A computer simulation of the effects of differing crop types on the water balance of small catchments over long time periods

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SUMMARY

A multilayer crop model is used to simulate the interception and evaporation of rainfall as well as transpiration loss for a pine canopy. A considerable improvement, in terms of physical realism, over the Rutter (Rutter et al. 1971) model appears to have been achieved and the results generally agree with experimental work. Simulation runs on synthetic meteorological data indicate that the Rutter model substantially underestimates the interception loss from low intensity rainstorms. The multilayer pine model, MANTA, is run with a year's data and the results compared with those from an equivalent unilayer pine and also a grass model. The results show that MANTA predicts a 20% increase in interception loss over the Rutter model estimate and that over the year the interception loss from grass is one quarter of that from pine.

1. INTRODUCTION

Over the last decade and a half, increasing interest has been directed towards the effect of differing crop types on catchment water balance. The results of this research are of importance not only to agronomists and forest managers but also to hydrologists.

Figure 1 summarizes the water balance of a small catchment covered by a specified

![](image)

Figure 1. Generalized water balance of a small, vegetated catchment.

\[
P - I = pP + D + \Delta C \\
pP + D - J - E_s = R_o + \Delta M
\]
vegetation type over a long time period. The effect of changing a crop type within a catchment is to alter the interception loss, transpiration and, to a lesser extent, soil evaporation rates. Changes in any of these will have feedback effects on the soil moisture content and the runoff. In view of the close relationship between catchment behaviour and crop type, the simulation part of this study was directed towards the building of physically realistic models capable of simulating all the exchanges shown in Fig. 1.

For a short crop, such as grass, the simulation techniques are fairly simple and well proven. Soer (1977) demonstrated that a single-layer model with a finite difference soil heat flux routine could perform accurately under non-precipitating conditions. The basic grass model, known as TERGRA, was adapted to include a simple description of rainfall interception. For a short crop the unilayer treatment does not diverge too much from reality as there is effectively a single surface in contact with the atmosphere. This is not true of tall crops such as pine because here the leaf area is distributed over a relatively large vertical distance.

Recent work (e.g. Thom and Oliver 1977) has indicated that interception loss from tall crops can be a large term in the total water balance of a small catchment. Research in the UK has been mainly in a relatively dry Scots Pine forest in East Anglia and a much wetter one in the Welsh Uplands. The total annual evapotranspiration from the first site was reported by Gash and Stewart (1977) to be just less than that for an open water surface while for the second it was found, according to Calder (1977), to be roughly double this amount. The difference between the two is thought to be largely due to higher interception losses in the second case. In conjunction with both these experimental projects, a predictive model, known as the Rutter (Rutter et al. 1971) model, was used to simulate the rates of interception loss and transpiration using hourly meteorological data as an input.

The Rutter model represents the canopy as a single layer store, located at zero plane displacement, capable of holding a preset amount of water, S, the storage limit. When this limit is exceeded by additional rainfall, the canopy drains at an exponential rate dependent upon the excess. Also a proportion of the rainfall, P, falls through the gaps in the canopy to the forest floor. If the canopy is fully wet, the evaporation rate is defined as \( E_p \) given by the Penman–Monteith equation. In this, the surface resistance is taken as being zero. When the water storage, C, is less than S, that is, when the canopy is not fully saturated and not draining, the evaporation rate is given as:

\[
E = E_p C / S
\]  

This last simplification is open to criticism in that it fails to allow for the differing distribution of intercepted rainfall with depth in the canopy.

Clearly, there is a requirement for a model that can overcome the above limitations. Furthermore, it is desirable to introduce a greater measure of physical reality into the unsaturated behaviour of the crop than that represented by the approximation inherent in Eq. (1).

2. THE MODELLING TECHNIQUE

A multilayer model has the following principal advantages:

1. It is capable of simulating the changing locations of heat and vapour sinks and sources.
2. It is possible to use the technique to describe leaf drainage and the redistribution of intercepted water between different parts of the canopy.
3. With the inclusion of a wetted area term, the leaf’s energy balance can be more
realistically modelled. This last represents perhaps the greatest single improvement over the Rutter model.

The multilayer approach, however, is demanding in terms of data and parametrization; in particular:

(i) The data available for this study were hourly measurements of $T_a$, $T_w$, $u_{10}$, total cloud cover, low cloud cover and $P$ as observed at standard meteorological sites in the United Kingdom. The sites are mainly grass covered and so the data are not directly applicable to another vegetation type.

(ii) Most multilayer models, for example, Waggoner and Reifsnyder (1968), Goudriaan and Waggoner (1972), Murphy and Knoerr (1975), require values of humidity and air temperature from below the canopy which are used as fixed points for the solution. They are not available in the above data set.

(iii) Long-term simulation necessitates the inclusion of some kind of runoff model if realistic feedback effects of soil moisture stress on transpiration are desired.

In an attempt to overcome these problems, three sub-models are run together. The final linked model, MANTA, is represented schematically in Fig. 2. The operation of each sub-model is described briefly below.

(a) Standard meteorological site model

Hourly meteorological data from standard sites are stored on magnetic tape at the

![Flowchart](image-url)
Meteorological Office, Bracknell. From them the model computes terms in the energy balance equation. Short-wave radiation ($F_{s}$) is estimated as in Lockwood (1979, p. 184) and amended for the effects of cloud cover as by Gadd and Keers (1970). Long-wave radiation is estimated following Brunt (1939). The method of calculating the effect of cloudiness on the exchange of long-wave radiation between the sky and individual leaf layers also depends on the work of Gadd and Keers (1970).

The model incorporates the Soer (1977) crop resistance description, an empirical soil heat flux routine, a simple interception description and variable soil moisture. Paulson's (1970) description of turbulent transfer is used iteratively to obtain values of surface temperature, latent heat flux ($E$), sensible heat flux ($H$) and friction velocity ($u_{*}$).

When the energy balance has been calculated, the following are computed:

1. $T_{a}$ and $T_{w}$ at 17 m using the formulations of Thom et al. (1975) and Paulson (1970).
2. The geostrophic wind speed ($G$) via Ayra's (1975) description. An existing computer model by Blackall (Meteorological Office) incorporating Ayra's analysis, forms the basis of this routine.

(b) *The hydrological model*

The hydrological model is based on Beven and Kirkby (1975). The complete catchment is represented as a vertical series of cascading soil moisture stores, the contents of which determine the runoff. The model simulates both the baseflow and overland flow components of runoff. Rainfall, runoff and actual evaporation data from the Grendon Underwood catchment in Buckinghamshire, UK, were used to optimize the model’s six parameters. A ninety-day simulation is compared with the actual runoff record in Fig. 3. Although arbi-
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...fixed soil water storage conditions are initially defined, the simulation converges to the actual record after about twenty days. The same basic hydrological model is used for all the crop simulation models.

(c) The multilayer model

Although models for wheat, oak and pine have been tested and placed into the MANTA framework as outlined in Fig. 2, only pine will be described here. The general structure of the model with its related fluxes, potentials and resistances is illustrated in Fig. 4. The characteristics of the model are summarized below:

Figure 4. Framework of the multilayer crop model with lower fixed points below the soil surface.

(1) Foliage. For pine a total leaf area index of 4 is assumed and is distributed normally within the canopy. This method was first used by Waggoner and Reifsnyder (1968) to describe a red pine canopy.

(2) Aerial resistance pathways. Above the canopy a non-neutral description after Ayra (1975) and Paulson (1970) is used. Within the canopy air space the wind profile description of Thom (1971) and Thom et al. (1975) extends down to the trunk region. In this zone a formulation based on Oliver’s (1975) observations is used to construct a wind profile. Goudriaan (1977) proposed an analysis of turbulent transfer within the canopy based on mean mixing lengths and wind speeds in the region. This ‘working hypothesis’ is used to yield values of $K_e$ and $K_s$ throughout the crop stand which are then integrated over the interlayer distances to give the canopy resistances. The boundary layer resistances are functions of local wind speed, needle density and shoot orientation. The expres-
sions of Jarvis et al. (1976) define \( r_b \) with the necessary adjustments for heat and vapour transfer included.

(3) Stomatal resistance. In coniferous foliage, stomatal resistance is thought to be a function of local air temperature, humidity, short-wave radiation, leaf water potential and needle age. The regression equations of Jarvis (1976) are used to include the first three variables in the resistance calculation, while soil moisture stress is accounted for by an empirical adjustment to the value so produced.

(4) Radiation distribution. Short-wave radiation is distributed by the simple Monsi and Saeki (1953) exponential extinction model. The extinction coefficient is made to vary with solar angle in accordance with the findings of Jarvis et al. (1976). Reflected short wave interception by leaf undersides is also taken into account. Long-wave exchanges are similarly modelled, with leaf temperature as one of the optimized variables.

(5) Lower fixed points. The below canopy air temperature and humidity values commonly used in multilayer models are replaced by the deep soil temperature and the soil moisture storage system. A Fourier analysis of the 100 cm soil temperature can be used with this value to estimate soil heat flux via a finite difference method (Soer 1977). However, to shorten the calculation this may be replaced by an empirical relationship derived from soil temperature and heat flux data from Sutton Bonnington, UK, for 1976. This technique was developed jointly by Elkington and the first author (unpublished).

Evaporation from the soil is estimated by means of a modified Penman–Monteith equation wherein the surface resistance term is dependent upon the soil water potential. The soil moisture storage system, comprising an interception store and a sub-surface reservoir also has a direct interface with the hydrological model. A numerical convergence computer program, published by the Numerical Algorithms Group (NAG 1979) is incorporated in the multilayer model.

For an estimate of \( H \) and \( E \) above the canopy, the above crop aerodynamic resistances and wind profiles are derived. From these, \( \delta e^l \) and \( T^l_n \) are computed and in turn are used to balance iteratively the energy budget of the first leaf layer. The net radiation of a leaf layer can be defined in terms of the leaf temperature as follows:

\[
R^l_n = \lambda e^l + h^l + T^l
\]

\[
\lambda e^l = \frac{p c_p}{\gamma} \int^l \left( \frac{1}{r_{b1} + s_1} + \frac{1}{r_{b2} + s_2} \right) \Delta r^l
\]

\[
h^l = \rho c_v 2L \left( \frac{T^l - T^l_n}{r_b} \right)
\]

\[
R^l_n = (F^l + F^l)(1 - \alpha) + N^l
\]

(2)

The values of \( e^l \) and \( h^l \) that satisfy Eq. (2) are then subtracted from the total fluxes above the canopy and the process is continued down through the foliage to the soil surface. Ultimately, three residuals are produced which reflect upon the 'accuracy' of the initial estimates of \( H \) and \( E \) above the canopy. The residuals are variously weighted according to the circumstances and iterative adjustments made to \( H \) and \( E \) by the NAG routine to effect a minimization of the sum of squares of the residuals. This process usually requires five to ten iterations.
(d) Interception

Rutter et al. (1971) defined the drainage rate (or leaf drip) from a wet canopy as

\[ D = D_s \exp\{b(C - S)\} \]  

When \( C \) is equal to \( S \), or when the whole canopy is just saturated, this simplifies to

\[ D = D_s \]  

The canopy can also be represented as a system of \( n \) vertically separated layers which, under the same circumstances as Eq. (4), yield the following expressions for the amount of water held on one layer

\[ C^l = S^l; \quad \text{for } l = 1, n \]

\[ S^l = L^l S^l / \sum_{l=1}^{n} (L^l) \]

The drainage from a given leaf layer reaching the ground would then be

\[ D^l = D_1 L^l V^l \]

When \( C = S \) and \( C^l = S^l \)

\[ \sum_{l=1}^{n} D^l = D_s \]

\( V^l \), the proportion of ground visible from below the \( l \)th layer, can be derived from a simple radiation extinction model. Thus \( D_1 \), the drainage coefficient per unit leaf area index, is obtained from Eqs. (6) and (7). \( b^l \), the exponential drainage coefficient for a leaf layer, is given by

\[ b^l = (b/L^l) \sum_{l=1}^{n} L^l \]

When \( C^l \) is finite but less than \( S^l \), the wetted area, \( W_A \), of the leaf layer is defined as lying between 0·1 and 0·8. The second constraint, that of \( W_A = 0·8 \), was decided on as a direct result of experimental observation: it was virtually impossible to wet more than 85% of the leaf’s upper surface at any time, regardless of the amount of water applied. The first constraint, \( W_A = 0·1 \), is more open to controversy as it defines a finite wetted area when \( C^l \) approaches zero. There are two arguments, however, for ignoring this apparent inconsistency. Firstly, the equation is a fair description of what actually happens: the experiment revealed that during the final phase of drying, isolated patches of water on the leaf surface dried out with only a slight contraction of their areas until the last few seconds. This reduction in the depth, rather than in the area of the wet patches, indicates that the adhesive forces between leaf and water droplet become dominant over cohesive forces within the droplet as the leaf water content diminishes. Secondly, if \( q \) in Eq. (10) were set to zero, an infinite time period would be predicted for the complete drying out of the wetted canopy under normal meteorological conditions. This would be due to the exponential decay form of equation (9) resulting from the change in the \( W_A \) term. This effect would not only be physically unrealistic but would also present numerical problems in the computer simulation.

The single wet leaf layer behaves in a fashion similar to that of the Rutter canopy in that it is represented as occupying one of two possible states defined as follows:
The unsaturated Rutter canopy corresponds to the real situation of a changing wetted area with little or no leaf drip.

The totally saturated canopy of the Rutter model drains at an exponential rate and maintains a constant wetted area. This phase corresponds well with reality and lends itself to simple modelling.

The state of the stored water on an unsaturated leaf layer with a proportionate wetted area, \( W_A \), can be defined as:

\[
dC^l/dt = -W_A E_w^l + P_i^l
\]

a situation corresponding to the right-hand side of Fig. 5. The \( E_w^l \) term in Eq. (9) is given by:

\[
E_w^l = \frac{\delta e^l + (T^l - T_d^l)\Delta \rho c_p L \Phi}{\gamma}
\]

\( E_w \) is the loss from a totally wet leaf layer of area \( L^l \) in mm h\(^{-1}\). \( W_A \), the wetted area, was defined as a function of \( C^l \) by experiment. Leaves of an evergreen shrub were marked by a pinpoint grid, wetted by a spray until saturated and then dried on a balance with a 200 W lamp. Wetted area was assessed using the pinpoint grid while changes in the amount of water held on the leaf were monitored with the balance. The relationship between wetted area, as a fraction of \( L^l \), and \( C^l/S^l \) can be seen in Fig. 6 together with an eye fitted curve.

\[
W_A = a \left( \frac{C^l}{S^l} \right)^2 + c \left( \frac{C^l}{S^l} \right) + q
\]

\[0 < C^l < S^l, \quad 0.1 \leq W_A \leq 0.8\]

The values of \( a, c \) and \( q \) in Eq. (10) are found from Fig. 6 to be \( a = 0.52 \), \( c = 0.18 \) and \( q = 0.1 \). Over a short time step an unchanging leaf temperature can be assumed thus making \( E_w^l \) and \( P_i^l \) constant.
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Figure 6. Wetted areas as functions of leaf water storage.

\[
\int E'_w \, dt = - \left\{ \frac{a}{2} \left( \frac{E'_w}{S^*} + \frac{c}{2a} \right)^2 - \frac{c^2}{4a} + q - \frac{P'_l}{E'_w} \right\}^{-1} \, dC^l \quad (11)
\]

Three solutions to this equation can be obtained upon integration, only one of which is real for a given set of values of \(E'_w, C^l\) and \(P'_l\).

The transpiration loss from the non-wetted part of the upper leaf surface, \(J^l\), is defined as a function of the leaf’s dry area:

\[
\frac{dJ^l}{dt} = (1 - W_A)E'_d \quad (12)
\]

where

\[
E'_d = \frac{E'_w \cdot L_p \cdot L_b}{E'_w \cdot (r_b + s'_1)}
\]

Combining Eq. (12) and (10)

\[
\frac{dJ^l}{dt} = \left( 1 - \frac{P'_l}{E'_w} + \frac{1}{E'_w} \frac{dC^l}{dt} E'_d \right) \quad (13)
\]

The saturated leaf layer represented schematically on the left-hand side of Fig. 5 has an unchanging wetted area but a variable drainage rate.

When \(C^l > S^l\), \(W_A = 0.8\)

\[
\frac{dC^l}{dt} = P'_l - 0.8E'_w - D^l \exp(b'(C^l - S^l)) \quad (14)
\]

For a short time-step \(P'_l\) and \(E'_w\) can be assumed constant, which allows the following substitution:

\[
R = (P'_l - 0.8E'_w), \quad \text{constant}:
\]

\[
Q = D^l \exp(-b_1 S^l), \quad \text{constant}
\]
Therefore

\[ \int dt = \int \left\{ R - Q \exp(b^l C^l) \right\}^{-1} dC^l \quad . \quad (15) \]

This also has three solutions, only one of which is real for given values of \( R, Q \) and \( C^l \).

In both Eqs. (11) and (15), \( P_i \) and \( E_w^l \) are assumed constant for short time-steps. It is more likely that they will be changing slowly but if the rates of change are near linear, the errors generated will be small. Over short time-steps, as total energy exchanges are considered, the effect is to converge to mean or near mean values of \( P_i \) and \( E_w^l \).

Wetting and drying canopies are associated with rapidly changing conditions of temperature and humidity in their air spaces. For greater accuracy, very short (12 minute) time-steps are used under these conditions. When the canopy is dry, the time-step is extended to one hour in length with little loss of realism. A variable time-step allows for much greater computational efficiency.

3. RESULTS

A clearer understanding of the mechanism of interception loss can be achieved by imposing an unchanging meteorological regime above the canopy during the simulation of processes associated with a rainstorm and the subsequent drying period. This allows the effect of the wet canopy on the local micro-climate to be observed uncluttered by weather changes.

Figure 7. MANTA and Rutter model predictions of interception loss during and after a simulated low intensity rainstorm.
Figures 7 and 8 illustrate the sequence of events following the interception of two four-hour rainstorms by an initially dry pine canopy. The simulations used the MANTA four-layer pine model and the Rutter unilayer model with the same bulk crop characteristics. The values of incoming radiation, air temperature and wet bulb depression were held constant above the canopy before, during and after the storms; a situation which would be highly unlikely to occur in nature due to the feedback effects of an increased evaporation rate on the above-canopy humidity profile, but which lends itself to a detailed analysis of the evaporative process. In both cases the contributions of transpiration (and soil evaporation in the case of MANTA), although integral parts of the calculations, have been omitted from the figures for greater clarity.

Figure 7 shows the rate of interception loss as predicted by both the MANTA and Rutter models for a low intensity, 0.5 mm h\(^{-1}\), rainstorm. Two features are immediately obvious. Firstly, the MANTA model predicts a swift rise in the rate of interception loss at the onset of the storm with a concomitant decrease in the sensible heat loss term, an effect consistent with the observations of Stewart (1977) at Thetford forest. The Rutter model, on the other hand, predicts a very gradual rise in the rate of interception loss coupled with a slow decrease in sensible heat loss. Secondly, the Rutter model simulates an exponential decline in the rate of interception loss after the storm while the MANTA prediction suggests a very rapid drying of the canopy from the top layer downwards.

The explanations for these differences are straightforward. The multilayer pine model considers the process of interception loss as a function of the interaction of a given rainfall
input, the energy available to each leaf layer and an aerodynamic transfer network. In this case, due to the low intensity of the rainfall input, the model predicts a quick change of leaf surface temperature as shown in Fig. 9. The Rutter model, on the other hand, defines the rate of interception loss as primarily a function of canopy water storage, which slowly increases as the storm continues resulting in a gradual rise in the predicted rate of interception loss. This course of development can be clearly seen in Fig. 9 where the apparent temperature of the unlayered surface is seen to decrease very slowly at the beginning of the storm. At the end of the storm the Rutter model represents the drying out of the canopy as an exponential decay of interception loss rate with time. By contrast, the MANTA model predicts a much shorter drying period for the following reasons:

(i) As the canopy dries out, approximately the same amount of energy is available for evaporation but this acts on a shrinking wetted area, so the absolute evapora-

Figure 9. Air temperature, leaf surface temperature and vapour pressure deficit profiles within and above the pine canopy as simulated by MANTA for the low intensity storm.

Symbols
- Temperature, vapour pressure deficit at 17 m
- Air temperature, vapour pressure deficit prediction of MANTA
- Leaf surface temperature prediction of MANTA
- Unleaf temperature prediction of Rutter model

Conditions imposed above the canopy
- Geostrophic wind speed 15.0 m/s
- Short wave radiative income 50 W/m²
- Air temperature at 17 m 15.0°C
- Wet bulb depression at 17 m 4.0°C
- Rainfall intensity 0.5 mm/hr
tion rate falls, but the rate per unit wetted area rises considerably.

(ii) When it rains, or while the upper layers of the canopy are wet, the flux of water vapour into the canopy air space and the downdraught of sensible heat to the upper leaf layers significantly reduces the vapour pressure deficit below the topmost layer. This has the effect of inhibiting the flux of vapour from the lower leaf layers until the superior ones dry out. As the top layers dry, the profile of vapour pressure deficit moves to the right, creating a more favourable evaporative regime for the lower layers. The result of this can be seen in Figs. 7 and 8 where the rates of interception loss from the lower layers rise sequentially.

The interdependence of the events outlined above is obvious.

Figure 8 illustrates the simulated course of events during and after a high intensity (5.0 mm h\(^{-1}\)) rainstorm. The Rutter and MANTA predictions are much closer to one another compared to the previous simulation, although the MANTA model still predicts a higher

Figure 10. Air temperature, leaf surface temperature and vapour pressure deficit profiles within and above the pine canopy as simulated by MANTA for the high intensity storm.

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Conditions imposed above the canopy</th>
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<tbody>
<tr>
<td>Temperature, vapour pressure deficit at 17 m</td>
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</tr>
<tr>
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<td>Air temperature at 17 m 15.0°C</td>
</tr>
<tr>
<td>+ 'Unsat' temperature prediction of Rutter model</td>
<td>Wet bulb depression at 17 m 4.0°C</td>
</tr>
<tr>
<td></td>
<td>Rainfall intensity 5.0 mm/hr</td>
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![Diagram showing temperature, leaf surface temperature, and vapour pressure deficit profiles within and above the pine canopy as simulated by MANTA for the high intensity storm.](image-url)
equilibrium rate of interception loss. This is largely due to the dominance of the upper leaf layer, positioned above the zero plane displacement as a vapour source. During the storm the first leaf layer accounts for roughly two-thirds of the total interception loss. The 'blip' on the MANTA curve during the first half hour of the storm is generated by the release of stored heat in the canopy biomass as the surface temperatures of the leaf layers drop; a process illustrated in Fig. 10.

The Rutter and MANTA simulations agree better for this second rainstorm as an equilibrium situation is reached very rapidly in both cases. The predictions of the drying process are remarkably similar in their early stages, a common feature of most Rutter/MANTA comparisons involving rainstorms with intensities of more than 1·5 mm h⁻¹ and lasting more than an hour or so. When the fully saturated MANTA canopy starts to dry out, the upper layer consumes most of the available energy. With time, however, the concentration of the wetted areas in the lower part of the canopy lowers the effective vapour source from its initial position above d. The lengthening resistance pathway combined with a slowly shrinking, but still large, wetted area gives rise to lower rates of interception loss. This process continues until only a small amount of water remains on the lowest leaf layer which is then rapidly lost by evaporation as the local vapour pressure deficit rises.

Figure 11. Rutter model and MANTA predictions of interception loss rates plotted against the canopy water storage.

Figure 11 shows the rates of interception loss as predicted by the MANTA and Rutter models, plotted against the amount of water held on the canopy. The Rutter predictions combine to give a slight curve up to the point where C = S and a straight horizontal line thereafter. This implies that the rate of interception loss in a univalued function of C/S and the prevailing meteorological conditions and is totally independent of whether it is raining or not, the rainfall intensity or, more importantly, of the geometry of the wetted surfaces.
The MANTA predictions, on the other hand, show a distinct hysteresis in their wetting and drying curves which is most marked for low rainfall intensities. Interception loss rates as predicted by MANTA are functions of rainfall rate, the meteorological conditions and the distribution of intercepted water with depth in the canopy.

The MANTA and Rutter predictions tend to converge when the canopy is at or near saturation and also in the early stages of drying from saturation. MANTA, however, consistently predicts higher evaporation rates. The significance of the upper part of the MANTA hysteresis loops is reduced when the model is applied to real data as they actually describe events which amount to a relatively small proportion of the total interception loss process in that they define evaporative losses during and just after rainstorms. The work of Hancock and Crowther (1979) and of Crowther et al. (1979) lends some qualitative support to the MANTA description of the drying phase of interception loss. After heavy rainstorms, the canopy of a Sitka spruce forest was observed to dry from the top downwards while roughly following the Rutter model’s predictions during the early stages of drying. The results also indicated that the Rutter model underestimates the evaporative loss from a saturated or nearly saturated canopy.

The MANTA formulation is more realistic and potentially more accurate than the Rutter model but it is more expensive to operate. It requires a large computer and fifty times as much central processor unit time for the same meteorological data. It is important to assess whether the two predictions differ significantly when the models are used for long runs on real data.

Figure 12 compares the MANTA and Rutter predictions of evapotranspiration losses using hourly meteorological data from Benson, Oxfordshire, for 1977. Each formulation
incorporated the Grendon Underwood hydrological model described previously. It is apparent that the differences are not as large as might be expected from a study of Figs. 7 to 11; the MANTA simulation gives a total annual figure for interception loss of 28.6 mm or 20.3% greater than that of the Rutter model. The mean rainfall intensity for the year 1977 was 0.77 mm h\(^{-1}\), and 60% of the total rainfall fell in storms with an intensity of 1.2 mm h\(^{-1}\) or more. This sort of rainfall regime would certainly help to reduce the divergence between the two predictions as the effect of the MANTA hysteresis response would be reduced. If the rainfall regime had consisted mainly of low intensity (i.e. less than 1.0 mm h\(^{-1}\)) storms, the two simulations could be expected to diverge more.

Finally, we return to the original aim of the project: a comparison of the effect of different vegetation types upon the water balance of a small catchment. The data used for the MANTA pine simulation described above was used to run the TERGRA based unilayer grass model. Figure 13 shows the interception and soil evaporation losses as well as the transpiration loss for both pine and grass over the year. Figure 14 compares the runoff generated under each crop.

![Graph showing daily rainfall and accumulated loss over time](image)

Figure 13. Simulated interception and transpiration losses from hypothetical grass and pine covered catchments. The meteorological data set is from Benson, Oxfordshire, for 1977.

Total transpiration losses for the two crops are very similar: that from grass is 21.5 mm, 8% greater than that from pine. The total interception loss from pine is over four times as great as that from grass (253 mm as compared to 63 mm) however, making the annual total evapotranspiration loss some 40% greater than that from grass (555 mm and 398 mm respectively). The effect of this difference on the runoff regimes of each crop is substantial. The total runoff from the hypothetical pine catchment was predicted to be 152 mm, a little over half the 303 mm predicted for the grass catchment. Furthermore, the peak streamflows generated under grass are often more than 30% higher than those produced by the same storms over pine.
Figure 14. Simulated runoff losses from the hypothetical pine and grass covered catchments. The meteorological data set is from Benson, Oxfordshire, for 1977.

4. Conclusion

A multilayer simulation is proposed for modelling interception loss from tall crops. Over a year's simulation on real meteorological data, the MANTA model predicted a 20% increase in interception loss over the estimate provided by the Rutter (Rutter et al. 1971) model. The hysteresis of interception loss rate when plotted against the amount of water held on the canopy is thought to lead to an underestimate of interception loss by the Rutter model for low rainfall intensities.

The MANTA simulation results generally agree with the experimental observations of other researchers on heat and vapour fluxes above both wet and dry coniferous canopies and the effects of plant geometry on the rate of interception loss and the processes by which this is augmented for tall crops are demonstrable. The greater interception loss predicted from a pine covered catchment gave rise to lower peak flows and roughly half the total runoff generated by the equivalent grass catchment over a year's simulation. The total annual interception loss from the pine canopy was calculated to be four times that from grass.

Acknowledgments

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Institute of Hydrology, Wallingford, for providing data, and R. M. Blackall of the Meteorological Office (Met. O. 22) for assistance with the friction velocity model.

**Notation**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>leaf wetted area coefficient</td>
</tr>
<tr>
<td>$b$</td>
<td>canopy drainage coefficient</td>
</tr>
<tr>
<td>$b_l$</td>
<td>as $b$; expressed per unit leaf area index</td>
</tr>
<tr>
<td>$c$</td>
<td>leaf wetted area coefficient</td>
</tr>
<tr>
<td>$c_p$</td>
<td>specific heat of air, J kg$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$C$</td>
<td>canopy water storage, mm</td>
</tr>
<tr>
<td>$C_l$</td>
<td>water storage of $l$th leaf layer, mm</td>
</tr>
<tr>
<td>$d$</td>
<td>zero plane displacement, m</td>
</tr>
<tr>
<td>$D$</td>
<td>drainage rate of whole canopy, mm h$^{-1}$</td>
</tr>
<tr>
<td>$D_s$</td>
<td>drainage coefficient, mm h$^{-1}$</td>
</tr>
<tr>
<td>$D_l$</td>
<td>drainage coefficient per unit leaf area index, mm h$^{-1}$</td>
</tr>
<tr>
<td>$e_l$</td>
<td>evapotranspiration loss of $l$th leaf layer, kg m$^{-2}$ s$^{-1}$</td>
</tr>
<tr>
<td>$E$</td>
<td>latent heat loss, W m$^{-2}$</td>
</tr>
<tr>
<td>$E_d$</td>
<td>transpiration rate from completely dry $l$th leaf layer, mm h$^{-1}$</td>
</tr>
<tr>
<td>$E_p$</td>
<td>latent heat loss from saturated canopy, W m$^{-2}$</td>
</tr>
<tr>
<td>$E_{w}$</td>
<td>evaporation rate from saturated $l$th leaf layer, mm h$^{-1}$</td>
</tr>
<tr>
<td>$F_s$</td>
<td>short-wave radiation, W m$^{-2}$</td>
</tr>
<tr>
<td>$F_l$</td>
<td>short-wave radiative income of $l$th layer upper surface, W m$^{-2}$</td>
</tr>
<tr>
<td>$F_l^l$</td>
<td>short-wave radiative income of $l$th layer lower surface, W m$^{-2}$</td>
</tr>
<tr>
<td>$G$</td>
<td>geostrophic wind speed, m s$^{-1}$</td>
</tr>
<tr>
<td>$h_l$</td>
<td>sensible heat loss of $l$th leaf layer, W m$^{-2}$</td>
</tr>
<tr>
<td>$H$</td>
<td>sensible heat loss, W m$^{-2}$</td>
</tr>
<tr>
<td>$I$</td>
<td>interception loss rate, mm h$^{-1}$</td>
</tr>
<tr>
<td>$J$</td>
<td>transpiration loss, mm</td>
</tr>
<tr>
<td>$K_{x,y}$</td>
<td>turbulent transfer coefficient of vapour, heat, m$^2$ s$^{-1}$</td>
</tr>
<tr>
<td>$L$</td>
<td>leaf area, m$^2$</td>
</tr>
<tr>
<td>$L_y$</td>
<td>green leaf area, m$^2$</td>
</tr>
<tr>
<td>$M$</td>
<td>soil moisture storage, mm</td>
</tr>
<tr>
<td>$n$</td>
<td>number of leaf layers</td>
</tr>
<tr>
<td>$N_l$</td>
<td>net long-wave radiative income of $l$th leaf layer, W m$^{-2}$</td>
</tr>
<tr>
<td>$p$</td>
<td>throughfall proportion</td>
</tr>
<tr>
<td>$P$</td>
<td>rainfall rate, mm h$^{-1}$</td>
</tr>
<tr>
<td>$P_l$</td>
<td>rainfall and drip input to $l$th leaf layer, mm h$^{-1}$</td>
</tr>
<tr>
<td>$q$</td>
<td>leaf wetted area coefficient</td>
</tr>
<tr>
<td>$Q$</td>
<td>substitution constant in equation (15)</td>
</tr>
<tr>
<td>$r_a$</td>
<td>aerodynamic resistance, s m$^{-1}$</td>
</tr>
<tr>
<td>$r_l$</td>
<td>leaf laminar boundary layer resistance, s m$^{-1}$</td>
</tr>
<tr>
<td>$r_c$</td>
<td>canopy air space resistance, s m$^{-1}$</td>
</tr>
<tr>
<td>$R$</td>
<td>substitution coefficient in Eq. (15)</td>
</tr>
<tr>
<td>$R_n$</td>
<td>net radiation, W m$^{-2}$</td>
</tr>
<tr>
<td>$s_l^1$</td>
<td>stomatal resistance of upper surface of $l$th leaf layer, s m$^{-1}$</td>
</tr>
<tr>
<td>$s_l^2$</td>
<td>stomatal resistance of lower surface of $l$th leaf layer, s m$^{-1}$</td>
</tr>
<tr>
<td>$S$</td>
<td>canopy water storage limit, mm</td>
</tr>
</tbody>
</table>
$T$ leaf surface temperature, °C
$T_a$ air temperature, °C
$T_d$ deep soil temperature, °C
$T_s$ soil surface temperature, °C
$T_w$ wet bulb temperature, °C
$u_{10}$ wind speed at 10 m, m s$^{-1}$
$u_a$ friction velocity, m s$^{-1}$
$V^l$ proportionate area of ground visible below $l$th layer, m$^2$ m$^{-2}$
$W_A$ proportionate wetted area
$z_0$ roughness length, m
$\alpha$ leaf albedo
$\gamma$ psychrometric constant 0·66 mb K$^{-1}$
$\delta e$ vapour pressure deficit, mb
$\Delta$ slope of saturated vapour pressure versus temperature curve, mb K$^{-1}$
$\phi$ conversion factor for changing evapotranspiration rate from W m$^{-2}$ to mm h$^{-1}$
$\lambda$ latent heat of vaporization, J kg$^{-1}$
$\rho$ air density, kg m$^{-3}$
$\tau^l$ change in heat storage of $l$th leaf layer, W m$^{-2}$

REFERENCES


Beven, K. J. and Kirkby, M. J. 1975 Towards a simple, physically based, variable contributing area model of catchment hydrology, Working Paper 154, School of Geography, University of Leeds.


Crowther, J. M., Hancock, N. H. and Olczycka, B. 1979 The direct measurement of evaporation of water intercepted by a forest canopy, Paper presented at the European Geophysical Society Meeting, Vienna.


Jarvis, P. G. 1976 The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, Phil. Trans. R. Soc., Lond., B.273, 593–610.


