winters with most rain falling between May and October (Gentilli, 1989). Long term annual rainfall exceeds 1200 mm year^{-1}. Soils are typically sandy gravels of inherently low fertility up to 30 m deep derived from deeply weathered granitic parent material (Churchward and Dimmock, 1989). Tree height was approximately 20 m at both jarrah sites and leaf area indices were 1.8 at Bates (measured over two wet seasons, 2008–2009) and 2.1 at Huntly (measured for one wet season, 2009).

The parameters used in the Gash and AWRA-L model comparison are listed in Table 2. For the Gash model, canopy capacity (S_c) and mean wet canopy evaporation rates (E_c) were estimated from regressions of throughfall plus stemflow ($T_f + S_f$) versus rainfall P_g (see Wallace and McJannet, 2006, 2008). The mean rainfall rates (R) were calculated from individual storms as the ratio of the total rainfall in a storm to its duration (see next section for details). In the rainforests canopy cover (c) and leaf area index (L_j) were measured using fish eye lens photography (McJannet et al., 2007a) and the free throughfall coefficient, p, taken as $(1 - c)$. In the jarrah forests leaf area and cover were estimated using digital cover photography (Macfarlane et al., 2007). At all sites the proportion of rainfall diverted to stem flow (p_t) was measured directly using stem flow gauges (e.g. McJannet et al., 2007a).

When the canopy storage capacity, S, is obtained from the negative intercept of the regression of ($T_f + S_f$) against P_g, it represents the average total water holding of all the elements of the forest canopy; leaves, branches and trunks. In order to derive a specific leaf water holding capacity, i.e. the amount of water held per unit leaf area, S_L, as used in the AWRA-L model (van Dijk, 2010), it is therefore necessary to separate S into its foliar and non-foliar (i.e. trunk including branches) components. In the jarrah forests the non-foliar component was estimated as 0.11 mm from the intercept of a regression of total storage versus L_j for the jarrah forest sites. Following Wallace and McJannet (2008), the trunk storage capacity of the rainforests, S_t, was taken from Lloyd et al. (1988) as 0.15 mm. An assessment of the effect of partitioning S into its foliar and non-foliar components in the rainforests is presented later in this paper.

The default AWRA-L parameters used for the forests are also given in Table 2. A key parameter is the ratio of the mean wet canopy evaporation rate over mean rainfall rate (E_c/R), which has been reported to vary between 0.05 and 0.25 in forests (Gash, 1995; van Dijk and Bruijnzeel, 2001b). Based on these literature values, AWRA-L uses a default value of E_c/R of 0.2 for all forests or '*deep rooted vegetation*' (Van Dijk, 2010). Canopy capacity is based on the water holding capacity per unit leaf area, S_L, and leaf area index L_j (Eq. (4)). Again the default value of S_L in AWRA-L, 0.1 mm, is based on a range of literature values for all vegetation types including forests (0.07–0.6 mm; see van Dijk and Bruijnzeel, 2001b). AWRA-L has a vegetation growth and phenology sub-model that calculates seasonally varying values of L_j based on the 'equilibrium' approach where transpiration (driven by radiation interception by the canopy) is controlled by the ability of the roots to withdraw water from the soil (controlled by soil hydraulic properties – see van Dijk, 2010). This is why the values of S and S_c for the AWRA-L model vary in Table 2.

2.3. Variation in R and E across Australia

The ratio of mean evaporation rate during rain (E) to mean rainfall rate (R) is a key determinant of canopy interception losses in the AWRA-L model, currently set to 0.2 for all forest types. To improve the estimation of these parameters within AWRA-L, and thus improve estimation of canopy interception, we tested the variation of both E and R, and their ratio, across a wide range of climate zones within Australia.

2.3.1. Rainfall rate

Pluviograph data (6 min interval) were obtained from the eWater online toolkit (http://toolkit.ewater.com.au) for 54 Bureau of Meteorology recording stations across Australia with a lengthy continuous record (see Appendix A). A range of stations was selected to represent tropical, arid and semi-arid, and temperate climate regions. Mean rainfall rate (R) was calculated as the ratio of total rainfall in an event divided by the length of the event. The estimation of R is sensitive to the choice of storm separation time, which must be long enough for the canopy to dry out to comply with the Gash model. Studies have used separation times ranging from 2 h to 6 h (see Wallace and McJannet, 2008). We used a storm separation time of 4 h as used by van Dijk et al. (2005) and Wallace and McJannet (2008). Individual rain events with less than 2 mm rain were ignored; the number of such daily records used for each station ranged from 441 to 6339 with a mean of 2303 (Appendix A).

2.3.2. Wet canopy evaporation rate

Wet canopy evaporation was calculated for the same Bureau of Meteorology stations used to estimate R. Daily potential evaporation (FAO56 – Allen et al., 1998) was taken directly from the SILO[1] patched point dataset (Jeffrey et al., 2001) for days when the canopy was likely to be wet for most or all of the day. These wet canopy evaporation days were selected using the corresponding pluviograph data according to the criteria that there were no gaps between rain events greater than 4 h and at least 50 mm of rain fell that day; with rainfall rates around 4 mm h^{-1} (Appendix A) this meant the canopy was wet for a least 12 h per day. The number of such daily records used for each station ranged from 1 to 267 with a mean of 17 (Appendix A). Since the FAO56 evaporation rate applies to short grass and uses weather data measured at 2 m we also estimated the evaporation rate during rainfall (E) over tall forests, ranging in height from 10 to 40 m. This requires the extrapolation of 2 m weather data to above the forest and a correction to the aerodynamic resistance to allow for the much rougher forest canopy. To do this we used the Matt-Shuttleworth method as described in Shuttleworth and Wallace (2009), from which E is given by;

$$E = \frac{\Delta A + \frac{\rho c_p u_2 D_2}{R_c^{50}}\left(\frac{D_{50}}{D_2}\right)}{\Delta + \gamma\left(1 + \frac{(r_s)_c u_2}{R_c^{50}}\right)} \tag{5}$$

where Δ is the rate of change of saturated vapour pressure with temperature, A is the available energy, D_2 is the vapour pressure deficit (measured at 2 m height), u_2 is wind speed at 2 m height (taken as 2 m s^{-1} in FAO56), γ is the psychrometric constant, ρ is the density of air, and c_p is the specific heat of air at constant pressure. D_{50} is the vapour pressure deficit at 50 m and is given by its ratio to D_2 as;

$$\left(\frac{D_{50}}{D_2}\right) = \left(\frac{(\Delta+\gamma)302 + 70\gamma u_2}{(\Delta+\gamma)208 + 70\gamma u_2}\right) + \frac{1}{r_{clim}}\left[\left(\frac{(\Delta+\gamma)302 + 70\gamma u_2}{(\Delta+\gamma)208 + 70\gamma u_2}\right)\left(\frac{208}{u_2}\right) - \frac{302}{u_2}\right] \tag{6}$$

where the climatological resistance term, r_{clim}, is given by;

$$r_{clim} = (\rho c_p D_2)/(\Delta A) \tag{7}$$

and the aerodynamic coefficient R_c^{50} for a forest of height h is;

$$R_c^{50} = \frac{1}{(0.41)^2}\ln\left[\frac{(50-0.67h)}{(0.123h)}\right]\ln\left[\frac{(50-0.67h)}{(0.0123h)}\right]\frac{\ln\left[\frac{(2-0.08)}{0.0148}\right]}{\ln\left[\frac{(50-0.08)}{0.0148}\right]} \tag{8}$$

The origins of the various numerical constants in Eqs. (6) and (8) are given by Shuttleworth and Wallace (2009). The final term in Eq. (5) is the canopy surface resistance to water vapour, $(r_s)_c$, which for a wet canopy is negligible compared to that of a dry canopy (i.e. no stomatal resistance) and we assumed a value of $(r_s)_c$ of 0 s m^{-1}, as have numerous published studies of interception loss from wet canopies (Asdak et al. 1998; Calder and Wright, 1986; Sraj et al., 2008).

Daily mean temperature was calculated as the mean of maximum and minimum temperature, and used to calculate values of temperature dependant parameters (Δ and γ). D_2 for each station was calculated according to the FAO56 guidelines (Allen et al., 1998) as the mean of D_2 at 9 am and 3 pm using data from the SILO patched point dataset. Monteith and Unsworth, 1990 have shown that net longwave radiation is close to zero under the cloudy skies present during heavy rain, hence, available energy (A) was calculated from SILO's daily insolation (Q) as 0.87Q, assuming an albedo of 0.13 and zero ground heat flux over 24 h (Roberts et al., 2005; Wallace and McJannet, 2008). For each of the 54 SILO stations a 'default' canopy height was estimated as 20 m based on continental-scale records indicating that the majority of forest and woodland is 10–30 m tall (Lee et al., 2009; Commonwealth of Australia, 2010). Given the height variation of natural vegetation, we also analysed the sensitivity of estimated E to variation in vegetation height from 0.5 to 40 m.

3. Results and discussion

3.1. Comparison of AWRA-L default and site data

3.1.1. Rainforests in Queensland

Fig. 1 shows the result of interception estimation by the Gash and AWRA-L models when they are parameterised independently at the lowland coastal rainforest at Oliver Creek. The Gash model uses the parameters specified in Table 2 and the AWRA-L model

[1] SILO is an Australian national climate data archive containing daily values of 15 variables including rainfall, temperature, radiation, evaporation and vapour pressure.

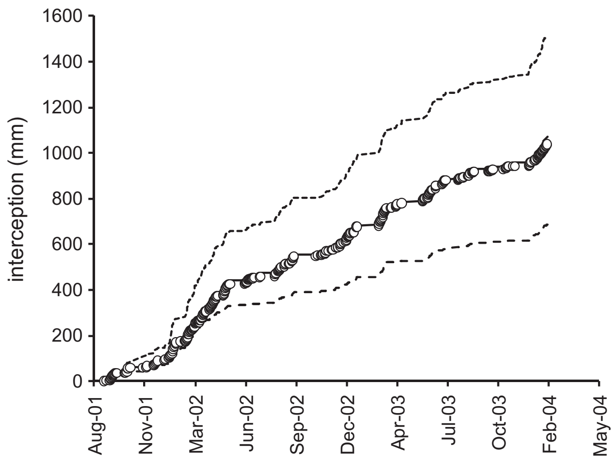

Fig. 1. Comparison of cumulative interception loss from the Oliver Creek rainforest calculated using the Gash (solid lines) and the AWRA-L models with all default parameters (long dashes). Also shown are the results from the AWRA-L model with all parameters optimised except E_c (short dashes) and the measured values of cumulative interception at this site (○).

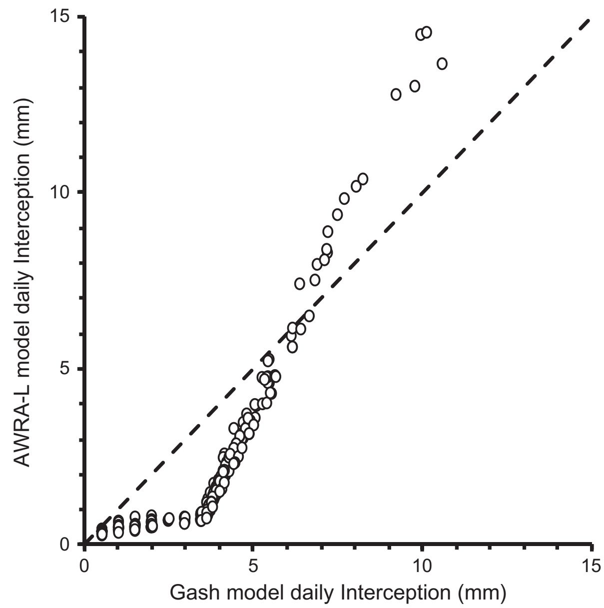

Fig. 2. Comparison of daily interception loss from the Oliver Creek rainforest calculated using the Gash and the AWRA-L models with all default parameters. The 1:1 line is also shown for comparison.

Table 3
Differences between modelled and measured interception (%) for a range of scenarios and associated parameter values used in the AWRA-L model for the two rainforest and two jarrah forest sites.

Scenario	Oliver Creek (%)	Upper Barron (%)	Huntly (%)	Bates (%)
1. Default AWRA parameters	−34	−40	−2	35
2. Scenario 1 with measured leaf area index (L_j)	−25	−40	−20	−18
3. Scenario 2 with measured cover (via κ)	−13	−31	−29	−31
4. Scenario 3 with estimated canopy storage (via S_L)	43	1	−32	−35
5. Scenario 4 with trunk storage (S_t)	45	3	−29	−29
6. Scenario 5 with optimised E_c/R (= Gash model)	5	5	2	−4

uses the 'default' parameters specified in the same Table. To identify the effect of sequentially changing individual parameters in the AWRA-L model, six separate scenarios were run as listed in Table 3.

When the AWRA-L model is used with default parameters the daily and cumulative interception losses are much lower than those predicted by the Gash model, Fig. 1. Over the entire 2.5 year period the Gash model total interception is 1072 mm, only 3.2% higher than the measured interception (1039 mm), Table 3. In contrast, the AWRA-L model total is only 688 mm, 34% lower than the measured interception. In default mode AWRA-L uses SILO rainfall data (4050 mm), but as this is very similar to the measured rainfall (4077 mm) for this location Wallace et al., 2011), none of the interception loss discrepancy is due to differences in rainfall input to the models. Comparison of scenarios 3 and 4 shows that the main reason for the reduction in the AWRA-L interception is the low value of canopy capacity it uses (S_v = 0.25–0.59 mm), which greatly reduces terms 2 and 4 of the interception model (see Table 1). The low value of S_v also indirectly affects the first term of the model as it leads to a much lower value of P'_g (=0.46 mm in AWRA-L compared to 3.7 mm in Gash). The effect of this difference in P'_g can be seen in Fig. 2, where for storms smaller than that required to saturate the canopy (3.7 mm in the Gash model), the AWRA-L model gives much lower interception values than the Gash model. When daily interception exceeds ~7 mm, the AWRA-L model interception values are higher than the Gash values and this is because term 3 (see Table 1) now dominates the interception loss and AWRA-L has a higher value of E_c/R.

When the AWRA-L model is used with default parameters for the lower montane rainforest at Upper Barron the daily and cumulative interception losses are again much lower than those measured and/or predicted by the Gash model, Fig. 3. Over the entire 3.5 year period the Gash model total interception is 424 mm, very similar to the measured interception (418 mm). In contrast, the AWRA-L model total is only 251 mm, 40% lower than the measured interception. Note that the AWRA-L interception loss is calculated using site rainfall data (1252 mm), which is considerably greater than the SILO rainfall data (1110 mm) for this location; use of the latter gives an interception loss of only 212 mm. At this site the shortfall in the AWRA-L interception is again almost entirely

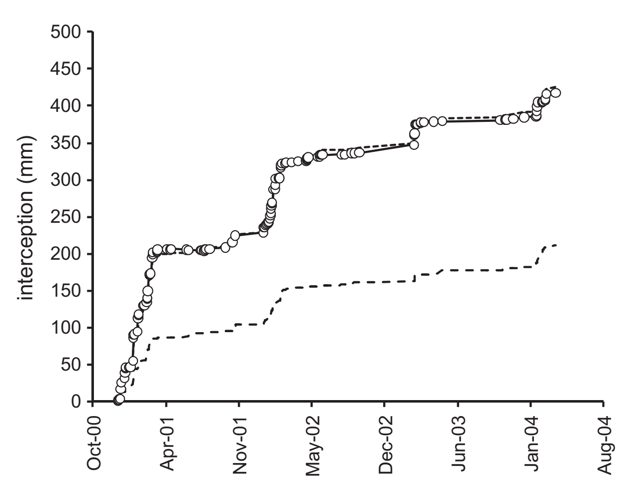

Fig. 3. Comparison of cumulative interception loss from the Upper Barron rainforest calculated using the Gash (solid lines) and the AWRA-L models with all default parameters (long dashes). Also shown are the results from the AWRA-L model with all parameters optimised except E_c (short dashes) and the measured values of cumulative interception at this site (○).

due to the low value of canopy capacity it uses (S_v = 0.13–0.63 mm), which directly reduces terms 2 and 4 of the interception model (see Table 1) and indirectly the first term of the model as above. Inspection of the daily interception values predicted by the two models (not shown), shows the discrepancy for small storms, as at Oliver Creek, but also that the AWRA-L interception values never exceed the Gash values. This is because the default value of E_c/R in the AWRA-L model (0.2) is less than the equivalent used in the Gash model for this site (0.21). Because of the similarity in these E_c/R values at this site, changing this parameter in the AWRA-L model has little effect on interception, Fig. 3 and Table 3.

The AWRA-L model underestimation of the interception loss at the two rainforest sites is largely due to the low canopy storage used in this model, which comes from the product of leaf area index (L_j) and the water holding capacity per unit leaf are, S_v. Fig. 4a shows there is a large seasonal and inter-annual variation in the leaf area generated by the AWRA-L model for the rainforest sites, with some very low values at times, for example, in January 2003 at Upper Barron when the modelled L_j is only 1.0, compared to the measured value of 4.1. At the one time (October 2002) when measured leaf area is available for Oliver Creek, the AWRA-L estimated is quite close, but this may be fortuitous; clearly more ground based measurements of L_j are needed, but unfortunately they are not available in this study. However, the measured values of L_j at Oliver Creek and Upper Barron are within (but at the lower end) of the range reported by Roberts et al. (2005) for a range of tropical rainforests (e.g. 4.5–6) and Roberts et al. (1996) show leaf litter data collected in the Amazonian rainforest which indicates that there is only slight seasonality (∼10%) in the total canopy leaf area. It may be, therefore, that the leaf area values estimated by the AWRA-L model can often be too low and that their seasonal variation is too high. One possible reason for this is that the AWRA-L forest growth model (van Dijk, 2010) is based on the physiological response of a single forest (held constant across the whole of Australia), whereas in a real rainforest multiple species exist which may have temporally complementary phenologies that interact to sustain a more constant seasonal total canopy leaf area. A further explanation of the low AWRA-L interception losses is the low 'default' value of the specific leaf water holding capacity, S_v = 0.1 mm. This is much lower than that derived from the Gash model total storage divided by the leaf area index (0.66–0.84 mm, Table 2), however, this calculation assumes all of the water is stored by leaves and we shall see later that when the possibility of significant non-foliar water storage is taken into account, the value of S_v derived from the Gash model decreases.

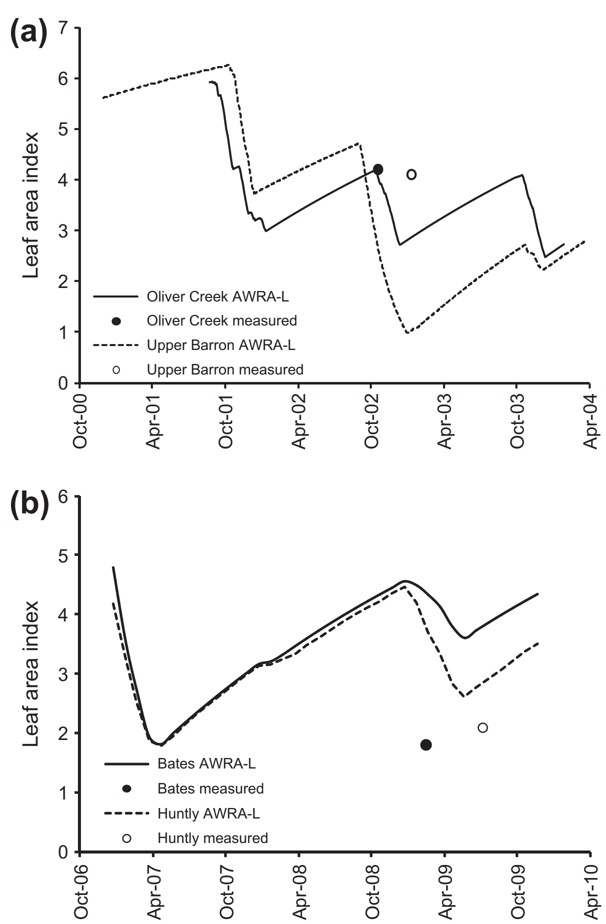

Fig. 4. Leaf area index of (a) two tropical rainforests and (b) two jarrah forests from the AWRA-L model (lines) and from once-off ground measurements (symbols).

3.1.2. Jarrah forests in Western Australia

Rainfall interception measurements from the two sites in jarrah forest in Western Australia were also used to optimise the Gash model and test the AWRA-L model. AWRA-L default parameters and optimised parameters from the Gash model for the three sites are presented in Table 2. The interception loss, mean rainfall rate, leaf area index and canopy cover were all considerably smaller than those at the rainforest sites. As a result, canopy storage and trunk storage were also smaller. A trunk storage of 0.11 mm was derived from the intercept of a linear regression of total storage versus L_j for seven jarrah forest sites (data not shown).

The optimised mean evaporation rate per unit canopy cover (E_c), 0.38–0.41 mm h^{-1}, was similar to that for the Oliver Creek rainforest. Based on actual measurements of cover and leaf area we estimated the light extinction coefficient at the zenith (κ) to be ∼0.3 in jarrah forests, compared to nearly 0.8 for rainforest. The rainforest value is consistent with other published values of κ for Malaysian (Kira, 1978) and Amazonian (Williams et al., 1971) rainforests. However, the calculated κ for jarrah forest does not account for foliage clumping, which is significant owing to the relative sparseness of jarrah forest (Macfarlane et al., 2007), resulting in underestimation of κ. At the zenith κ has been estimated at between 0.45 and 0.50 (Macfarlane et al., 2007). The light extinction coefficient, κ is used with leaf area index to calculate cover in the AWRA-L model (see Eq. (3)).

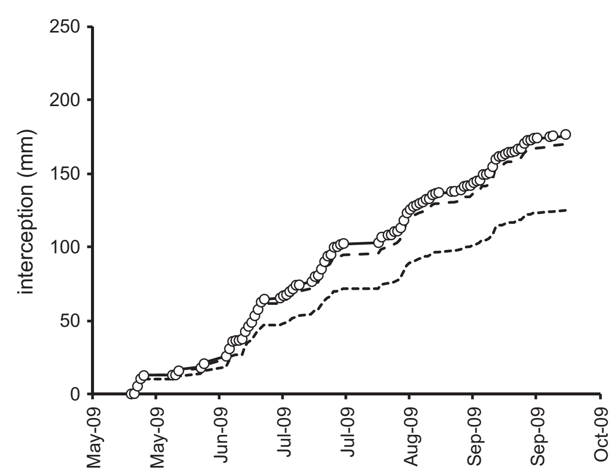

Fig. 5a. Comparison of cumulative interception loss from the Huntly jarrah forest site calculated using the Gash (solid lines) and the AWRA-L models with all default parameters (long dashes). Also shown are the results from the AWRA-L model with all parameters optimised except E_c (short dashes) and the measured values of cumulative interception at this site (○).

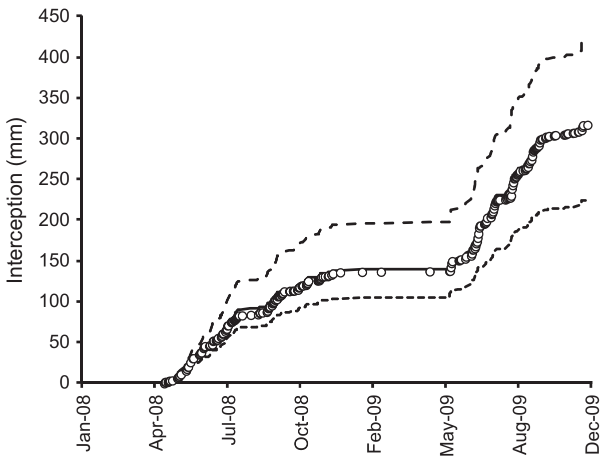

Fig. 5b. Comparison of cumulative interception loss from the Bates jarrah forest site calculated using the Gash (solid lines) and the AWRA-L models with all default parameters (long dashes). Also shown are the results from the AWRA-L model with all parameters optimised except E_c (short dashes) and the measured values of cumulative interception at this site (○).

Cumulative measured and modelled interception for the two jarrah forest sites are shown in Fig. 5 and the differences between each AWRA-L scenario parameterisation and total measured interception is summarised in Table 3. At the Bates forest the AWRA-L default (scenario 1 in Table 3) overestimates interception by 35%, whereas the default model run at the Huntly site follows the measured values quite closely. This latter agreement occurs despite the model overestimating leaf area by as much as 100% (Fig. 4b). In fact, substituting measured values of L_j at the jarrah forest sites substantially lowered AWRA-L modelled rainfall interception and using measured values of canopy cover further increased the difference between AWRA-L and measurements (Table 3). Substituting measured values of leaf-specific canopy storage (S_v) and accounting for trunk storage had little further effect on the AWRA-L results for these sparse jarrah forests. Using realistic canopy parameters in the jarrah forests (i.e. leaf area, canopy cover and S_v – scenario 4 in Table 3) in the AWRA-L model resulted in ~30% underestimation of interception (Table 3) and to close this gap it was necessary to use the optimised value of mean evaporation rate during rainfall per unit cover (E_c), as demonstrated in Fig. 5. Effectively, in jarrah forest, the default AWRA-L model has two errors, i.e. underestimation of E_c and overestimation of canopy cover and storage (via L_j), and fortuitously these errors compensated for each other at the Huntly site.

3.2. Variation in R and E across Australia

To improve the estimation of the ratio of E_c to R within AWRA-L (currently fixed at 0.2) we undertook an analysis of the spatial variation of both E (per unit ground area) and R, and their ratio, across a wide range of climate zones within Australia. Rain rate (calculated using 6 min pluivograph data – see Section 2) increased with proximity to the equator and ranged from as little as 1 mm h^{-1} at high latitudes to nearly 6 mm h^{-1} at low latitudes, Fig. 6a. A similar range of R has been observed across many studies of rainfall interception (Gash and Morton 1978; Lousteau et al., 1992; Llorens et al., 1997; Valente et al., 1997; Sraj et al., 2008; Wallace and McJannet, 2008). R was not correlated with mean annual rainfall, but the relationship between R and latitude (Φ) was strongly curvilinear and the following equation was derived following square-root transformation of R;

$$R = (2.56 + 0.040\Phi)^2 \quad r^2 = 0.80,\ p < 0.001. \tag{9}$$

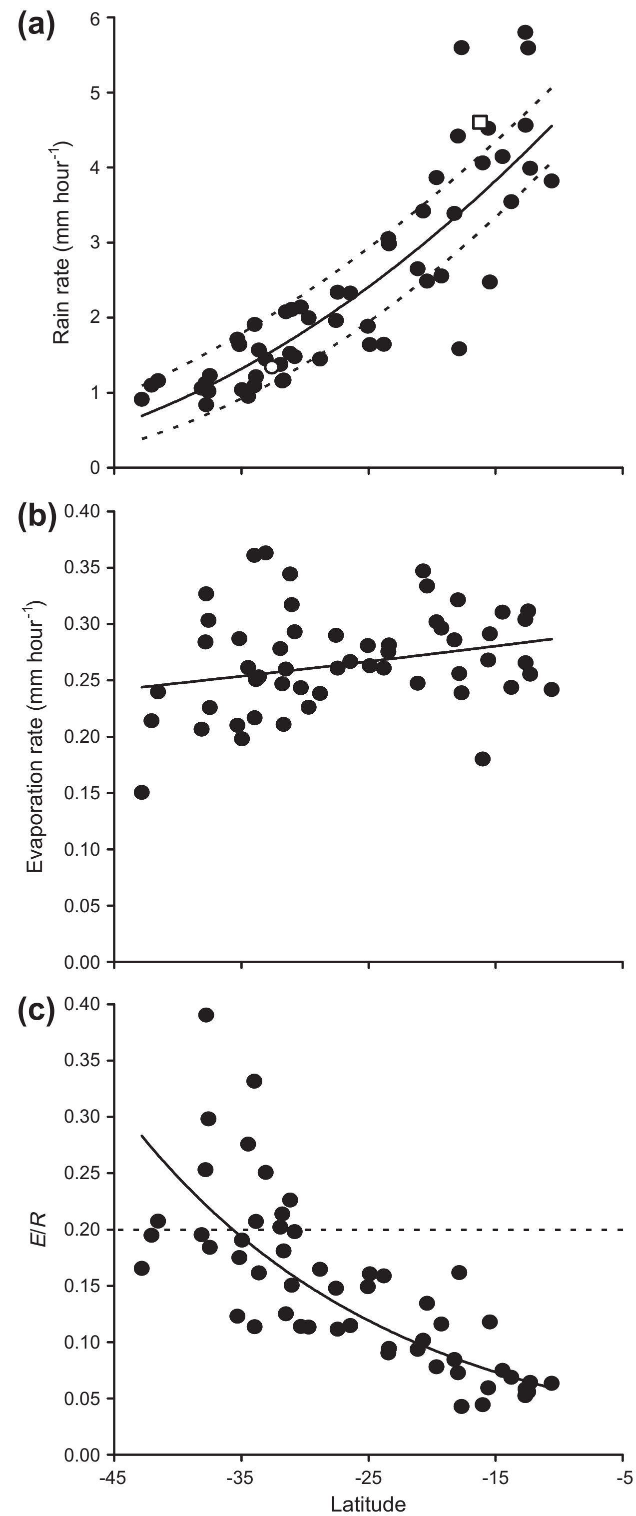

Fig. 6. (a) Rain rate (R), (b) evaporation rate during rainfall (E) and (c) their ratio (E/R) versus latitude for 54 sites across Australia. Values of E were calculated for a vegetation height of 20 m (the effect of vegetation height on E is illustrated in Fig. 8). The dashed lines in (a) represent the regression line ± 1 standard deviation and the open circle and open square represent the measured values of R for jarrah forest and rainforest respectively. The horizontal dashed line in (c) represents the value of E/R assumed by AWRA-L.

The increase of rain rate towards the equator is well documented across the world and in Australia (e.g. Jennings, 1967; Calder, 1996). Western et al. (2011) recently observed a similar trend of rainfall intensity with latitude based on the 6 min pluviograph

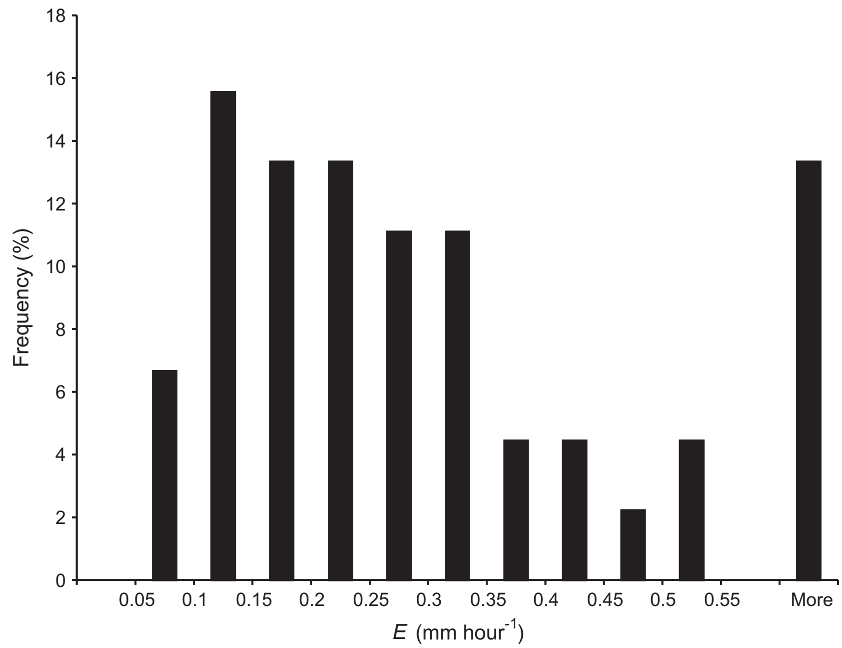

Fig. 7. Frequency (%) of observations of evaporation rate during rainfall from Murakami (2007) and Holwerda et al. (2012). The median evaporation rate was 0.26 mm h^{-1}.

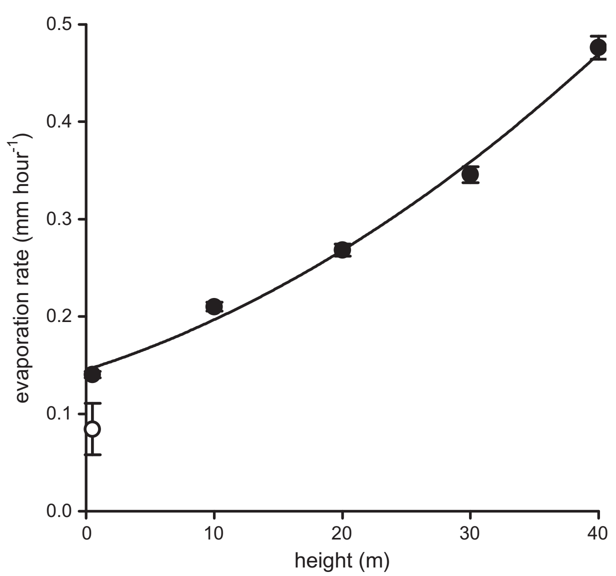

Fig. 8. Mean values of wet-canopy evaporation rate (E) calculated for vegetation of different heights using the Matt-Shuttleworth approach (closed circles) at 54 sites across Australia. The standard errors of the mean are also indicated by the error bars on each point. The FAO56 estimate of the mean evaporation rate for wet grass is indicated by the open circle.

record for Australia, to that observed in our study. Increased rain intensity is related to rain drop size, which is larger nearer the equator where rain derives from high intensity convective storms.

The evaporation rate from forests (E) during rainfall (calculated using SILO data in the Matt-Shuttleworth method; Eq. (5)) appears to increase slightly with proximity to the equator but it was not significantly correlated with either latitude or mean annual rainfall, Fig. 6b. Based on the 'default' value of a 20 m tree height, E ranged from 0.15 to 0.36 mm h^{-1}, and mean E across all sites was 0.27 mm h^{-1}, which is similar to that estimated or calculated in many other studies (Fig. 7). Murakami (2007) compiled estimates of E for the Gash model from 22 studies and found that most were less than 0.5 mm h^{-1}. Holwerda et al. (2012) compiled estimates of E for a further eight sites that ranged from 0.17 mm h^{-1} to 0.30 mm h^{-1}. The median value of E for all sites from both their studies is 0.26 mm h^{-1}. FAO56 estimates of wet-canopy evaporation rate (from short grass) were much smaller, 0.084 (±3%) mm h^{-1}, than those derived from the Matt-Shuttleworth approach, confirming that the FAO56 method is not suitable for wet forest canopies.

Fig. 6c shows that E/R decreased with proximity to the equator owing to the strong relationship of R with latitude and ranged from less than 0.05 near the equator to more than 0.3 at higher latitudes. Most of the values estimated are less than the default value of E/R assumed in AWRA-L of 0.2, and near the equator the values are much smaller and similar to the value of 0.05 assumed for crops. This suggests that the values of E/R originally selected for forests in AWRA-L may have been biased by published studies from high latitudes.

The wet canopy evaporation rate E estimated using the Matt-Shuttleworth approach is very sensitive to tree height (Fig. 8); a 10 m increase in tree height increased E by about 25%. Tree heights greater than 40 m were not tested in this study owing to the arbitrary blending height of 50 m used in the Matt-Shuttleworth method. However, 0–40 m covers the height range of most Australian woodlands and forests as well as the range of continental-scale height maps produced from sources such as space borne LiDAR (Simard et al., 2011). The empirical equation relating wet canopy evaporation rate to vegetation height is:

$$E = 0.0000985h^2 + 0.00417h + 0.145 \quad r^2 = 0.99, \ p < 0.001 \tag{10}$$

It is therefore possible for a revised version of the AWRA-L to vary E with vegetation height according to Eq. (10) and vary R according to latitude using Eq. (9). This would also provide the opportunity in the future for rain rate to be incorporated into sub-models of AWRA-L that estimate surface runoff (e.g. Mertens et al., 2002). The effects of these modifications to the AWRA-L model are presented in the following section.

Table 4
A summary of the canopy properties affecting the storage of water on the canopy of five rainforests and two jarrah forests. Parameters shown are; leaf area index (L), free throughfall coefficient (p), canopy cover (c), light extinction coefficient (κ), total storage per unit canopy (S_c), total storage per unit ground area (S), trunk storage per unit ground area (S_t), leaf storage per unit ground area ($S_{foliage}$) and specific leaf water holding capacity (S_L).

	L	p	$c = (1 - p)$	κ	S_c (mm)	S (mm)	S_t (mm)	$S_{foliage}$ (mm)	S_L (mm)
Oliver Creek	4.2	0.04	0.97	0.80	3.6	3.4	2.2	1.2	0.29
Hutchinson Creek	3.8	0.05	0.95	0.78	2.0	1.9	1.2	0.7	0.18
Mount Lewis 1	4.5	0.03	0.97	0.79	3.6	3.5	2.2	1.3	0.28
Mount Lewis 2	4.1	0.04	0.96	0.80	2.9	2.8	1.8	1.0	0.24
Upper Barron	4.1	0.04	0.96	0.79	2.7	2.6	1.7	0.9	0.23
Rainforest average	4.1	0.04	0.96	0.79	3.0	2.8	1.8	1.0	0.25
Std. devn.	0.25	0.01	0.01	0.01	0.66	0.66	0.42	0.24	0.05
CV (%)	6	22	1	1	22	23	23	23	18
Huntly	2.1	0.51	0.49	0.32	0.51	0.25	0.11	0.14	0.07
Bates	1.8	0.58	0.42	0.30	0.52	0.22	0.11	0.11	0.06
Jarrah average	2.0	0.55	0.46	0.31	0.52	0.23	0.11	0.12	0.06
Std. devn.	0.21	0.05	0.05	0.01	0.01	0.02	0.00	0.02	0.00
CV (%)	11	9	11	4	1	10	0	18	7

3.3. Improving AWRA-L performance

In tropical rainforests the key variable that needs to be improved in the AWRA-L model is the canopy capacity, S. This is determined by the water holding capacity per unit leaf area, S_v, leaf area index L_j and water storage on the trunks and branches, $S_{t,j}$ (Eq. (4)). To improve the estimation of S_v using canopy storage capacity data reported by Wallace and McJannet (2008) it is necessary to separate the total canopy storage S into its foliar and non-foliar components. Wallace and McJannet (2008) found S values ranging from 2.0 to 3.6 mm in Australian rainforests, and suggested one possible explanation for these comparatively high values was the contribution of epiphytes and mosses that are prevalent on the branches of these forests. It is also possible that the tree bark itself can store significant quantities of water, as demonstrated by Herwitz (1985) for rainforest trees in north Queensland. His laboratory wetting experiments indicated that the 'maximum' water holding capacity of the bark of 5 tree species ranged from 1.6 to 6.8 mm and that this constituted 50–75% of the total water holding capacity of the entire canopy. Similar bark wetting experiments in birch, hickory and oak trees in Massachusetts, USA have also found comparatively large bark storage capacities (0.4–2.5 mm; Levia and Herwitz, 2005).

The above bark storage capacities have been considered to be extreme upper values due to the long (days) bark immersion times used in the studies, but a number of other studies using both immersion techniques (for much shorter times, ~minutes) and spraying methods have also found that the storage of water in the bark may dominate the total canopy capacity. For example, in dry sclerophyll eucalypt forest in south east Australia, Crockford and Richardson (1990) reported that only 20% of the total canopy storage capacity of this forest (0.39 mm) was due to its foliage, the rest being caught by woody structures. Similarly, in the cypress and pine forests of north-central Florida, Liu (1998) found the foliage only accounted for 20–40% of total canopy storage, again the rest was held on branches and stems. Even smaller foliar contributions, 5–12% have been reported, e.g. in mixed species Mediterranean pine forest in the eastern Pyrenees in Spain (Llorens and Gallart, 2000). There is also evidence that short duration immersion experiments can produce storage capacities that are lower than those obtained from spraying or simulated rainfall (e.g. see Garcia-Estringana et al., 2010), so it would seem that some immersion wetting experiments may be giving reliable estimates of the effective storage capacity of the woody components of forests, rather than upper limit values.

Given the above evidence for a major contribution of woody structure to total canopy storage and the remaining possibility of a contribution from epiphytes and mosses, to obtain a specific leaf water holding capacity, S_L, it is therefore necessary to partition the total canopy storage values obtained by Wallace and McJannet (2008) into foliar and woody components. In the absence of specific information from their rainforest sites, one simple approach to this is to use the average fraction of canopy storage held on the bark, reported by Herwitz (1985) for a range of rainforest species in north Queensland, as 64%. Table 4 shows the results of this analysis for the 2 rainforest sites presented here plus 3 other rainforest sites from which equivalent data are also available (see Wallace and McJannet, 2008).

Leaf area and ground cover in these rainforests are relatively consistent at 4.1 (±0.3) and 96 (±1)% respectively. Total storage capacity per unit ground area (S) is only slightly less than its per unit canopy value (S_c) because of the high canopy cover. The average value of S is 2.8 (±0.7) mm, with 1.8 (±0.4) mm associated with storage on the trunks and branches leaving 1.0 (±0.2) mm stored on the foliage ($S_{foliage}$). This foliage water storage capacity is similar to the total canopy storage capacity reported for other tropical rainforests (e.g. 0.74 mm in the Amazon: Lloyd et al., 1988 and 1.15 mm in Puerto Rico: Schellekens et al., 1999). Dividing $S_{foilage}$ by L gives the specific leaf water holding capacity, S_L (Table 4); which has a mean value of 0.25 (±0.05) mm in the rainforests. This value is within the range of S_L values for all forests reported by Van Dijk (2010), 0.07–0.6 mm, and close to the S_L values for tropical rainforest species that can be derived from the data published by Hertwitz (1985), i.e. 0.23–0.33 mm. The equivalent canopy storage parameters for the two jarrah forests are also given in Table 4. These forests are much sparser ($L \sim 2$), have only got partial ground cover (~50%) and hold less canopy water in total and per unit leaf area (~0.06 mm). The latter may be due to the water repellent eucalyptus leaves that hang almost vertically; a display form which is reflected in the much lower light extinction coefficient for this species compared with rainforests (Table 4).

In order to derive a method to allow the canopy storage parameters for forests of any leaf area the S_L and S_t data in Table 4 are plotted against leaf area index in Fig. 9a and b. The empirical curves fitted to the data are best fit exponentials which can be used to calculate S_L and S_t provided L is known. Although the precise shape of these relationships would require more data from other forest types with a range of leaf areas, an increase in S_L with L would be expected due to variations in leaf size, leaf surface characteristics and leaf angle as canopies become more dense.

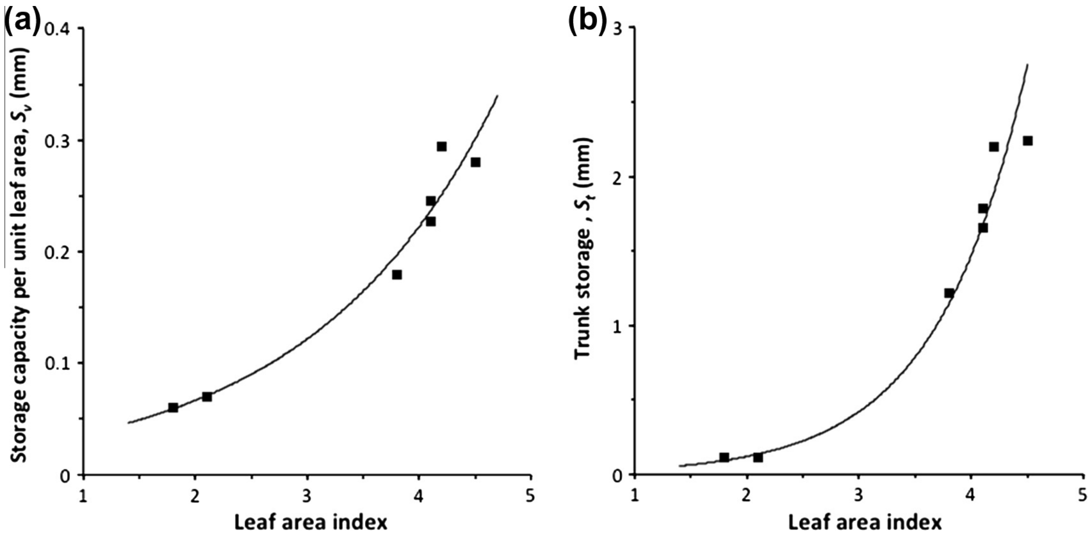

Fig. 9. The relationship between (a) storage capacity per unit leaf area (S_L) and (b) trunk storage capacity (S_t) and leaf area index (L). The empirical regressions have the form (a) $S_L = 0.02\ \exp(0.603L)$; $r^2 = 0.98$ and (b) $S_t = 0.01\ \exp(1.25L)$; $r^2 = 0.99$.

Forexample, it has been frequently demonstrated that leaf size increases in warmer and more humid environments (Grubb, 1977; Tanner 1980, Royer et al., 2005), where higher leaf area forest are more prevalent. Conversely, in drier environments leaves tend to be thicker and often have waxy coatings to reduce transpiration loss (Holloway, 1970). Such coatings also promote water shedding and reduce the water storage per unit leaf area. Leaves in drier climate also tend to have steeper leaf angles which is likely to be an adaptation to reduce exposure to radiation (and hence water stress) in the middle of the day (e.g. King, 1997; Cowan, 1982). This increased leaf angle is also likely to reduce S_v and κ as seen in the jarrah forests in the presentstudy (Table 4). Finally, the density of the canopy may also result in variations in S_L as wind speeds within the canopy and leaf movement are likely to be greater in a sparse open canopy than in a dense closed canopy (e.g. Pereira et al., 2009). Table 4 also shows that trunk storage (S_t) is much higher in rainforests, most likely because they support epiphytes and mosses (Wallace and McJannet, 2008) and their barks can absorb more water than the smooth water repellent eucalypts (Herwitz, 1985).

Table 5 shows the effect of replacing the default values of S_L and S_t used in the AWRA-L model with those calculated using the regressions shown in Fig. 9. In order to calculate S_L and S_t the improved canopy storage term uses the measured site leaf area index and also the measured cover (via the derived values of the light extinction coefficient (κ) – Table 4); two parameters which are a prerequisite of the improved continental scale model method. At Oliver Creek improving the canopy storage terms alone led to a large increase in interception loss (I) such that it became 34% of rainfall, much higher than the measured value of I. Adding the update to the ratio of E/R at this site, with R calculated using Eq. (9) and E derived from Eq. (10), reduces the modelled I to 25% of rainfall, identical to the measured I. Improving the canopy storage term at Upper Barron increases the modelled I to 34% of rainfall, slightly more than the measured I. However, adding the E/R derived from Eqs. (9) and (10) at this site decreases modelled I to 25%, significantly lower than the measured I. The main reason for the under prediction of I at this site is because Eq. (10) assumes a wind speed of 2 m s^{-1} (at 2 m), which is much lower than the average wind speed measured at the same height (in a clearing) at this site during rainstorms (6.8 m s^{-1}; Wallace and McJannet, 2008). Recalculation of E using Eq. (5) with the site wind speed increases E from 0.31 mm h^{-1} to 0.79 mm h^{-1} (close to the optimised value of E for this site, 0.81 mm h^{-1}; see Wallace and McJannet, 2008), which in turn increases I to 38% of rainfall. However, as specific site wind speeds are not routinely available (especially during rainfall) it is currently unavoidable for any operational version of AWRA-L to use a fixed wind speed (2 m s^{-1}) in the derivation of E using Eqs. (5) and (10), accepting that the model will underestimate I at windier locations.

Table 5 also shows that the AWRA-L model default parameters produced an interception loss that was much higher than the measured interception at the Bates jarrah forest site, but very close to the measured loss at the Huntly jarrah site. However, we have already noted that the agreement at Huntly was the fortuitous consequence of compensating errors in the default values of canopy storage (too high) and the ratio of E/R (too low) – see Table 2. The use of site based canopy storage parameters from the two jarrah sites (Table 5) leads to a decrease in I, taking the values significantly below the measured values of I and adding the updated values of E/R for these sites lowers the modelled I values slightly further (Table 5). Again the main reason for the resultant low AWRA-L model estimate is that its value of E derived from equation 10, 0.26 mm h^{-1}, is lower than the optimised values of E for these sites, 0.41 mm h^{-1} at Huntly and 0.38 mm h^{-1} at Bates. One possible explanation for the higher E values at the two jarrah sites may be due to the sparse nature of the forest, where higher ventilation rates around the trees may increase turbulent transfer (Pereira et al., 2009). Teklehaimanot et al. (1991) found this to be the case in their study of Sitka spruce trees of variable spacing. They concluded that the higher interception losses per tree in the sparse

Table 5
AWRA-L modelled interception loss (as a% of rainfall) obtained (1) in default mode, (2) by updating the canopy storage terms and (3) by updating the ratio of E/R for two rainforest and two jarrah forests. The measured interception loss (4) is also shown.

AWRA-L model conditions	Oliver Creek (%)	Upper Barron (%)	Huntly (%)	Bates (%)
1. Default AWRA-L parameters[a]	17	20	16	19
2. Improved canopy storage terms	34	34	11	9
3. As in 2 plus E/R from Eqs. (9) and (10)	25	25	9	8
4. Measured interception loss	25	33	16	14

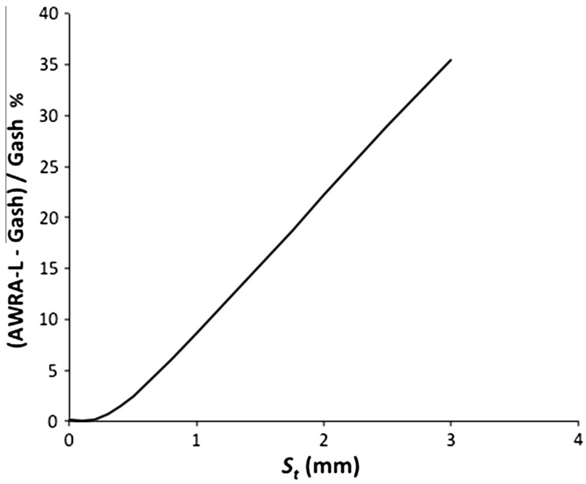

Fig. 10. The difference between the AWRA-L and Gash interception model estimates of interception as a function of trunk storage, S_t.

canopies were directly attributable to lower aerodynamic resistance and hence higher E rates during rainfall. Estimates of E made using Eq. (10) for sparse forests may therefore be too low, leading to underestimates of the interception loss in these types of forest.

The effect of partitioning total canopy storage into leaf and trunk components leads to a significant discrepancy between the AWRA-L and Gash modelled interception, Fig. 10. This shows that with identical parameterisations the AWRA-L model gives significantly higher values of interception than the Gash model once trunk storage exceeds ~0.5 mm. This discrepancy between the models is due to the different ways in which trunk storage (S_t) is treated in the two models. In the Gash model S_t is specified as a water store which has two components associated with storms that do not saturate the trunk ($p_t \bullet P_g$) and those which saturate the trunk (S_t). So with this specification the Gash model effectively accounts for evaporation from the trunks after rainfall, but does not allow for evaporation of water from the trunks during rainfall. In the AWRA-L model S_t is simply treated as part of the total canopy storage and so its value affects evaporation losses both during and after rainfall. When trunk storage is small, this difference is also small, but as S_t increases the Gash model interception is less than the AWRA-L model interception by the amount of the evaporation from the trunks during rainfall. Clearly further information on the partitioning of canopy storage into its foliar and non-foliar components along with measurements of their respective evaporation rates during rainfall are needed to determine which interception model is best suited to Australian forests.

4. Conclusions

Several important issues have been revealed by the current analysis of interception loss calculated by a continental scale model. Firstly, in default mode, models such as AWRA-L are driven by large scale gridded weather and rainfall data that are derived with spatial estimation methods such as those used in the SILO data system. This is a necessary perquisite of a continental scale model, but at some of the locations studied SILO rainfall is very poorly correlated with rainfall measured at the site. In consequence, it is difficult to reconcile AWRA-L interception estimates made with SILO data with site interception measurements unless the AWRA-L model is re-run with site based rainfall data. When this is done, there are still considerable differences, as described below, but it should be noted that in its normal operational mode AWRA-L will use SILO data and so in locations where this is significantly different from site specific rainfall differences may result in the interception loss simply because of the different rainfall input data. Furthermore, when AWRA-L is used to produce a water balance for an entire catchment it is possible that the SILO data provide a better estimate of catchment wide rainfall and hence the catchment scale water balance (including runoff) may be more reliable than a site based comparison suggests. Catchment scale water balance data would be required to see if this is the case.

When the AWRA-L model is run in default mode with site specific rainfall data there can still be very large differences between modelled and measured interception (up to 40%). This is particularly so in rainforests where the discrepancy arises largely because of AWRA-L's poor estimation of leaf area index, which results in a canopy storage capacity which is only 5–20% of the optimised canopy capacity in the Gash model. The AWRA-L default estimation of leaf area also has unrealistic seasonal variations and does not compare very well with the occasional point data available for the rainforest sites investigated. It is clear that this aspect of the model must be improved if this models interception estimation is to be made more reliable. When this is done (e.g. by improving the forest growth algorithms and or assimilating remotely sensed leaf area data) we recommend that the improved canopy storage method based on the regressions shown in Fig. 9 is adopted. Note that the continental scale model also has to derive ground cover (e.g. from leaf area) and this is also important parameter in interception modelling, especially in sparse forests.

At some rainforest locations the second major parameter controlling interception, E/R, is up to three times higher than that in the Gash model and this leads to an over estimation of interception in the AWRA-L model. Somewhat fortuitously, the AWRA-L overestimation of E/R and underestimation of canopy capacity compensate in some sparse jarrah forests, but not always. In these sparse forest types where the canopy capacity is small, E/R is the dominant factor leading to the AWRA-L underestimates of interception. Use of the improved method for estimating R (based on equation 9) give values which are not too different to those measured at the jarrah sites, so the main cause of the remaining model underestimation of interception loss is due to the use of E values which are too low. This may be due to the sparse nature of these forests where higher ventilation enhances E, however, more information on the relationship between a readily measurable index of sparseness (e.g. stem number per unit area, leaf area index or canopy cover) and aerodynamic resistance (used to derive E) is needed before this effect could be included in a continental scale model such as AWRA-L.

Overall, the adoption of updated canopy storage and E/R ratios outlined in this paper does provide a measurable improvement to the performance of the AWRA-L interception model. When interception is expressed as a percentage of rainfall (I) the modified AWRA-L model produces values of I which are within 1–8% of the measured I values at all four test sites. This level of uncertainty will propagate to the AWRA-L estimation of runoff, but may be significantly amplified especially in periods and places where rainfall is low (Wallace and McJannet, 2012).

Our analysis of the role of forest trunks and branches in storing and evaporating water has demonstrated that they may have a larger role in the interception process than hitherto thought. We have derived some preliminary values for trunk and leaf storage in both the rainforests and jarrah forests, which can be readily used in the interception modelling of other forests where leaf area is known. However, introducing a significant proportion of total canopy storage associated with trunks has revealed a potential underestimation of interception by the Gash et al. (1995) model, which ignores the potential for significant evaporation from the trunks during rainfall. The van Dijk and Bruijnzeel (2001a) model (used in AWRA-L) does allow for trunk evaporation during rainfall and therefore should provide a better estimate of interception loss when there is a significant component of trunk storage in a forest canopy.

Finally, it is worth noting that while the analysis and approaches developed in this study were aimed at improving the AWRA-L continental scale water balance model for Australia, the findings are also relevant for other studies looking to apply interception models, such as the Gash model and its derivatives, at large spatial scales (e.g. Miralles et al., 2010).

Acknowledgements

We would like to acknowledge the financial support provided by the Water Information R&D Alliance (WIRADA) between the Bureau of Meteorology and CSIRO's Water for a Healthy Country Flagship. We are also grateful to the internal (CSIRO) and external reviewers' whose comments and suggestions have greatly improved the manuscript.

Appendix A.

List of meteorological stations used and derived data including latitude (Lat), longitude (Long), Koeppen climate class (Koeppen class), annual rainfall (R_{annual}, mm/year), rain rate (R, mm/h), number of rain observations for calculation of rain rate ($n(R)$), daily evaporation (E_{daily}), FAO56 evaporation (FAO56), evaporation rate during rainfall (E), number of evaporation observations ($n(E)$) and the ratio of rain rate to evaporation rate (E/R). Rain rate was calculated for storms with at least 2 mm rain and no gap between adjacent rain gauge bucket tips more than 4 h. Evaporation rate was the mean daily evaporation rate for days with at least 50 mm rainfall and no gap between bucket tips of more than 4 h during that day. Estimates of E are based on a vegetation height of 20 m and an aerodynamic resistance of 10 s m^{-1}.

Station	Name	Lat	Long	Koppen class	R_{annual} (mm/year)	R (mm/h)	n (R)	E_{daily} (mm/day)	FAO56 (mm/day)	n (E)	E (mm/h)	E/R
2012	HALLS CREEK AIRPORT	−18.23	127.66	BSh	543	5.86	1843	6.86	2.32	5	0.29	0.05
3003	BROOME AIRPORT	−17.95	122.24	BSh	600	7.72	1509	7.71	2.67	10	0.32	0.04
4032	PORT HEDLAND AIRPORT	−20.37	118.63	BWh	307	4.40	823	8.01	2.65	11	0.33	0.08
6011	CARNARVON AIRPORT	−24.89	113.67	BWh	235	3.35	802	6.31	1.87	3	0.26	0.08
8051	GERALDTON AIRPORT	−28.80	114.70	Csa	453	2.27	2210	5.72	1.70	3	0.24	0.10
9021	PERTH AIRPORT	−31.93	115.98	Csa	809	1.87	2879	6.68	1.36	5	0.28	0.15
9053	PEARCE RAAF	−31.67	116.02	Csa	712	1.78	1183	5.06	1.20	1	0.21	0.12
9067	UPPER SWAN RESEARCH STATION	−31.76	116.02	Csa	740	1.58	1287	5.93	1.28	4	0.25	0.16
9510	BRIDGETOWN COMPARISON	−33.96	116.14	Csb	826	1.67	2942	8.66	2.50	1	0.36	0.22
9592	PEMBERTON	−34.45	116.04	Csb	1218	1.38	3439	6.27	1.43	4	0.26	0.19
9741	ALBANY AIRPORT	−34.94	117.80	Csb	863	1.47	3267	4.75	1.27	3	0.20	0.13
9789	ESPERANCE	−33.83	121.89	Csb	656	1.76	2279	6.01	1.94	5	0.25	0.14
12038	KALGOORLIE−BOULDER AIRPORT	−30.78	121.45	BSh	254	2.75	1230	7.03	2.17	3	0.29	0.11
13017	GILES METEOROLOGICAL OFFICE	−25.03	128.30	BWh	239	4.10	1081	6.74	2.35	6	0.28	0.07
14015	DARWIN AIRPORT	−12.42	130.89	Aw	1661	8.00	4033	7.48	2.51	39	0.31	0.04
14198	JABIRU AIRPORT	−12.66	132.89	Aw	1391	8.30	1577	7.30	2.55	6	0.30	0.04
14508	GOVE AIRPORT	−12.27	136.82	Aw	1423	6.67	1602	6.13	2.26	11	0.26	0.04
14903	KATHERINE AVIATION MUSEUM	−14.44	132.27	Aw	995	6.94	700	7.45	2.60	3	0.31	0.04
15135	TENNANT CREEK AIRPORT	−19.64	134.18	BSh	389	6.60	945	7.25	2.65	8	0.30	0.05
15590	ALICE SPRINGS AIRPORT	−23.80	133.89	BWh	262	3.44	1066	6.26	1.99	10	0.26	0.08
16001	WOOMERA AERODROME	−31.16	136.81	BWh	180	2.84	797	8.27	2.50	1	0.34	0.12
17043	OODNADATTA AIRPORT	−27.56	135.45	BWh	155	3.33	411	6.96	2.00	1	0.29	0.09
26021	MOUNT GAMBIER AERO	−37.75	140.77	Csb	727	1.22	4739	7.85	2.30	1	0.33	0.27
27006	COEN AIRPORT EVAP	−13.76	143.12	Aw	1177	5.78	1705	5.85	2.13	16	0.24	0.04
27022	THURSDAY ISLAND MO	−10.59	142.21	Aw	1721	6.17	2200	5.80	2.24	29	0.24	0.04
27042	WEIPA EASTERN AVE	−12.63	141.88	Aw	1766	7.40	2934	6.38	2.32	42	0.27	0.04
28000	LAURA POST OFFICE	−15.56	144.45	Aw	953	8.32	1515	6.43	2.40	4	0.27	0.03
28004	PALMERVILLE	−16.00	144.08	Aw	1048	6.55	1763	4.32	1.90	1	0.18	0.03
29041	NORMANTON POST OFFICE	−17.67	141.07	Aw	915	8.97	1234	5.73	2.18	17	0.24	0.03

(*continued on next page*)

Appendix A. (*continued*)

Station	Name	Lat	Long	Koppen class	R_{annual} (mm/year)	R (mm/h)	n (R)	E_{daily} (mm/day)	FAO56 (mm/day)	n (E)	E (mm/h)	E/R
29127	MOUNT ISA AERO	−20.68	139.49	BSh	430	6.13	1100	8.33	2.79	9	0.35	0.06
31017	COOKTOWN MISSION STRIP	−15.45	145.19	Aw	1688	5.39	1136	6.99	2.41	15	0.29	0.05
31083	KOOMBOOLOOMBA DAM	−17.84	145.60	Cfa	2352	3.18	5637	6.14	2.27	267	0.26	0.08
32040	TOWNSVILLE AERO	−19.25	146.77	Aw	1143	5.68	2519	7.11	2.53	49	0.30	0.05
33119	MACKAY M.O	−21.12	149.22	Cwa	1632	5.39	3432	5.94	2.17	59	0.25	0.05
36031	LONGREACH AERO	−23.44	144.28	BSh	436	4.86	1106	6.61	2.15	4	0.28	0.06
39083	ROCKHAMPTON AERO	−23.38	150.48	Cfa	878	5.20	2854	6.75	2.40	29	0.28	0.05
40223	BRISBANE AERO	−27.42	153.11	Cfa	1145	4.90	3168	6.26	1.98	38	0.26	0.05
44021	CHARLEVILLE AERO	−26.41	146.26	BSh	494	3.95	1758	6.40	2.08	4	0.27	0.07
48027	COBAR MO	−31.48	145.83	BSh	379	3.82	1438	6.24	2.02	5	0.26	0.07
50102	CONDOBOLIN SOIL CONSERVATION	−33.08	147.15	BSk	437	2.62	618	8.71	2.30	1	0.36	0.14
55024	GUNNEDAH RESOURCE CENTRE	−31.03	150.27	Cfa	603	3.27	2601	7.61	2.36	8	0.32	0.10
56013	GLEN INNES AG RESEARCH STN	−29.70	151.69	Cfb	842	3.55	2276	5.43	1.64	12	0.23	0.06
59040	COFFS HARBOUR MO	−30.31	153.12	Cfa	1680	4.13	3981	5.84	1.73	72	0.24	0.06
66037	SYDNEY AIRPORT AMO	−33.94	151.17	Cfa	1070	3.53	3092	5.20	1.54	35	0.22	0.06
70014	CANBERRA AIRPORT COMPARISON	−35.30	149.20	Cfb	600	2.72	3122	5.04	1.43	7	0.21	0.08
72150	WAGGA WAGGA AMO	−35.16	147.46	Cfa	554	2.71	2468	6.89	1.75	2	0.29	0.11
75050	NARADHAN (URALBA)	−33.61	146.32	BSk	430	2.58	916	6.07	2.20	1	0.25	0.10
84122	GENOA (FOOLS HAVEN)	−37.48	149.64	Cfb	947	2.38	2753	5.42	1.71	20	0.23	0.09
85072	EAST SALE AIRPORT	−38.12	147.13	Cfb	598	1.99	3052	4.96	1.53	7	0.21	0.10
86071	MELBOURNE REGIONAL OFFICE	−37.81	144.97	Cfb	650	2.07	6339	6.82	1.96	8	0.28	0.14
90135	CASTERTON SHOWGROUNDS	−37.59	141.41	Csb	666	1.67	2178	7.28	1.90	1	0.30	0.18
91104	LAUNCESTON AIRPORT COMPARISON	−41.54	147.20	Cfb	684	1.69	4453	5.76	1.20	1	0.24	0.14
94008	HOBART AIRPORT	−42.83	147.50	Cfb	516	1.98	2527	3.61	0.78	4	0.15	0.08

References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop Evapotranspiration. Irrigation and Drainage Paper 56. United Nations FAO, Rome, Italy.

Arnell, N.W., 1999. A simple water balance model for the simulation of streamflow over a large geographic domain. J. Hydrol. 217, 314–335.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Allen, P.M., 1999. Continental scale simulation of the hydrological balance. J. Am. Water Resour. Assoc. 35, 1037–1051.

Asdak, A., Jarvis, P.G., Gardingen, P.V., 1998. Evaporation of intercepted precipitation based on an energy balance in unlogged and logged forest areas of central Kalimantan, Indonesia. Agric. For. Meteorol. 92, 173–180.

Australian Water Act, 2007. ComLaw Authoritative Act C2012C00229. Office of Legislative Drafting and Publishing, Attorney-General's Department, Canberra, Australia.

Calder, I.R., 1996. Rainfall interception and drop size – development and calibration of the two-layer stochastic interception model. Tree Physiol. 16, 727–732.

Calder, I., Wright, I., 1986. Gamma ray attenuation studies of interception from Sitka spruce: some evidence for an additional transport mechanism. Water Resour. Res. 22, 409–417.

Churchward, H.M., Dimmock, G.M., 1989. The soils and landforms of the northern jarrah forest. In: Dell, B., Havel, J.J., Malajczuk, N. (Eds.), The Jarrah Forest. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 13–21.

Commonwealth of Australia, 2010. Australia's Forests at a Glance 2010. Canberra, Bureau of Rural Sciences.

Crockford, R.H., Richardson, D.P., 1990. Partitioning of rainfall in a Eucalypt forest and pine plantation in south eastern Australia. III Determination of the canopy storage capacity of a dry sclerophyll Eucalypt forest. Hydrol. Process. 4, 157–167.

Cowan, L.R., 1982. Regulation of water use in relation to carbon gain in higher plants. In: Lange, O.L., Bewley, J.D. (Eds.), Encyclopedia of Plant Physiology. vol. 12B, Springer-Verlag, Berlin, pp. 535–562.

Garcia-Estringana, P., Alonso-Blázquez, N., Algre, J., 2010. Water storage capacity, stemflow and water funneling in Mediterranean shrubs. J. Hydrol. 389, 363–372.

Gash, J.H.C., Morton, A.J., 1978. An application of the Rutter model to the estimation of the interception loss from Thetford forest. J. Hydrol. 201, 49–58.

Gash, J.H.C., 1979. An analytical model of rainfall interception in forests. Quart. J. Roy. Meteorol. Soc. 105, 43–55.

Gash, J.H., Lloyd, C.R., Lachaud, G., 1995. Estimating sparse forest rainfall interception with an analytical model. J. Hydrol. 170, 79–86.

Gentilli, J., 1989. Climate of the jarrah forest. In: Dell, B., Havel, J.J., Malajczuk, N. (Eds.), The Jarrah Forest. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 23–40.

Grubb, P.J., 1977. Control of forest growth and distribution on wet tropical mountains: with special reference to mineral nutrition. Annu. Rev. Ecol. Syst. 8, 83–107.

Herwitz, S.R., 1985. Interception storage capacities of tropical rainforest canopy trees. J. Hydrol. 77 (1–4), 237–252.

Holloway, P.J., 1970. Surface factors affecting the wetting of leaves. Pestic. Sci. 1, 156–163.

Holwerda, F., Bruijnzeel, L.A., Scatena, F.N., Vugts, H.F., Meesters, A.G.C.A., 2012. Wet canopy evaporation from a Puerto Rican montane rain forest: the importance of realistically estimated aerodynamic conductance. J. Hydrol. 414–415, 1–15.

Jeffrey, S.J., Carter, J.O., Moodie, K.B., Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australian climate data. Environ. Modell. Softw. 16 (4), 309–330.

Jennings, J.N., 1967. Two maps of rainfall intensity in Australia. Aust. Geogr. 10, 256–262.
King, D.A., 1997. The functional significance of leaf angle in Eucalyptus. Aust. J. Bot. 45, 619–639.
Kira, T., 1978. Community architecture and organic matter dynamics in tropical lowland rain forests of Southeast Asia with special reference to Pasoh Forest, West Malaysia. In: Tomlinson, P.B., Zimmerman, M.H. (Eds.), Tropical Trees as Living Systems. Cambridge University Press, Cambridge, pp. 561–590.
Leavesley, G.H., 1994. Modelling the effects of climate change on water resources – a review. Clim. Change 28, 159–177.
Lee, A., Scarth, P., Gerrand, A., 2009. A new dataset for forest height across Australia: pilot project to calibrate ICESat laser data with airborne LiDAR. In: Jones, S., Reinke, K. (Eds.), Innovations in Remote Sensing and Photogrammetry, Lecture Notes in Geoinformation and Cartography. doi: http://dx.doi.org/10.1007/978-3-540-93962-7_4.
Levia, D.F., Herwitz, S.R., 2005. Interspecific variation of bark water storage capacity of three deciduous trees in relation to stemflow yield and solute flux to forest soils. Catena 64, 117–137.
Llorens, P., Pouch, R., Latron, J., Gallart, F., 1997. Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area 1. Monitoring design and results down to the event scale. J. Hydrol. 199, 331–345.
Llorens, P., Gallart, F., 2000. A simplified method for forest water storage capacity measurement. J. Hydrol. 240, 131–144.
Lloyd, C.R., Gash, J.H.C., Shuttleworth, W.J., Marques-Filho, A.de O., 1988. The measurement and modelling of rainfall interception by Amazonian rain forest. Agric. For. Meteorol. 43, 277–294.
Liu, Shuguang, 1998. Estimation of rainfall storage capacity in the canopies of cypress wetlands and slash pine uplands in North-Central Florida. J. Hydrol. 201, 32–41.
Lousteau, D., Berbigier, P., Granier, A., El Hadj Mussa, F., 1992. Interception loss, throughfall and stemflow in a maritime pine stand: I. Variability of throughfall and stemflow beneath the pine canopy. J. Hydrol. 138, 449–467.
Macfarlane, C., Hoffman, M., Eamus, D., Kerp, N., Higginson, S., McMurtrie, R., Adams, M., 2007. Estimation of leaf area index in eucalypt forest using digital photography. Agric. For. Meteorol. 143 (3–4), 176–188.
Macfarlane, C., Ogden, G.N., Silberstein, R.S., 2011. Water Balance of 31 Mile Brook, Western Australia. Report to the WA Water Foundation. CSIRO, Floreat WA, 54 pp.
McJannet, D., Wallace, J., Reddell, P., 2007a. Precipitation interception in Australian tropical rainforests: I. Measurement of stemflow, throughfall and cloud interception. Hydrol. Process. 21, 1692–1702.
McJannet, D., Wallace, J., Reddell, P., 2007b. Precipitation interception in Australian tropical rainforests: II. Altitudinal gradients of cloud interception, stemflow, throughfall and interception. Hydrol. Process. 21, 1703–1718.
Mertens, J., Raes, D., Feyen, J., 2002. Incorporating rainfall intensity into daily rainfall records for simulating runoff and infiltration into soil profiles. Hydrol. Process. 16, 731–739.
Miralles, D.G., Gash, J.H., Holmes, T.R.H., de Jeu, R.A.M., Dolman, A.J., 2010. Global canopy interception from satellite observations. J. Geophys. Res. 115, D16122. http://dx.doi.org/10.1029/2009JD013530.
Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics. Edward Arnold, UK.
Murakami, S., 2007. Application of three canopy interception models to a young stand of Japanese cypress and interpretation in terms of interception mechanism. J. Hydrol. 342, 305–319.
Neilson, R.P., 1995. A model for predicting continental-scale vegetation and water balance. Ecol. Appl. 5, 362–385.
Pereira, F.L., Gash, J.H.C., David, J.S., Valente, F., 2009. Evaporation of intercepted rainfall from isolated evergreen oak trees: do the crowns behave as wet bulbs? Agric. For. Meteorol. 149, 667–670.
Roberts, J.M., Cabral, O.M.R., da Costa, J.P., McWilliam, A.-L.C., Sa, T.D.de A., 1996. An overview of the leaf area index and physiological measurements during ABRACOS. In: Gash, J.H.G., Nobre, C., Roberts, J.M., Victoria, R.L. (Eds.), Amazonian Deforestation and Climate. John Wiley & Sons Ltd., Chichester, England, pp. 287–306.
Roberts, J.M., Gash, J.H.C., Tani, M., Bruijnzeel, L.A., 2005. Controls on evaporation in lowland tropical rainforest. In: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, Cambridge, UK, pp. 287–313.
Royer, D.L., Wilf, P., Janesko, D.A., Kowalski, E.A., Dilcher, D.L., 2005. Correlations of climate and plant ecology to leaf size and shape: potential proxies for the fossil record. Am. J. Bot. 92, 1141–1151.
Schellekens, J., Scatena, F.N., Bruijnzeel, L.A., Wickel, A.J., 1999. Modelling rainfall interception by a lowland tropical rainforest in northeastern Puerto Rico. J. Hydrol. 225, 168–184.
Shuttleworth, W.J., Wallace, J.S., 2009. Calculating the water requirements of irrigated crops in Australia using the Matt-Shuttleworth approach. Trans. ASABE 52, 1895–1906.
Simard, M., Pinto, N., Fisher, J.B., Baccini, A., 2011. Mapping forest canopy height globally with spaceborne lidar. J. Geophys. Res. 116, G04021.
Sraj, M., Brilly, M., Mikos, M., 2008. Rainfall interception by two deciduous Mediterranean forests of contrasting stature in Slovenia. Agric. For. Meteorol. 148, 121–134.
Tanner, E.V.J., 1980. Studies of the biomass and productivity in a series of montane rain forests in Jamaica. J. Ecol. 68, 573–588.
Teklehaimanot, Z., Jarvis, P.G., Ledger, D.C., 1991. Rainfall interception and boundary layer conductance in relation to tree spacing. J. Hydrol. 123, 261–278.
Valente, F., David, J.S., Gash, J.H.C., 1997. Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. J. Hydrol. 190, 141–162.
van Dijk, A.I.J.M., 2010. The Australian Water Resources Assessment System. Technical Report 3. Landscape Model (Version 0.5) Technical Description. Water for a Healthy Country National Research Flagship, CSIRO, 75pp.
Van Dijk, A.I.J.M., Bruijnzeel, L.A., 2001a. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1 Model description. J. Hydrol. 247, 230–238.
Van Dijk, A.I.J.M., Bruijnzeel, L.A., 2001b. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 2. Model validation for a tropical upland mixed cropping system. J. Hydrol. 247, 239–262.
van Dijk, A.I.J.M., Meesters, A.G.C.A., Schellenkens, J., Bruijnzeel, L.A., 2005. A two-parameter exponential rainfall depth–intensity distribution applied to runoff and erosion modelling. J. Hydrol. 300, 155–171.
van Dijk, A.I.J.M., Peña-Arancibia, J.L., Bruijnzeel, L.A., 2011. Top-down analysis of collated streamflow data from heterogeneous catchments leads to underestimation of land cover influence. Hydrol. Earth Syst. Sci. 8, 4121–4150.
Wallace, J.S., McJannet, D.L., 2006. On interception modelling of a lowland coastal rainforest in northern Queensland, Australia. J. Hydrol. 329, 477–488.
Wallace, J.S., McJannet, D.L., 2008. Modelling interception in coastal and montane rainforests in northern Queensland, Australia. J. Hydrol. 348, 480–495.
Wallace, J.S., McJannet, D.L., 2012. Climate change impacts on the water balance of coastal and montane rainforests in northern Queensland, Australia. J. Hydrol. 475, 84–96 .
Wallace, J., Ellis, T., Grigg, A., Hawdon, A., Keen, R., Macfarlane, C., McJannet, D., 2011. The Australian Water Resources Assessment System: Improvements to Vegetation Hydrology in the AWRA-L Model. Progress Report on Extension to CSIRO Water for a Healthy Country Flagship, 13 June 2011, 63pp.
Western, A.W., Anderson, B., Siriwardena, L., Chiew, F.H.S., Seed, A., Bloschi, G., 2011. The within-day behaviour of 6 minute rainfall intensity in Australia. Hydrol. Earth Syst. 15, 2561–2579.
Williams, W.A., Loomis, R.S., Alvim, de T.P., 1971. Environments of evergreen rain forests on the lower Rio Negro, Brazil. Trop. Ecol. 13, 65–78.
Wood, E.F., Lettenmaier, D., Laing, X., Nijssen, B., Wetzel, S.W., 1997. Hydrological modelling of continental-scale basins. Annu. Rev. Earth Planet. Sci. 25, 279–300.