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Estimating sparse forest rainfall interception with an analytical model

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Abstract

Gash's analytical model of rainfall interception is reformulated, with improved boundary conditions, to give a better description of the evaporation from sparse forest. The model is tested against data from Les Landes Forest collected during HAPEX-MOBILHY. The new formulation requires an estimate of the evaporation per unit area of canopy, rather than per unit ground area. When the evaporation per unit area of canopy is equated with the estimates of evaporation derived from the Penman–Monteith equation there is an improved description of the observations.

1. Introduction

The storm-based analytical model described by Gash (1979) demonstrated that the evaporation of rainfall intercepted by forest canopies can be estimated from the forest structure, the mean evaporation and rainfall rates, and the rainfall pattern. The model has been used with some success over various different forests, including, for example, coniferous forest in the UK (Gash et al., 1980), evergreen mixed forest in New Zealand (Pearce and Rowe, 1981), oak forest in the Netherlands (Dolman, 1987), tropical plantation forest (Bruijnzeel and Wiersum, 1987), and natural rainforest in Amazonia (Lloyd et al., 1988) and West Africa (Hutjes et al., 1990), but with less success for sparse forest (Teklehaimanot et al., 1991). Indeed, the model contains a weakness in the description of sparse forest, which can prevent the modelled canopy from wetting up.

This paper presents an improved, more rigorous, formulation of the original

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version of Gash's model, which should give improved predictions of interception loss, particularly for sparse forests. Data from Les Landes Forest, collected during HAPEX-MOBILHY (André et al., 1988), are used to demonstrate the difference between the original model and the new formulation.

2. Theory

2.1. The original model

Gash's (1979) model considers rainfall to occur as a series of discrete events, each comprising a period of wetting up, when the rainfall, P_G, is less than the threshold value necessary to saturate the canopy, P'_G, a period of saturation and a period of drying out after rainfall ceases. The canopy is assumed to have sufficient time to dry out between storms. The forest structure is described in terms of a canopy capacity, S, which is defined as the amount of water left on the canopy in zero evaporation conditions when rainfall and throughfall have ceased (Gash and Morton, 1978), and a free throughfall coefficient, p, which determines the amount of rain which falls directly to the forest floor without touching the canopy (p is often assumed equal to one minus the canopy cover). Evaporation from the trunks is described in terms of a trunk storage capacity, S_t, and the proportion of the rainfall diverted to stemflow, p_t. The mean evaporation rate during rainfall, $\overline{E}$ and the mean rainfall rate, $\overline{R}$ for saturated canopy conditions, are also required. The separate components of the interception loss are calculated as shown in Table 1. Although it is not strictly

Table 1
The original form of the analytical model compared with the form proposed in this paper; in the revised form no rainfall enters the trunk store when $P_G < P'_G$.

Component of the interception loss	The original Gash (1979) model	Revised analytical form
For m small storms, insufficient to saturate the canopy	$(1-p-p_t)\sum_{j=1}^{m} P_{G,j}$	$c\sum_{j=1}^{m} P_{G,j}$
Wetting up the canopy, for n storms $> P'_G$ which saturate the canopy	$n(1-p-p_t)P'_G - nS$	$ncP'_G - ncS_c$
Evaporation from saturation until rainfall ceases	$(\overline{E}/\overline{R})\sum_{j=1}^{n}(P_{G,j}-P'_G)$	$(c\overline{E}_c/\overline{R})\sum_{j=1}^{n}(P_{G,j}-P'_G)$
Evaporation after rainfall ceases	nS	ncS_c
Evaporation from trunks, for q storms $> S_t/p_t$, which saturate the trunks and in the left column for the $n+m-q$, or in the right column for the $n-q$, which do not	$qS_t + p_t\sum_{j=1}^{m+n-q} P_{G,j}$	$qS_c + p_t\sum_{j=1}^{n-q} P_{G,j}$

necessary, the model is usually calculated from daily rainfall totals assuming one storm per rainday.

2.2. Reformulation of the model for a sparse canopy

As can be seen from the formulation in Table 1, the model assumes a quasi-two-dimensional structure for the surface. Rain which is diverted to free throughfall and to the trunks is not available for the canopy. Although this results in a correct water balance on a per unit area basis, it has the effect of reducing the rainfall rate onto the canopy, such that for a rainfall rate R, the modelled rainfall onto the canopy will be $(1-p-p_t)R$. When $(1-p-p_t)\overline{R} < \overline{E}$, the modelled canopy fails to wet up, resulting in a negative logarithm in the calculation of P'_G, the rainfall necessary to saturate the canopy, as can be seen below:

$$P'_G = -\frac{\overline{R}S}{\overline{E}}\ln\left[1 - \frac{\overline{E}}{\overline{R}(1-p-p_t)}\right] \tag{1}$$

In addition, if the evaporation is specified or calculated using the Penman–Monteith equation on a per unit area basis, then, as p approaches unity, the model predicts an increasing evaporation rate per unit area of canopy where it is present, i.e. it approaches the limit of infinite evaporation from zero canopy as p approaches unity. Clearly, this boundary condition is not sensible. Although the evaporation rate of sparse forest, per unit area of canopy, may be enhanced as a result of greater turbulent mixing (Teklehaimanot et al., 1991), it will in the end be limited, if only by the restriction that its surface temperature cannot fall below that of a well-ventilated wet bulb thermometer.

If the evaporation rate from the canopy, where it is present, is denoted by E_c, Eq. (1) derived in terms of the mean rates of rainfall and evaporation to and from the canopy becomes

$$P'_G = -\frac{\overline{R}S_c}{\overline{E}_c}\ln[1 - (\overline{E}_c/\overline{R})] \tag{2}$$

where c is the canopy cover and $S_c = S/c$ is the canopy capacity per unit area of cover, and the additional assumption has now been made that stemflow is diverted to the trunks only after the canopy has become saturated. In broad terms, as a canopy becomes more sparse S_c will remain constant, whereas S (the canopy capacity per unit ground area) will decrease with c.

To be consistent with the treatment of stemflow in the derivation of Eq. (2), it is necessary to make a small modification to the original formulation so that water is diverted to the trunks only after the canopy is saturated. The original and the revised formulation are given in Table 1.

2.3. Estimation of the mean evaporation rate from a saturated canopy

The philosophy of the analytical model requires a simple but robust method of calculating the rate of evaporation from sparse forest, preferably requiring no more information than that which was used in the previous version to calculate the evaporation from a forest with a complete canopy. The simplest assumption that can be made is that the evaporation from a sparse forest can be adequately estimated simply by reducing the evaporation calculated for a complete canopy in proportion to the canopy cover. Such an assumption assumes implicitly that the evaporation is one dimensional and that there is no horizontal interaction or advection. The validity of this simple approach will be tested in this analysis.

3. Comparison of the model against Les Landes Forest data

3.1. Site and instrumentation

Les Landes Forest is situated in south-west France. It is a plantation forest of predominantly Maritime pine (*Pinus pinaster* Ait.). The site was near the village of Estampon (44°5′N, 0°5′W) and was in a stand of Maritime pine with an average tree height of 20.3 m and a density of some 430 stems ha^{-1}. The leaf area index was estimated to be 2.3 at the time of the study. Although there was a variable understorey of bracken this was removed from the throughfall measurement site and for the purposes of this analysis has been ignored. Further details of the site have been given by Gash et al. (1989) and Granier et al. (1990).

Hourly average meteorological data (net and solar radiation, wet and dry bulb temperature, and wind speed and direction) were recorded by an automatic weather station mounted above the canopy on a tower of 25 m height (see Gash et al., 1989). Rainfall was measured with a funnel mounted on the top of this tower connected to a tipping bucket gauge on the ground; this gave a resolution of 0.16 mm per tip. Rainfall was also measured by a separate gauge in a small clearing some 500 m from the tower. The results from the tower gauge were not significantly different from those obtained from the clearing gauge and the tower gauge has been used as the preferred gauge. When the tower gauge was not operational, data from the clearing gauge have been used.

Throughfall was measured with 22 simple collection gauges located at random positions on a 30 m by 30 m grid. These gauges were measured and relocated at new positions normally at 2-week intervals. In addition, ten 0.5 mm tipping bucket raingauges were located at random, but fixed, positions in the grid. These were logged to give hourly throughfall. Stemflow was measured on six trees using similar 0.5 mm tipping bucket gauges to measure the flow diverted by collars around the trunks. A survey of the canopy cover using an anascope (see Ford, 1976) at 1 m intervals over the throughfall grid gave the canopy cover as 45%.

Data were collected from 9 February 1986 to 3 January 1987. Failure of the loggers resulted in there being no weather station data available between 18 March and 14 April 1986, and no rainfall data between 7 and 14 April 1986. These periods have been omitted from the analysis. Stemflow data were available for only half the periods. However, the average for those periods when stemflow was available showed that it was only 1% of gross rainfall. The stemflow for missing periods has been assumed to be 1% of gross rainfall.

3.2. Results

For the periods with complete rainfall and weather station data 613 mm of rainfall were recorded, of which 534 mm were collected as throughfall and 6 mm as stemflow, giving an interception loss of 73 mm or 11.9% of the gross rainfall. The data from the tipping bucket gauges were used in a storm analysis similar to that carried out by Gash and Morton (1978). Values of $S = 0.25$ mm, $S_t = 0.17$ mm and $p_t = 0.0275$ were obtained. In an independent analysis of the same data as presented here, Lankreijer et al. (1993) derived values of 0.26 mm for S. A value of 0.25 mm for S, with $c = 0.45$, implies a value of 0.56 mm for S_c.

Gash (1979) assumed that the average value of evaporation for all hours with rainfall greater than 0.5 mm represented evaporation from a saturated canopy. Following this, the procedure for the application of the original model is then to equate $\overline{E}$, the mean evaporation rate per unit ground area, with the average evaporation calculated using the Penman–Monteith equation for those hours. With the aerodynamic resistance calculated using the relation derived from the eddy correlation measurements of momentum flux described by Gash et al. (1989), i.e.

$$1/r_a = 0.056u \ (\mathrm{ms}^{-1}) \tag{3}$$

where u is the windspeed, $\overline{E}$ required for the original model is estimated as 0.17 mm h^{-1}. From the same hours' data, $\overline{R}$ is calculated as 1.65 mm h^{-1}. Applying these figures to the original model with $p = 0.55$ (the value implied by the canopy survey) gives the result shown in Fig. 1. Interception loss is estimated to be 102 mm, or 17% of gross rainfall, an overestimate of 28 mm or 39% of the measured interception loss.

For the new formulation $\overline{E}_c$, the mean evaporation rate from the canopy, where it is present, is assumed to be given by the Penman–Monteith estimate of closed canopy evaporation, i.e. 0.17 mm h^{-1} (when this is scaled down in proportion to the canopy cover a value of 0.08 mm h^{-1} is obtained for the evaporation rate per unit ground area). The interception loss calculated using the new formulation is then 70 mm, an underestimate of 4 mm. This result is also shown in Fig. 1.

3.3. Error analysis

The error in the measured interception loss has been estimated assuming a random error of 5% in the rainfall for each measurement period, and an error in the throughfall given by the variability in the throughfall gauge catch. When these are summed quadratically, with an arbitarily assumed 20% error in the stemflow, an error of 11 mm, or 15% of the interception loss, was obtained. The prediction with the new formulation of the model is within these measurement error limits. The error in the prediction with the original model, estimated following the procedure used by Lloyd et al. (1988), was dominated by the errors in S, p and $\overline{E}$, which were assumed to

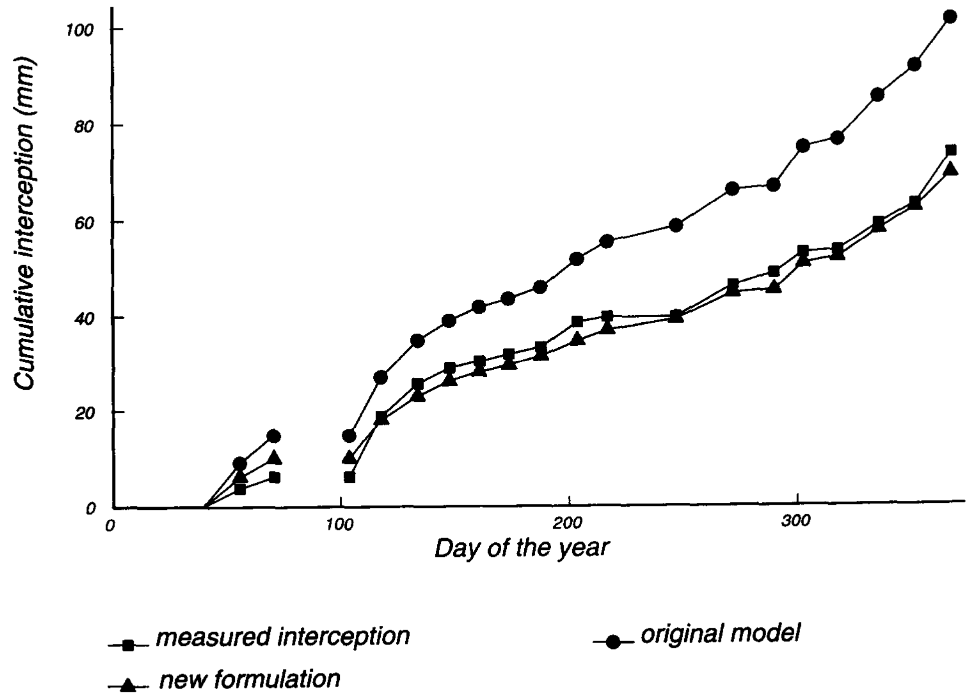

Fig. 1. The measured cumulative interception loss from Les Landes Forest compared with that estimated using Gash's (1979) model, and the revised formulation with the evaporation calculated using the Penman–Monteith equation to give the evaporation rate per unit area of canopy, where it is present.

be ±0.1 mm, 0.7 and 0.02 mm h^{-1}, respectively. The method of Rosenblueth (1975) was used to derive an estimated error of ±13 mm. A standard difference of means test between the measured and estimated interception loss showed them to be significantly different at the 5% level.

4. Concluding remarks

It is clear that reformulating the analytical model and calculating the mean evaporation rate so that the evaporation rate per unit ground area is reduced as the canopy cover falls, not only improves the physics, but also improves the agreement between the estimated and measured interception loss. When the simple Penman–Monteith estimate is applied only to the area of canopy, good agreement is found between observation and prediction. The estimated interception loss is then within estimated errors of the observed loss.

Although it is not so obvious in the numerical Rutter model (Rutter et al., 1971), the description of rainfall partition is essentially the same as in the original formulation of the analytical model, and the Rutter model suffers from the same limitations and poor boundary conditions. The next step should therefore be to apply the arguments developed here to the production of a sparse forest Rutter model.

One of the reasons for the success of the analytical model has been its combination of a low demand for data with a simple but realistic approach to the interception process. Previous attempts to modify the model to improve the representation of special situations, for example high stem evaporation (Gash et al., 1980) or long storms (Pearce and Rowe, 1981) have not been used in subsequent studies. However, the changes proposed here do not result in a more complex model and will also demand no more data, provided that the evaporation per unit ground area can be approximated by that given by the Penman–Monteith equation reduced in proportion to the canopy cover. The results of the present study indicate that that approximation is reasonable. It thus appears that the revised formulation of the model, in combination with that approximation, should give more accurate estimates of interception loss than the original method and should therefore be preferred in future applications.

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