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Modelling canopy and litter interception in commercial forest plantations in South Africa

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Abstract

There is a gap in the knowledge of both canopy and litter interception in South African forest hydrology. Interception is typically considered to constitute only a small portion of the total evaporation and in some models is disregarded. Interception is a threshold process, as a certain amount of water is required before successive processes can take place. Therefore an error introduced in modelling interception, especially disregarding it, will automatically introduce errors in the calibration of subsequent models/processes. Field experiments to assess these processes, viz. canopy and litter interception were established for the three main commercial forestry genera in South Africa, namely, *Pinus*, *Acacia* and *Eucalyptus*. Drawing on both field and laboratory data, the "variable storage Gash" model for canopy interception and an idealised drying curve litter interception model were developed to represent these processes. It was found that canopy and litter interception can account for as much as 26.6 % and 13.4 % of gross precipitation, respectively, and are therefore important hydrological processes. The models developed were able to adequately represent these interception processes and provide a way forward for more representative water resources planning modelling.

1 Introduction

There is a gap in the knowledge of both canopy and litter interception in South African forest hydrology, as well as internationally. Interception is typically considered to constitute only a small portion of total evaporation and in some models is disregarded completely (Gerrits et al., 2008) or merely lumped with total evaporation and not considered as a separate process (Savenije, 2004). Interception is a threshold process, as a certain amount of water is required before successive processes such as infiltration and runoff can take place. Therefore an error introduced in modelling interception, especially disregarding it, will automatically introduce errors in the calibration of subsequent models/processes (Savenije, 2004).

The first reference to the development of canopy interception models in current literature can be ascribed to Horton (1919) who defined interception loss as “leaf storage capacity and evaporation loss during the storm” which he expressed as:

$$I_\mathrm{l} = E\,\mathrm{d}t + S_\mathrm{c} \tag{1}$$

where:
E = evaporation rate of intercepted water during rainfall,
S_c = canopy storage capacity, and
t = rainfall duration.

Until the early 1970’s, attempts to generalise interception losses were usually expressed in the form of regression analyses of interception loss and bulk rainfall (Llorens, 1997).

Rutter et al. (1971, 1975) were the first to model forest rainfall interception with a physically based model using hourly rainfall and meteorological data (Llorens, 1997), having recognised that the process was primarily driven by evaporation from the wetted canopy. The evaporation from the wet canopy is calculated using the Penman-Monteith equation with the canopy resistance set as zero (Rutter, 1971). The canopy structure is described by the throughfall coefficient (p), the stemflow partitioning coefficient (p_t), the canopy storage (S_c) and the trunk storage (S_t). The throughfall, stemflow and interception loss is estimated in the model using input rainfall and meteorological data (Rutter, 1971; Valente et al., 1997) The model is essentially based on the dynamic calculation of the water balance of the canopy and trunk through Eqs. (2) and (3).

$$(1 - p - p_t)\int P\mathrm{d}t = \int D\mathrm{d}t + \int E\,\mathrm{d}t + \Delta C \tag{2}$$

$$p_t\int R\mathrm{d}t = \mathrm{Sf} + \int E_t\mathrm{d}t + \Delta C_\mathrm{t} \tag{3}$$

where R is the intensity of gross rainfall, D is the rate of drainage from the canopy, E is the rate of evaporation of water intercepted by the canopy, ΔC is the change in canopy

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storage, Sf is stemflow, E_t is the evaporation of water intercepted by the trunk, and ΔC_t is the change in trunk storage.

Later, Gash (1979) proposed a rainfall interception model, which is essentially a simplified analytical form of the Rutter et al. (1971, 1975) model. While Gash (1979) recognised that Rutter's model was the most rigorous method for estimating interception loss at the time, he identified practical disadvantages in its use. Firstly, it requires detailed meteorological data and, secondly, it was computationally intensive. These two problems are however, not so significant today, as data collection and computational processing have advanced considerably (Llorens, 1997).

The original Gash (1979) model is based on three main components;

1. the bulk rainfall input,
2. canopy structure parameters, and
3. evaporation of intercepted water.

The model is also based on three main assumptions, as follows;

1. the rainfall pattern is represented by a series of discrete storms which are separated by sufficiently long intervals to allow the canopy to dry,
2. the rainfall and evaporation rates are constant during the storm, and under conditions of canopy saturation the mean rainfall and evaporation rates are used, and
3. there is only one storm per rain day (which is a definite weakness of the model).

The original Gash (1979) model considers rainfall as a series of discrete events, during which three phases can be identified. These are the wetting phase, saturation phase, and the drying phase after the rainfall has stopped.

The meteorological conditions prevailing during the first two phases are assumed to be the same and average values of gross rainfall intensity ($\bar{R}$) and evaporation rate ($\bar{E}$) for saturated canopy conditions are calculated for the whole simulation period and

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then applied in a generalised form to all individual rainfall events (Valente et al., 1997). The model uses total daily rainfall and assumes that there is only one storm per day and that there is sufficient time between storms for the canopy to dry (Zhang et al., 2006) in its calculation of canopy interception. The model was therefore not intended for use on short crops in temperate regions where the vegetation may stay wet for prolonged periods of time (van Dijk and Bruijnzeel, 2001a). Like the Rutter model, Gash's analytical model requires prior estimates of structural parameters of the forest canopy which are described in terms of the storage capacity (S_c), which is the amount of water left on a saturated canopy under conditions of zero evaporation after the rainfall and canopy drainage have ceased (Gash and Morton, 1978). The model also requires a free throughfall coefficient (p) and a stemflow coefficient (p_t). The Gash model has been used with considerable success to predict interception in a wide range of environments, including temperate coniferous and broadleaf forests, and tropical forests (van Dijk and Bruijnzeel, 2001a).

However, both the original Rutter et al. (1971, 1975) and Gash (1979) models only performed well for modelling interception in relatively closed canopies. This is especially true for the evaporative process, due to the assumption that the canopy and trunk storages extend to the whole plot area. Results from various studies (Lankreijer et al., 1993; Gash et al., 1995) suggest that the models should not be applied to sparse forests as the models tend to overestimate the interception loss. This led to the development of a "sparse canopy" variant (Gash et al., 1995) in which evaporation from a wet canopy was considered linearly dependant on the canopy cover fraction (van Dijk and Bruijnzeel, 2001a).

Gash et al. (1995) revised the original model by addressing both a conceptual error and its poor performance in sparse canopy forests. This was corrected by introducing an additional parameter for the canopy cover fraction (c) as well as making the canopy storage (S_c) and the wet canopy evaporation rate linearly dependant on it. By doing this the conceptual error was removed, as it was assumed in the original model that the relative evaporation rate (E/R) was independent of ($1 - p - p_t$). Had this not been corrected, a negative algorithm would result when calculating the rainfall necessary to saturate the canopy (P'_G), in a situation where $(1 - p - p_t)R < E$ (Gash et al., 1995). Recent applications of the model indicate that it is suitable for predicting a wide range of conditions, from closed canopies to sparse canopies (David et al., 2005).

Van Dijk and Bruijnzeel (2001a,b) then modified the Gash et al. (1995) revised model by allowing it to be applied to rapidly growing vegetation where the leaf area index (LAI) is changing through time. The modifications are based on the following three hypotheses:

1. The canopy capacity (S_c) is linearly related to LAI.
2. The relative evaporation rate (E/R) can be expressed as a function of LAI.
3. The water that is retained on the stems can be treated in a similar way to that retained by the canopy (i.e. evaporation from saturated stems during the storm may be included in the simulations).

The modifications by van Dijk and Bruijnzeel (2001a,b) to the Gash et al. (1995) model essentially revolve around the leaf area index (LAI) parameter. For this model LAI is defined as the cumulative one-sided area of (healthy) leaves per unit area. LAI and the canopy cover fraction (c), can be related to one another via the Beer-Lambert equation that describes the attenuation of radiation (e.g. photosynthetically active radiation, PAR) as a function of LAI. PAR however, does not penetrate through leaves much, therefore the Beer-Lambert equation may be expressed in terms of canopy cover fraction using similar parameters. The relationship between c and LAI is thus given by Eq. (4):

$$c = 1 - \mathrm{e}^{-K \cdot \mathrm{LAI}} \tag{4}$$

where K is the extinction coefficient. The value of K for a particular radiation wavelength depends on the inclination angle and distribution of the leaves, and for PAR usually ranges between 0.6 and 0.8 in forests (van Dijk and Bruijnzeel, 2001a,b).

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A shortcoming of previous versions of the Gash model is that they consider the canopy storage capacity to be constant. Bulcock and Jewitt (2012) show that the storage capacity varies with rainfall intensity and has been corroborated by Calder (1996) and Hall (2003), a canopy interception model that considers a variable storage capacity with rainfall intensity is required. With this in mind, the "variable storage Gash model" was developed. The results from the "variable storage Gash model" were used as an input to model litter interception, as it is the throughfall that determines the amount of water that will reach the litter. Unlike canopy interception which is dependent on many factors including the storage capacity, potential evaporation, rainfall intensity and rainfall duration, the litter interception is largely dependent on the storage capacity. This is due to evaporative drivers under the canopy such as radiation, temperature and wind speed being moderated by the above canopy. Therefore, as long as the input of simulated throughfall from the "variable storage Gash model" and litter storage capacity is estimated accurately, then the idealised drying curve model should perform well. While the "variable storage Gash model" may be considered complex and the idealised drying curves fairly simple, it is important to develop models that are useful at the scale of implementation and can use readily available data. A way of negotiating complex problems is by considering a requisite simplicity. A requisite simplicity attempts to discard some detail, while retaining conceptual clarity and scientific rigour (Stirzaker et al., 2010). Therefore, by combining the "variable storage Gash model" and the idealised drying curves to simulate "total interception" a requisite simplicity is achieved.

In order to provide further insight into these processes, field experiments to assess canopy and litter interception were established for the three main commercial forestry genera in South Africa, namely, *Pinus, Acacia* and *Eucalyptus* to assess interception of "broadleaf", "compound leaf" and "needle-leaf" trees. The study took place in the well documented CSIR Two Streams research catchment, located in the Seven Oaks area, about 70 km north-east of Pietermaritzburg in the KwaZulu-Natal Midlands. In this paper we show how information from these studies can be used to improve the representation of interception in hydrological models. The field data collected, as well

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as laboratory data were used to improve modelling these two important hydrological processes, using as few parameters as possible but retaining a requisite simplicity.

2 Variable storage Gash interception model

The original Gash (1979) and later the revised Gash et al. (1995) model are probably the best known canopy interception models. *Both* the Gash (1979) and revised Gash et al. (1995) models classify storms according to the amount of gross rainfall (P_g) generated and then compute interception loss (I), throughfall (T), and stemflow (Sf). The Gash (1979), Gash et al. (1995) models, and subsequently the "variable storage Gash model" which has been developed for this study, require canopy structure parameters, climate parameters, and interception parameters.

The "variable storage Gash model" is based on three assumptions, the first two being from the original Gash model:

1. The rainfall distribution pattern may be represented as a succession of discrete storms, separated by sufficiently long periods to allow the canopy and trunks to dry (Gash, 1979; Gash et al., 1995);

2. The rainfall and evaporation rates are constant during each storm and may be considered as constant between several storms during the same period (Gash, 1979; Gash et al., 1995); but introduces an additional assumption i.e. that,

3. The maximum canopy storage capacity (S_c^{max}) is linearly related to LAI (van Dijk and Bruinzeel, 2001a,b), but the storage capacity (S_c) varies with different rainfall intensites (R).

The integrity of the original Gash model has not been jeopardised by the modifications made to the "variable storage Gash model". The process of interception loss is a function of several properties of the tree, including branch, stem and crown characteristics, and the structure of the stand (Rutter et al., 1975). Widely spaced trees have larger

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spaces between them, therefore the ventilation within the stand increases and may result in more rainfall being intercepted and evaporated from the tree. However, tree spacing also affects the leaf area per unit ground area and the spatial distribution of leaf area density and will modify both the available energy and boundary layer conductance of the stand and thus influence the rate of evaporation of intercepted water (McNaughton and Jarvis, 1983) in Teklehaimanot et al. (1991). In the "variable storage Gash model" this has been accounted for by using LAI as the primary parameter to describe the canopy structure. The model requires just five parameters to describe canopy interception, and seven if stemflow is required i.e. gross precipitation, evaporation, rainfall rate and LAI and maximum storage capacity. For stemflow, the additional parameters are trunk storage capacity (S_t) and the stemflow partitioning coefficient (p_t). Table 1 summarizes the names of the various versions of the Gash models and authors referred to in this document.

2.1 Interception parameters

One of the most important parameters in all versions of the Gash model, including the "variable storage Gash model" is the rain to fill canopy storage ($P'g$) which is described by Eq. (5):

$$P'g = -\ln(1 - \{E/[R(1-p-p_t)]\}) \cdot S_\mathrm{c}(R/E). \tag{5}$$

In this equation, the main term is the $S_\mathrm{c}(R/E)$ term, which is the amount of rain needed to fill the storage given, that most of the rain passes through the tree canopy. It must be noted that it must be impossible for $E/R > (1-p-p_t)$, because $(1-p-p_t)$ equals interception *and* canopy drip throughfall, whereas E/R is only interception.

The rain to fill the trunk storage ($P't$) (Gash, 1979) is described by Eq. (6):

$$P't = S_\mathrm{t}/p_\mathrm{t}. \tag{6}$$

The stemflow partitioning coefficient (p_t) is the fraction of rain that runs down the stem of a tree during a storm, and the trunk storage capacity (S_t) is the total amount of water the trunk can hold (mm). The intercepted coefficient is therefore the fraction of rain held in the canopy during a storm and is described as $(1 - p - p_t)$.

2.2 Analytical model equations

The equations in the original Gash (1979), revised Gash et al. (1995) and "variable storage Gash" models used to distribute rainfall from individual storms between the different storage terms are described below. Some are constant for all storms while others depend on the actual rainfall amount.

For small storms, where the rainfall amount is insufficient to saturate the canopy (i.e. $Pg < P'g$), the evaporation from the canopy (I_c) is described as Eq. (7):

$$I_c = Pg(1 - p - p_t). \tag{7}$$

For large storms (i.e. $Pg > P'g$), evaporation is considered in four phases (Eqs. 8 to 11):

Evaporation during wetting phase

$$(I_w) = [(1 - p - p_t)P'g)] - S_c. \tag{8}$$

Evaporation of saturated canopy

$$(I_s) = (E/R)(Pg - P'g). \tag{9}$$

Evaporation after rain ceases

$$(I_a) = S_c. \tag{10}$$

Evaporation from trunks

$$(I_t) = St(\text{ if } Pg < P't, \text{ then } I_t = p_t \cdot Pg). \tag{11}$$

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For all storms, irrespective of size, the stemflow (F) (Eq. 12) and throughfall (T) (Eq. 13) are considered as:

$$\mathrm{Sf} = pt(Pg - P't) \tag{12}$$

$$T = Pg - I - \mathrm{Sf}. \tag{13}$$

The stemflow is the product of the stemflow partitioning coefficient (p_t) and the difference between gross precipitation and rain to fill the trunk storage. Throughfall is simply the difference of gross precipitation, interception loss and stemflow.

2.3 Canopy structure parameters

Gash et al. (1995) introduced the canopy cover fraction (c) to account for inadequacies in modelling sparse canopies in the original model. Van Dijk and Bruijnzeel (2001a,b) then modified the revised Gash et al. (1995) model allowing it to be applied to rapidly growing vegetation where the LAI is changing through time. In addition, the “variable storage Gash model” introduces a vegetation/species specific parameter, termed the maximum elemental volume (v_e^{max}), which accounts for the water holding characteristics of the canopy. LAI is defined as the cumulative one-sided area of leaves per unit area. In this model, LAI and c, can be related to one another via the Beer-Lambert equation (Eq. 14) which describes the attenuation of radiation (i.e. photosynthetically active radiation, PAR) as a function of LAI. PAR however, does not penetrate far through leaves, therefore the Beer-Lambert equation may be expressed in terms of canopy cover fraction using similar parameters. The relationship between c and LAI is thus given by Eq. (14) and is illustrated in Fig. 1, where the extinction coefficient $k = 0.5$ (Landsberg and Waring, 1997; Battaglia et al., 2004) was used to model the results in this study. Gazarini et al. (1990) found that a value of $k = 0.50$ was appropriate in their study of *E. globulus*, while Pierce and Running (1988) and Sampson and Lee Allen (1998) used values of 0.52 and 0.60 for pine, respectively. No values for *Acacia* could be found.

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$$c = 1 - e^{-k \cdot \mathrm{LAI}} \tag{14}$$

The free throughfall coefficient (p) is the fraction of rain that passes through a canopy during a storm without touching the canopy and can be described as $p = 1 - c$ (van Dijk and Bruijnzeel, 2001a).

2.4 Storage capacity and drop size

An often ignored factor when modelling or measuring canopy interception which has been incorporated into the "variable storage Gash model" is that of drop size. The importance of drop size when determining canopy interception losses was first established through experimental work in the tropical climates of Indonesia and India by Calder (1986). Calder (1986) developed a stochastic interception model that predicts that for storms with the same total rainfall, interception losses would be larger for those with smaller drop sizes. The model also considers the drop retention by the canopy, and is partially dependent on the kinetic energy and hence drop size. The ability of a canopy to retain rain drops is parameterised in the model by q, the drop retention number. The drop retention is dependent upon the size and kinetic energy of the impacting drop, as well as canopy properties such as "wettability" and leaf angle (Hall, 2003).

To incorporate the dependence of q on both drop volume and therefore kinetic energy into the model, a vegetation/species specific parameter is introduced, termed the maximum elemental volume (v_e^{max}) and is expressed in Eq. (15). This is calculated by considering drops impacting the surface with a kinetic energy as close to zero as possible to determine the maximum storage capacity (S_c^{max}), which according to Calder (1996) are events with an intensity of less than $0.36\,\mathrm{mm\,h^{-1}}$ and the LAI. The v_e^{max} values used in this study are as follows:

- *Eucalyptus grandis* = 0.24

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- *Acacia mearnsii* = 0.63
- *Pinus patula* = 0.51

$$v_\mathrm{e}^{\max} = q \cdot v_0 \left(\text{i.e. } q = \frac{v_\mathrm{e}^{\max}}{v_0} \right) \tag{15}$$

where:
q – drop retention
$v_\mathrm{e}^{\max}$ – is the maximum volume of water retained by a canopy element (mm^3), and
v_0 – is the mean volume of the rain drop (mm^3) with almost zero kinetic energy.

The term maximum storage capacity ($S_\mathrm{c}^{\max}$) which is obtained when the canopy is wetted with drops of almost "zero" kinetic energy and is defined as:

$$S_\mathrm{c}^{\max} = v_\mathrm{e}^{\max} \cdot \mathrm{LAI} = q \cdot v_0 \cdot \mathrm{LAI}. \tag{16}$$

The storage capacity (S_c) for non-zero kinetic energy drops can therefore be defined as:

$$S_\mathrm{c} = v_\mathrm{e} \cdot \mathrm{LAI} = q \cdot v \cdot \mathrm{LAI}. \tag{17}$$

The drop volume (v) is estimated using the Marshall-Palmer (1948) equation:

$$v = a \cdot R^b \tag{18}$$

where parameters $a = 0.124$, $b = 0.63$, and R – Rainfall rate or intensity ($\mathrm{mm\,h^{-1}}$).

In order to operate the model for a particular vegetation type requires values for two vegetation specific parameters $S_\mathrm{c}^{\max}$ and $v_\mathrm{e}^{\max}$. A functional relationship between $S_\mathrm{c}/S_\mathrm{c}^{\max}$ (Eqs. 19a and b) and v is also required. Calder (1996) developed the following empirical exponential relationship from rainfall simulator experiments:

$$S_\mathrm{c}/S_\mathrm{c}^{\max} = 1 \qquad \text{for } v < 0.065 \tag{19a}$$

$$S_\mathrm{c}/S_\mathrm{c}^{\max} = 0.5 + 0.73 \cdot \exp(-5.5 \cdot v) \qquad \text{for } v > 0.065. \tag{19b}$$

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Then, rearranging the Marshall-Palmer (1948) equation to determine R for $v < 0.065$ it can be established that $S_c/S_c^{max} = 1$ for $R < 0.36\,\mathrm{mm\,h^{-1}}$. From field measurements of leaf area index and storage capacity for events with $R < 0.36\,\mathrm{mm\,h^{-1}}$, the vegetation/species specific v_e^{max} can be calculated. By knowing the v from the Marshall-Palmer (1948) equation and S_c^{max}, the variable S_c can be calculated as the product of S_c/S_c^{max} and S_c^{max}.

The maximum elemental volume (v_e^{max}) does not change with the growth of the tree due to the linear relationship between S_c^{max} and LAI. The linear relationship between storage capacity and LAI for a given vegetation type of constant physiognomy and configuration has been corroborated by the results of Aston (1979), Von-Hoyningen-Huene (1981), Pitman (1989), Liu, (1998) and van Dijk and Bruijnzeel (2001).

2.5 Climatic parameters

The climatic parameters required for the "variable storage Gash model" are, gross precipitation (P_g), mean rainfall rate (R) and mean evaporation rate (E) per event. In this study the Penman-Monteith reference potential evaporation was used with the stomatal resistance term (r_s) equal to zero for the period that the rainfall event took place.

3 Litter interception model

A smaller, although significant role is played by litter interception. According to Schaap and Bouten (1997) in their study of a Douglas fir stand, as much as half of the total forest evaporation may originate from the canopy and litter interception processes. The water holding capacity of the surface horizon depends on the surface area of the material, similar to the storage of the foliage. Researchers have shown that litter interception is governed primarily by the moisture holding capacity and initial storage capacity of the litter, but also by the evaporative demand following the rainfall event (Rowe, 1955; Helvey and Patric, 1965). Throughfall that reaches the dry litter gradually increases

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the litter moisture to field capacity and then saturation. The saturated litter can lose as much as 75 % of its moisture in the first four days of drying (Blow, 1955; Jacobsz, 1987) and reaches an equilibrium after 10 to 12 days (Metz, 1958). Based on these considerations and field observations, the litter interception model was developed.

Litter model conceptualization

The litter interception model is based on the drying curves of *E. grandis, A. mearnsii and P. patula*, developed from samples collected at the Two Streams study site. A drying curve for naturally drying litter samples is determined from calculations of moisture content in the litter in the days following a saturating rainfall event following the approach of Jewitt (1991). A representative sample of the litter was collected for each of the three genera and placed in an aluminium foil tray that had holes punched into it to allow for free drainage of water. The samples were then dried in an oven overnight at 100 °C for 24 h. Once the samples were dried, they were weighed. They were then saturated and weighed again to obtain the litter storage capacity as shown in Table 2. The samples were then weighed daily for twelve days. This process was repeated twice annually for the three years of the study, to obtain the idealized drying curves illustrated in Fig. 2. The drying curves were derived from samples dried in the laboratory and under a shaded outdoor area.

The drying curve equations, litter storage capacity and litter thickness for each of the three genera are summarized in Table 2.

The litter model, which is programmed in a Microsoft® Excel spreadsheet, is site specific, as the litter characteristics will vary between species, age and climatic region. The model uses the daily throughfall simulated using the "variable storage Gash model" as an input. A "bookkeeping" method is then used to calculate the litter moisture content depending on the preceding dry days following the wetting of the litter from the drying curves in Table 2. Once saturation (storage capacity) is reached, any excess throughfall will infiltrate to the soil.

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4 Study site

The Mistley-Canema estate is situated in the Seven Oaks district in the KwaZulu-Natal Midlands, South Africa. The climate is humid, with an annual rainfall ranging from 800 mm to 1280 mm per annum and the mean annual temperature is 17 °C. Commercial afforestation has long been practiced in the area and is the most widespread land use, with gum (*Eucalyptus*), pine (*Pinus*) and wattle (*Acacia*) being the genera of choice. Sugarcane is also grown at sites where drainage of cold air is good, ensuring that no frost or only light frost may occur (Everson et al., 2006). In this study, 5 yr old *Eucalyptus grandis* and *Acacia mearnsii*, as well as 16 yr old *Pinus patula* stands with LAI values of 2.7, 2.3, and 1.9 respectively were considered.

5 Field data collection

Gross precipitation and evaporation data were supplied by the CSIR from two automatic weather stations forming part of an ongoing Water Research Commission (WRC) project (Everson et al., 2006). One was for the *A. mearnsii* and *E. grandis* which is situated on a tower above the canopy and the other for the *P. patula* site is situated in the open, but not above the canopy, but is closer to the study site. In order to validate the models, canopy and litter interception data was collected from April 2008 to March 2011. Data from September 1998 to March 2011 was then used to model canopy and litter interception for almost a thirteen year period.

5.1 Throughfall and canopy interception measurements

Throughfall measurements were undertaken using a nest of three “V” shaped troughs based on the design of Cuartus et al. (2007) constructed from galvanised sheeting. The dimensions of each trough are 10 cm wide × 200 cm long. Conventional “U” or “V” shaped troughs are susceptible to blockage by fallen debris and water loss from splash out, however, this system minimizes splash out by using steep “V” shaped sides. The

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troughs were covered with mosquito netting to minimize the entry of debris, which reduces the demand of cleaning and maintaining the system. The troughs were then connected to a tipping bucket gauge and an event data logger. Because the trough represents a linear and continuous sampling surface, the length scale variation of leaves, branches, and tree crown, it is assumed to be a representative integral of the throughfall caught (Cuartus et al., 2007). During the study period, canopy interception accounted for more between 14.9 % and 27.7 % of gross precipitation.

5.2 Litter interception and water drained to soil measurements

The litter interception and water that drains to the soil was measured using two round galvanized iron basins that fit into each other. The upper basin which had a diameter of 0.5 m and was filled with litter and had a geotextile lining on top of a wire mesh base, so water can percolate into the lower basin. The water that was collected in the lower basin drains into a tipping bucket and records the water that would have drained to the soil. The litter interception was then calculated as the difference between throughfall and the water that drained to the soil. The amount of litter interception measured was about 12.1 % for *P. patula,* 8.5 % for *E. grandis*, and 6.6 % for *A. mearnsii*.

6 Results and discussion

6.1 Canopy interception

The importance of canopy and litter interception in the water balance of a forested catchment are illustrated in Figs. 3 and 5 from the observed and modelled results of this study. The canopy and litter interception data collected during the study period were used to validate the models. Canopy and litter interception were then modelled using historical rainfall and evaporation data obtained from the CSIR from September 1998 to March 2011. The parameters used in validating the models during the study

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period from April 2008 to March 2011 were kept constant, with only the rainfall and evaporation data changing when modelling from September 1998 to March 2011.

The results of this study show that the modelled canopy interception ranges from 16.9 % to 26.6 % for *E. grandis* and *A. mearnsii*, respectively, and *P. patula* with 23.3 % of gross precipitation being intercepted. Figure 3a, b and c illustrate that the modelled *E. grandis, A. mearnsii* and *P. patula* canopy interception results summarized in Table 3 corresponded well with the observed data, with the difference between the modelled and observed ranging between 1.1 % and 2.0 %. This corresponds to a relative error of between 4.0 % and 13.4 % between modelled and observed results.

Rainfall interception from the canopy was responsible for a large amount of the total evaporation from a forested catchment, and perhaps more than many may anticipate, as shown in Table 3. A noticeable result is that *Eucalyptus grandis* has the lowest interception of the three species in this study even though it has the highest LAI. The small difference between the observed and modelled canopy interception can therefore be largely attributed to the successful estimation of the canopy storage capacity. While *E. grandis* has the highest LAI, it also had the smallest elemental volume (v_e) and canopy retention (q), therefore having the smallest canopy storage capacity. It is therefore important to consider the retention characteristics of the canopy when modelling canopy interception and not just base the estimation of the canopy storage capacity on LAI. Furthermore, the estimation of canopy storage capacity took the rainfall intensity into account, which was an important consideration in a mistbelt area where there are a large number of low intensity events, but the bulk of the rainfall comes from the relatively few large, high intensity storms. From Fig. 4 it can be seen that 50.8 % of the rainfall events during this study period were less than 1 mm day^{-1}, with 10.9 % and 7.4 % of the events being between 1 and 2 mm and 2 and 3 mm, respectively. The rainfall record from September 1998 to March 2011 showed a very similar trend in the rainfall distribution to that recorded during the study period. This indicates that the rainfall during the study period was typical for the catchment. In these small events almost 100 % of the gross rainfall would be intercepted by the canopy and the remainder by

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the litter (Jacobsz, 1987). It must be noted that the raingauges did not have a mist interceptor, but any mist captured by the canopy would be accounted for by throughfall if there is a rainfall event that occurs after the canopy has been wetted by mist (i.e. that canopy storage capacity has been partially or fully filled by the mist interception), so the interception amount may in fact be slightly underestimated.

The performance of the "variable storage Gash model" in comparison with the observed data for the period April 2008 to March 2011 is summarised in Table 4.

From Table 4 it can be seen that the descriptive statistics for observed and modelled canopy interception correspond well. The worst performing being *P. patula* with a R^2 and Root Mean Square Error (RMSE) of 0.56 and 0.54, respectively. The R^2 for *E. grandis* and *A. mearnsii* are 0.76 and 0.83, respectively, as well as low RMSE values of 0.24 and 0.26 indicating that the model performed well.

6.2 Litter interception

The results of the litter interception study are illustrated in Fig. 5 and summarised in Table 5.

This study shows that litter interception has an important role in the forest hydrological cycle, with as much as 13.4 % of gross precipitation being intercepted by the 16 yr old *P. patula* litter. The results of the cumulative modelled and observed litter interception are illustrated in Fig. 5. The model results were good, with the actual difference between modelled and observed for *E. grandis*, *A. mearnsii* and *P. patula* being 1.6 %, 1.2 % and 1.3 %, respectively. This corresponds with a relative error of 18.8 %, 18.2 % and 10.7 %, respectively. From the summarized results in Table 5, it can be seen that *A. mearnsii* has the lowest litter interception with between 5.4 % and 6.6 % of gross precipitation being intercepted. *E. grandis* and *P. patula* had the highest modelled and observed litter interception with the modelled results being 10.1 % and 13.4 %, respectively.

Relative to the depth of litter (cf. Table 2), *E. grandis* has a high litter interception value. This may be due to the shape of the leaves that form the litter layer. The broad

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leaves act as "cups" that catch the throughfall, and provide very little resistance to the evaporative process. The simple litter interception model based on idealised drying curves is dependent upon the accuracy of the canopy interception model as the modelled throughfall is used as the model input. If the throughfall or canopy interception is modelled poorly, then the input into the litter interception model will induce a systematic error from the beginning of the simulation.

The statistics describing the performance of the litter interception model derived from the drying curves in comparison with the observed data measured at Two Streams for the period April 2008 to March 2011 is summarised in Table 6.

From Table 6 it can be seen that mean, standard error, standard deviation and sample variance for the modelled and observed litter interception results are similar, indicating that the model performed well. This is also seen by the RMSE values for *E. grandis, A. mearnsii* and *P. patula* being between 0.1 and 0.24. The R^2 values are also very good with *A. mearnsii* having the highest at 0.85 and *E. grandis* the lowest at 0.77. To determine how the two models performed together, the cumulative water that drains to the soil was also considered.

6.3 Water that drains to the soil

The observed results for the water that drains to the soil, i.e. the "useable water", are a good indicator of how the canopy and litter interception models performed together as a whole/system. This is because the measured water that drains to the soil is measured as a separate entity and is not dependant on measured throughfall to calculate, as is the case with litter interception. Therefore, if the canopy and litter models did not perform well, then the modelled water that drained to the soil would not correspond well to the observed results, as the litter model depends on the modelled throughfall as an input. The comparative results of the cumulative modelled and observed water that drains to the soil is illustrated in Fig. 6.

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Figure 6 shows that the modelled and observed results compare well, illustrating that the combination of the relatively complex canopy interception model and simple litter interception model work well together. The results are summarized in Table 7.

From Table 7, it can be seen that the modelled water that drains to the soil is 3.3 %, 1.4 % and 3.2 % higher than the observed results for *E. grandis, A. mearnsii* and *P. patula*, respectively, with between 63.3 % and 72.9 % of gross precipitation reaching the soil. This corresponds to a relative error of 4.3 %, 2.1 % and 4.8 % for *E. grandis, A. mearnsii* and *P. patula* respectively as shown in Table 7.

The statistics of the performance of the model derived from the drying curves to estimate the water that drains to the soil in comparison with the observed data measured at Two Streams for the period April 2008 to March 2011 are summarised in Table 8.

From Table 8 it can be seen that the combination of the "variable storage Gash model" and the litter interception model derived from drying curves worked well, as the descriptive statistics for the modelled and observed water that drains to the soil are very similar. This is also seen by the high R^2 values for *E. grandis*, *A. mearnsii*, and *P. patula* of 0.83, 0.85 and 0.81, respectively.

Based on the results obtained, it is accepted that the model is representative of the processes and on this basis the modelling study was extended to a longer period. The same model variables used to model for the study period between April 2008 to March 2011 was assumed for the extended period from September 1998 to March 2011. The results of the data modelled for the period from September 1998 to March 2011 are summarized in Table 9.

The modelled results for the study period between April 2008 and March 2011 are similar to those obtained from modelling between September 1998 and March 2011. The difference in the results of the modelled water that drains to the soil for the two periods are 3.1 %, 2.3 % and 2.0 % for *E. grandis*, *A. mearnsii* and *P. patula*, respectively. This once again highlights that the climatic conditions during the study period are typical of the catchment as the difference in canopy and litter interception as well as water that drains to soil are very similar.

7 Conclusions

This study confirms that interception plays a very important role in the forest hydrological cycle, with between 63.3 % and 72.9 % of gross precipitation being available water that drains to the soil, after the losses due to canopy and litter interception. This also highlights the importance of including and accurately representing canopy and litter interception in water resources planning models. Both the "variable storage Gash model" and litter interception models performed well. The "variable storage Gash model" is conceptually complex, but can be applied with readily available data. Although the input data requirements are fewer than the original model, an added consideration of the change in canopy storage capacity depending on the rainfall intensity has been added and is an important conceptual advance. This addition along with the consideration for the canopy water retention characteristics have resulted in the canopy interception simulations being very good. This point was highlighted by considering that *E. grandis* had the highest LAI, but had the lowest canopy interception due to is low water retention because of the angle at which the large leaves hang, as well as their smooth, waxy surface. Conversely, the *A. mearnsii* had the second largest LAI, but the largest canopy interception due to the high water retention characteristics of its small pinnately compound leaves. While the "variable storage Gash model" may be considered complex, the litter interception model which is based on idealised drying curves is very simple. However, although the model may be simple, it performed well. This can be explained by the fact that unlike canopy interception which is strongly influenced by many factors such as storage capacity, potential evaporation, rainfall intensity, rainfall duration amongst others, litter interception is mostly dependant on storage capacity and modelling it is dependent on the accurate estimation thereof. This is because the evaporative drivers under the canopy such as wind, temperature and radiation are moderated relative to those above canopy. Therefore, as long as the inputs of simulated throughfall from the "variable storage Gash model" are adequate and the litter storage capacity is estimated accurately, the model should perform well. It could in fact be argued that

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the "variable storage Gash model" and litter interception models should not be considered as separated models, but as one model that simulates "total interception" (i.e. canopy + litter interception). Therefore, a model should aim for a requisite simplicity by discarding some detail but maintains conceptual clarity and scientific rigour (Stirzaker et al., 2010).

The canopy interception model described here could be applied for national scale studies as it is not site specific. However, although the litter interception model performed well, it cannot be transferred and used elsewhere as the data was site, species and age dependant. However, litter samples can easily be obtained and dried and further studies to generate national litter interception characteristics are a logical way forward. However, the CSIR Two Streams research catchment where the models were developed was situated in a mist belt area, so the high canopy interception results could be attributed to this fact, as over 50 % of the daily rainfall events were less than 1 mm. Therefore, further research in other climatic areas, with different rainfall characteristics is required.

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Table 1. Evolution of the various versions of the Gash model referred to in this document.

Author	Name of model
Gash (1979)	Original Gash model
Gash et al. (1995)	Revised Gash model
Van Dijk and Bruijnzeel (2001)	Modified Gash model
Bulcock and Jewitt (2012)	Variable storage Gash model

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Table 2. Drying curve equations and litter storage capacity derived from laboratory experiments for three litter types in the KZN Midlands.

Species	Drying curve equations	Litter storage capacity (mm)	Litter thickness (mm)
E. grandis	$y = 2.2202 \cdot (x)^{-1.1879}$	2.6	38
A. mearnsii	$y = 1.40 \cdot (x)^{-0.983}$	1.8	20
P. patula	$y = -1.5935 \cdot \ln(x) + 4.1419$	4.5	97

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Table 3. Summary of observed and modelled canopy interception results for April 2008 to March 2011.

Genus	Gross Precipitation (mm)	Observed canopy interception (mm)	Observed canopy interception (%)	Modelled canopy interception (mm)	Modelled canopy interception (%)	Relative Error (%)
Eucalyptus	1884.7	280.4	14.9	318.4	16.9	13.4
Acacia	1884.7	522.4	27.7	501.4	26.6	4.0
Pinus	1909.7	408.7	21.4	444.1	23.3	8.9

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Table 4. Summary of "variable storage Gash model" and observed canopy interception statistics for the period April 2008 to March 2011.

Statistic	*Eucalyptus grandis*		*Acacia mearnsii*		*Pinus patula*	
	Modelled	Observed	Modelled	Observed	Modelled	Observed
Sample size	1066	1066	1066	1066	1066	1066
Mean (mm)	0.30	0.26	0.47	0.49	0.42	0.38
Standard Error (mm)	0.015	0.014	0.029	0.030	0.022	0.025
Standard Deviation (mm)	0.48	0.44	0.93	0.97	0.72	0.81
Sample Variance (mm)	0.23	0.19	0.86	0.95	0.52	0.64
RMSE	0.24		0.26		0.54	
R^2	0.76		0.83		0.56	

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Table 5. Summary of observed and modelled litter interception results from April 2008 to March 2011.

Genus	Gross Precipitation (mm)	Observed litter interception (mm)	Observed litter interception (%)	Modelled litter interception (mm)	Modelled litter interception (%)	Relative Error (%)
Eucalyptus	1884.7	160.4	8.5	191.1	10.1	18.8
Acacia	1884.7	124.7	6.6	102.1	5.4	18.2
Pinus	1909.7	231.2	12.1	255.9	13.4	10.7

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Table 6. Summary of litter interception model and observed litter interception statistics for the period April 2008 to March 2011.

Statistic	*Eucalyptus grandis*		*Acacia mearnsii*		*Pinus patula*	
	modelled	observed	modelled	observed	modelled	observed
Sample size	1066	1066	1066	1066	1066	1066
Mean (mm)	0.18	0.15	0.10	0.12	0.24	0.21
Standard Error (mm)	0.016	0.014	0.01	0.01	0.023	0.021
Standard Deviation (mm)	0.51	0.46	0.28	0.33	0.74	0.68
Sample Variance (mm)	0.26	0.21	0.08	0.11	0.54	0.46
RMSE	0.24		0.10		0.23	
R^2	0.77		0.85		0.83	

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Table 7. Summary of observed and modelled water that drained to soil for April 2008 to March 2011.

Genus	Gross Precipitation (mm)	Observed water drained to soil (mm)	Observed water drained to soil (%)	Modelled water drained to soil (mm)	Modelled water drained to soil (%)	Relative Error (%)
Eucalyptus	1884.7	1437.0	76.2	1375.2	72.9	4.3
Acacia	1884.7	1237.7	65.7	1281.5	64.3	2.1
Pinus	1909.7	1269.8	66.5	1209.7	63.3	4.8

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Table 8. Summary of modelled and observed water that drains to the soil statistics for the period April 2008 to March 2011.

Statistic	*Eucalyptus grandis*		*Acacia mearnsii*		*Pinus patula*	
	modelled	observed	modelled	observed	modelled	observed
Sample size	1066	1066	1066	1066	1066	1066
Mean (mm)	1.29	1.35	1.20	1.16	1.13	1.20
Standard Error (mm)	0.134	0.141	0.131	0.123	0.128	0.132
Standard Deviation (mm)	4.36	4.44	4.10	4.01	4.13	4.20
Sample Variance (mm)	19.05	19.14	16.80	16.33	17.10	17.60
RMSE	0.33		0.27		0.55	
R^2	0.83		0.85		0.81	

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Table 9. Summary of all results modelled from September 1998 to March 2011.

Genus	Gross Precipitation (mm)	Modelled canopy interception (mm)	Modelled canopy interception (%)	Modelled litter interception (mm)	Modelled litter interception (%)	Modelled water drained to soil (mm)	Modelled water drained to soil (%)
Eucalyptus	11 145.5	1805.6	16.2	869.3	7.8	8470.6	76.0
Acacia	11 145.5	3020.4	27.1	702.2	6.3	7422.9	66.6
Pinus	11 145.5	2708.4	24.3	1605.0	14.4	6832.2	61.3

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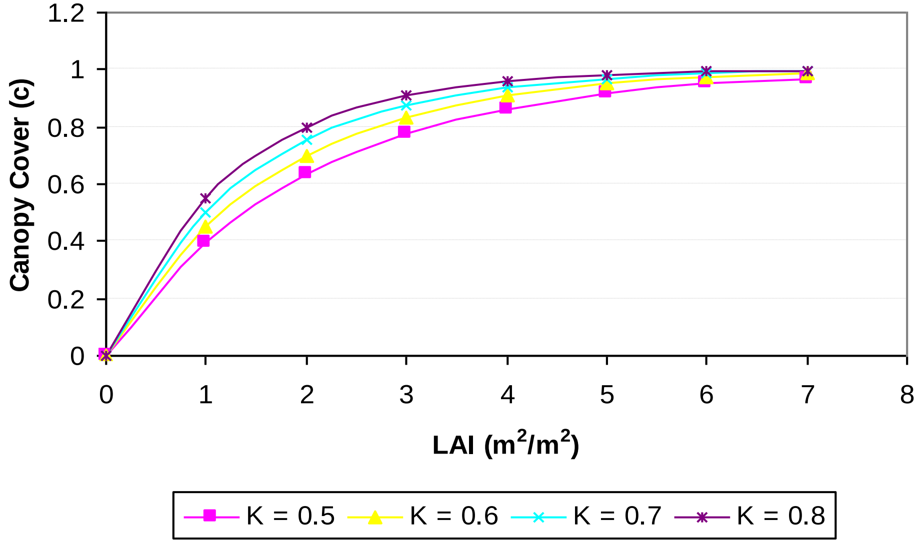

Fig. 1. Beer-Lambert canopy cover curves for different extinction coefficients.

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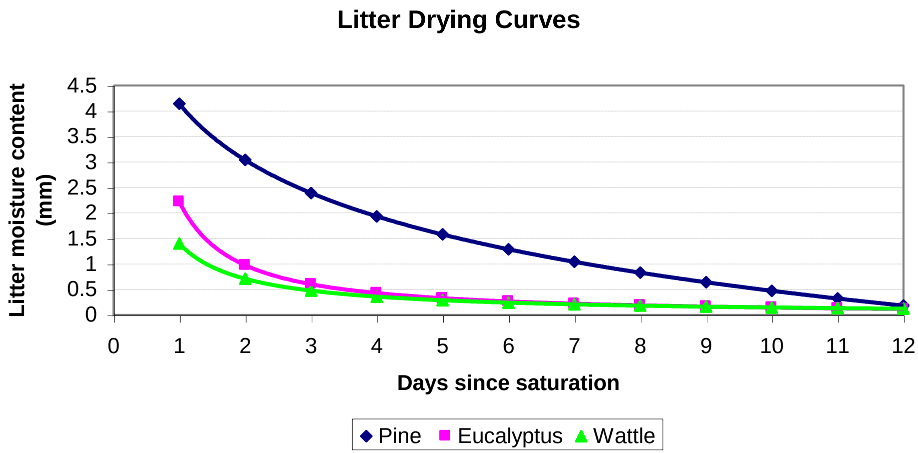

Fig. 2. Idealised drying curves derived from laboratory experiments for three litter types in the KZN midlands.

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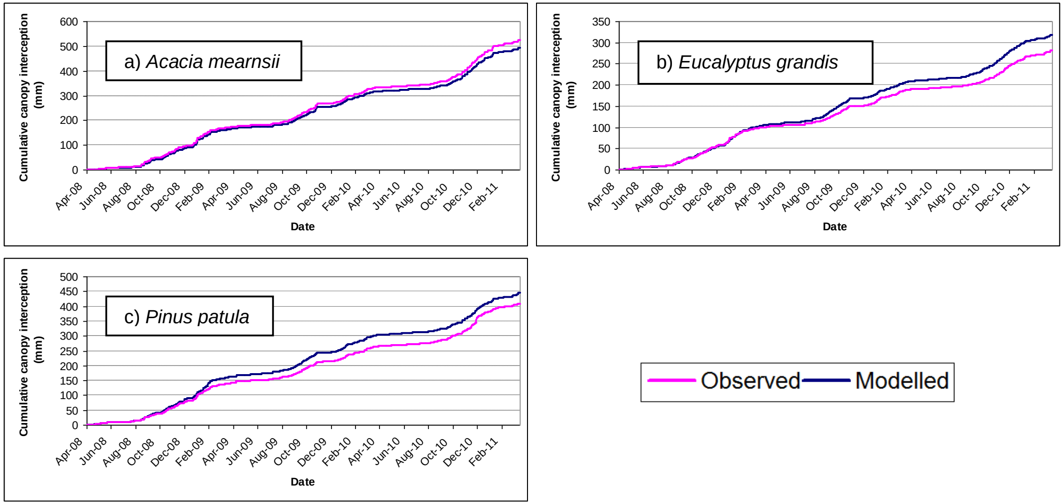

Fig. 3. Cumulative observed and modelled canopy interception simulated with the "variable storage Gash model" from April 2008 to March 2011 at Two Streams.

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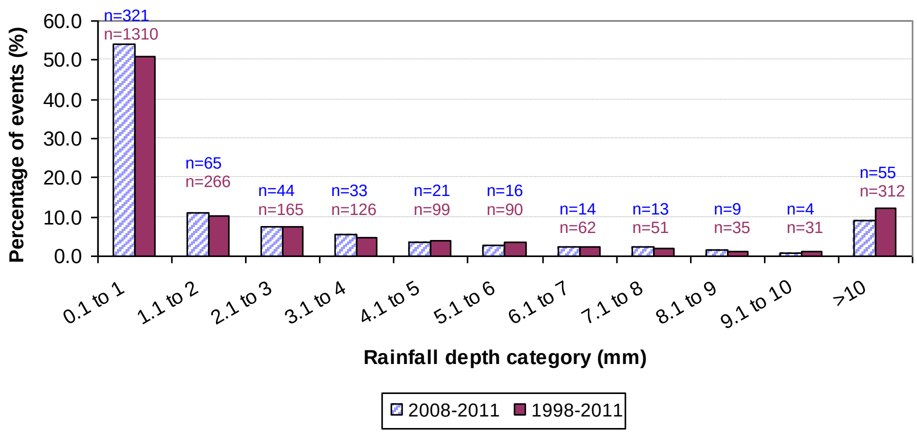

Fig. 4. Percentage of rainfall events per rainfall depth category (n = 595 and n = 2577) for the periods April 2008 to March 2011and September 1998 to March 2011, respectively.

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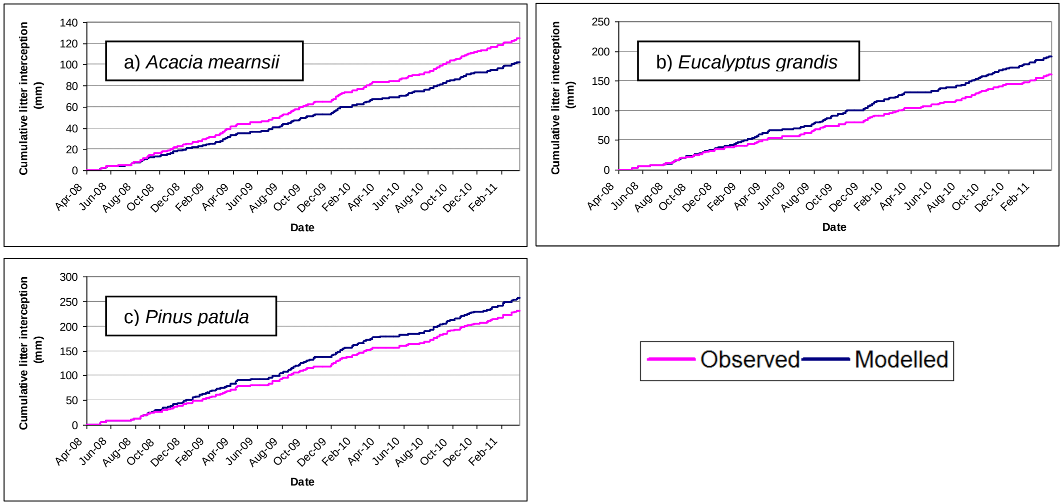

Fig. 5. Cumulative observed and modelled litter interception simulated using idealised drying curves for three species at Two Streams.

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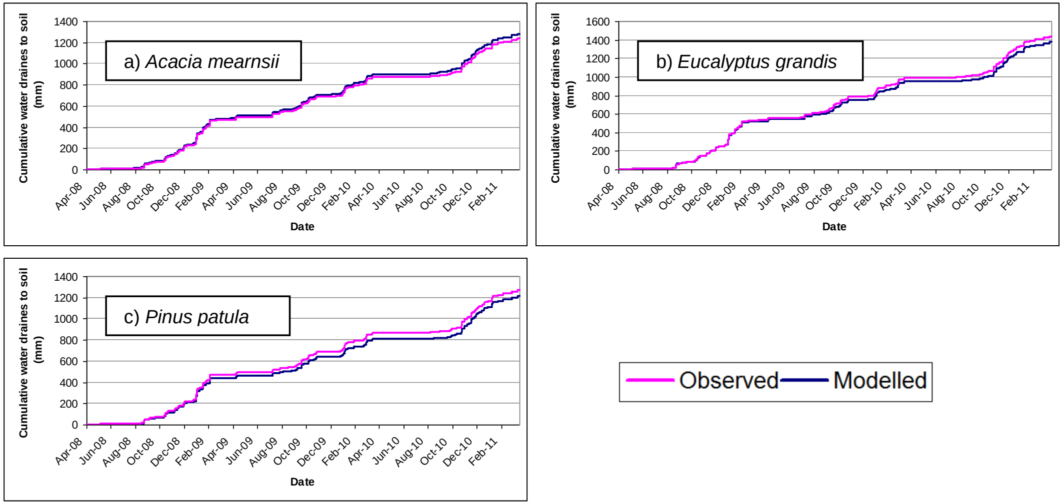

Fig. 6. Cumulative observed and modelled water that drains to soil from April 2008 to March 2011 for three species at Two Streams.

HESSD

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Modelling canopy and litter interception in forest plantations

H. H. Bulcock and G. P. W. Jewitt

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