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Modelling the water balance of a free-draining lysimeter using the downward approach

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Abstract:

A 2600 m^3 free-draining lysimeter constructed in a *Pinus sylvestris* plantation forest in Colbitz, Germany, has been monitored daily since 1974, with the intent of improving the understanding the effect of afforestation upon groundwater recharge (drainage). The objective of this research was to employ a downward approach in the development of a conceptual water balance model applicable to the site. Observed annual and inter-annual trends were successfully replicated by a simple capacitance model using a simplified representation of vegetation growth. An important limitation of the capacitance approach in simulating the timing of drainage at sub-annual time scales was identified, which could not be overcome by adding complexity to the model basis. Given the *a priori* use of capacitance approaches for simulating drainage in many hydrological models, the findings of this study suggest that (a) these approaches are sufficient where the prediction of annual and inter-annual drainage behaviour is the primary objective, and that (b) an alternative basis accounting for the time delay between precipitation inputs and drainage generation is required for modelling if the prediction of drainage at sub-annual time scales is a priority. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS downward modelling approach; water balance modelling; capacitance models; drainage; lysimeter; Monte Carlo analysis

INTRODUCTION

The work of Budyko (1974) established the primary importance of precipitation (water availability) and evaporative demand (energy availability) in determining long-term water balance behaviour. Milly (1994) further identified the role of soil moisture storage in mediating this interaction between precipitation and evaporative demand. These findings suggest that, at sufficiently large temporal and spatial scales, hydrological behaviour can be captured with reasonable accuracy using a minimum of data and with minimal complexity. At the opposite end of the spectrum, a whole range of system attributes are considered to be influential in determining hydrological behaviour at small scales; these include soil hydraulic and structural properties, vegetation properties and topography.

At intermediate temporal and/or spatial scales (e.g. catchment scale, at monthly and daily time scales), which are frequently found in hydrological applications, model development can proceed by one of two routes. The traditional reductionist approach is to attempt to apply knowledge developed at fine scales to progressively higher levels of scale. Behaviour at large temporal and spatial scales is regarded simply as the

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aggregation of the behaviour at sufficiently small scales quantified using conventional physical understanding (e.g. the SHE model of Abbott *et al.* (1986)). Refinement of reductionist models could involve the systematic removal or simplification of processes (and related modelling parameters) to which model output is found to be insensitive at progressively coarser levels of scale, although examples of this are hard to find in the literature. In some cases, the physics itself may be reformulated to improve its applicability or simplicity at coarser scales (e.g. Reggiani *et al.*, 1998, 2000). The reductionist approach is initially data intensive, with the accuracy of model output particularly limited by the availability of spatially defined data required for correct parameterization.

The downward (or holistic) approach employs the observation that laws at higher levels of scale can be considered as an expression of averages or integrals of laws dominant at lower levels of scale (Klemeš, 1983). Models, which are quantifications of these laws, should, therefore, decrease in complexity with increasing scale; the findings of Budyko (1974) and Milly (1994) are examples of this. Modelling, therefore, commences at the coarsest possible scales with simple conceptualizations, such as the capacitance ('bucket') model of Manabe (1969). Model refinement involves the identification of additional complexity (i.e. additional process description, or more detailed parameterization of existing processes) to explain behaviour at progressively lower levels of scale (Jothityangkoon *et al.*, 2001; Atkinson, 2002; Farmer *et al.*, 2002; Atkinson *et al.*, 2003). In contrast to the reductionist approach, the downward approach has the advantage of having a minimum initial data requirement, with refinement continuing until either a model of sufficient accuracy is obtained at the required scale, or else until the availability or quality of the data does not justify further model refinement. A long (but not necessarily detailed) data record is generally required, however, since the initial validation relates to coarse temporal scales.

The objective of this study is to develop a model capable of simulating a unique 21 year daily drainage record obtained from a 2800 m^3 (4·3 m deep, 29 m diameter) free-draining lysimeter located in Colbitz, Germany, between 1974 and 1995. The hydrology of the system is complicated by the presence of a growing *Pinus sylvestris* (Scots pine) stand within the lysimeter, and the resulting dynamic variability in hydrological response must be accounted for in modelling. The lack of detailed data relating to soil heterogeneity and vegetation properties, together with the length of the data record, make employment of the downward approach in model development preferable. The initial aim of modelling is to determine the extent to which simple conceptual models are capable of characterizing the hydrological behaviour of a dynamic system at coarse temporal scales. The ability of simple refinements to improve the predictive ability of the model at finer temporal scales is subsequently investigated.

SITE DESCRIPTION AND DATA COLLECTION

A detailed description of the study site is given by Glugla *et al.* (1982). The lysimeter is located within a larger pine plantation, and contains sandy soils similar to the surrounding landscape. Daily meteorological data and drainage measurements were available for the entire simulation period, as well as periodic measurements of plant height and stem diameter. Soil hydraulic properties were evaluated by laboratory analysis of multiple soil samples. Potential evapotranspiration was estimated by several methods, based upon meteorological measurements, with the FAO Penman–Monteith evapotranspiration (also known as FAO reference evapotranspiration; Smith *et al.*, 1992) being used in modelling to represent potential evapotranspiration E_p.

The average hydrological regime (Figure 1) shows that minimum drainage occurs in September–October, such that an October–October hydrological year is assumed in this study. It is also evident from the hydrological regime that, whereas potential evapotranspiration exhibits a strong seasonality, precipitation P occurs year-round. This suggests that the intra-annual trend in drainage D is a response to the intra-annual trend in evapotranspiration, although a significant lag is evident between the timing of minimum evaporative forcing (December–February) and maximum drainage (March–May). This lag is likely to reflect the time

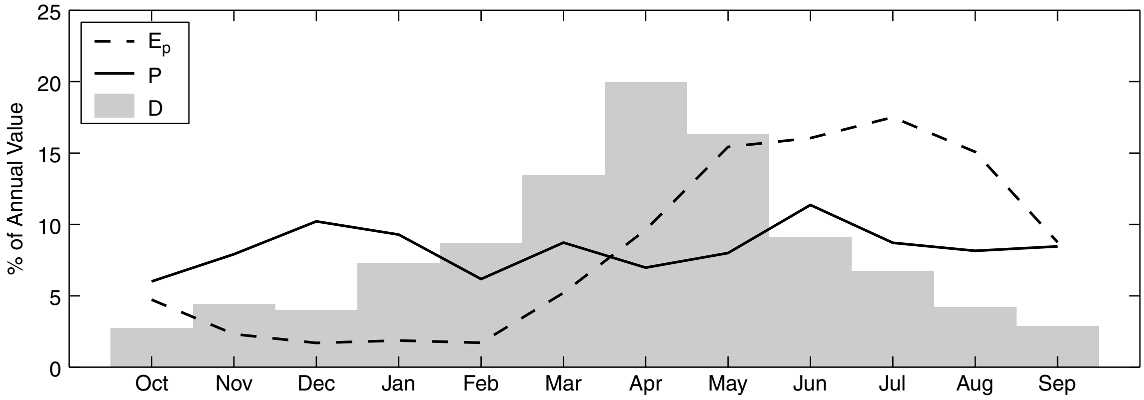


Figure 1. Average hydrological regime (1974–95), showing average monthly trends in potential evapotranspiration E_p, precipitation P and lysimeter drainage D

taken to replenish soil moisture prior to drainage generation, together with the time taken for generated drainage to reach the lysimeter base (and the collector drains). Snowfall and soil freezing, which act to delay infiltration and drainage generation following precipitation, may also contribute to this lag.

Interannual variability in precipitation and potential evapotranspiration is random, whilst annual drainage clearly decreases over the course of the data record (Figure 2). This inter-annual drainage trend reflects the increased interception of precipitation and increased soil water utilization accompanying growing vegetation. The hydrological impact of growing vegetation is illustrated in Figure 3, which shows the drainage regimes and drainage duration curves (analogous to flow duration curves used in runoff analysis) that result when the dataset is arbitrarily divided into three segments, representing early (1974–81), intermediate (1981–88) and late (1988–95) growth phases. Drainage duration curves indicate that drainage changes from being continuous to intermittent as vegetation grows, accompanied by a steady decrease in average daily drainage magnitudes. The trend towards intermittency is also evident in the drainage regime, which shows a decrease in the length of the 'drainage season' as vegetation grows, with drainage becoming increasingly concentrated around April and May.

MODELLING

The lysimeter structure, combined with the lack of topographical gradient and relative homogeneity of the soil profile, is likely to limit significantly the extent of lateral surface and sub-surface flow in this application. In keeping with the desire for parsimony in the downward modelling approach, lateral flow is therefore ignored. Simulation of drainage is thus achieved by determination of the vertical one-dimensional water balance, with the change in lysimeter soil moisture storage ΔS being given by

$$\Delta S = P - E_i - E_{bs} - E_t - D \tag{1}$$

A certain quantity of precipitation P is intercepted within the canopy E_i, with the remainder entering the soil system, replenishing soil moisture. Evaporative demand results in direct removal of moisture from bare soil E_{bs}, as well as loss via plant water uptake and subsequent transpiration E_t. Soil moisture is also susceptible to drainage D due to gravity.

The hydrology of the lysimeter soil system is conceptualized using a simple capacitance ('bucket') modelling approach. This considers the soil system to behave uniformly, such that the soil is considered to have a moisture storage value functional on its average moisture content θ and thickness L:

$$S = L\theta \tag{2}$$

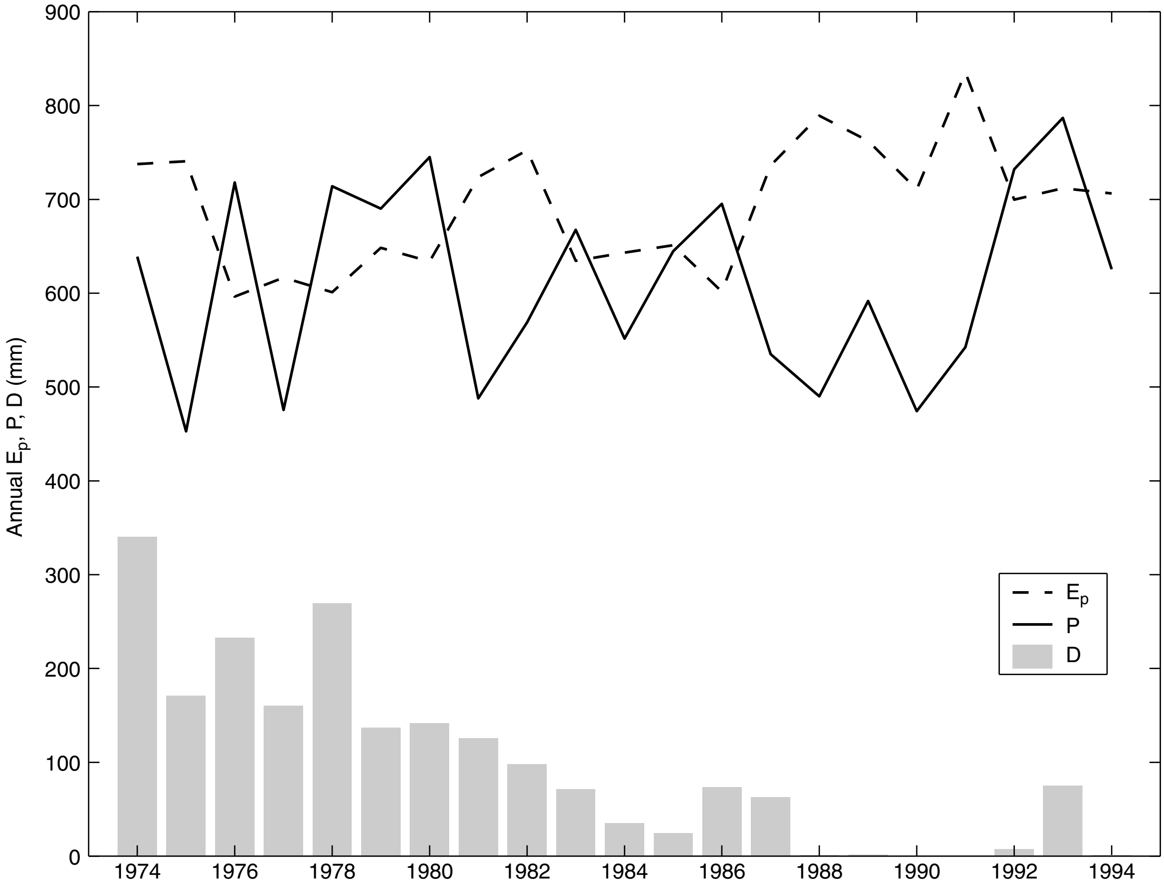


Figure 2. Annual time series (using October–October hydrological year) for potential evapotranspiration E_p, precipitation P and lysimeter drainage D

The soil is considered to have a water holding capacity, equivalent to a conceptual field capacity θ_{fc}, above which drainage will occur. Since soils have a finite thickness and hydraulic conductivity, it is unlikely that all excess water $(S - S_{fc})$ is drained within a given, small time step. A conceptual drainage time t_d is therefore used, such that the quantity of drainage in a given time step is given by

$$D = \frac{S - S_{fc}}{t_d} \tag{3}$$

Equation (3) reflects the physical understanding that the unsaturated hydraulic conductivity of a given soil decreases with decreasing soil moisture content. It describes a 'linear bucket' model, since the quantity of outflow is linearly related to the quantity of excess water. A more general form of the outflow equation is (Wittenberg, 1999)

$$D = \left(\frac{S - S_{fc}}{a}\right)^{1/b} \tag{4}$$

where a and b are empirical constants. If $b \neq 1$, Equation (4) represents a 'non-linear bucket' model. Although other equation forms exist (e.g. Jury *et al.*, 1991), effectively representing different parameterizations of the relationship between unsaturated hydraulic conductivity and soil water content, this study considers only the linear and non-linear models given in Equations (3) and (4).

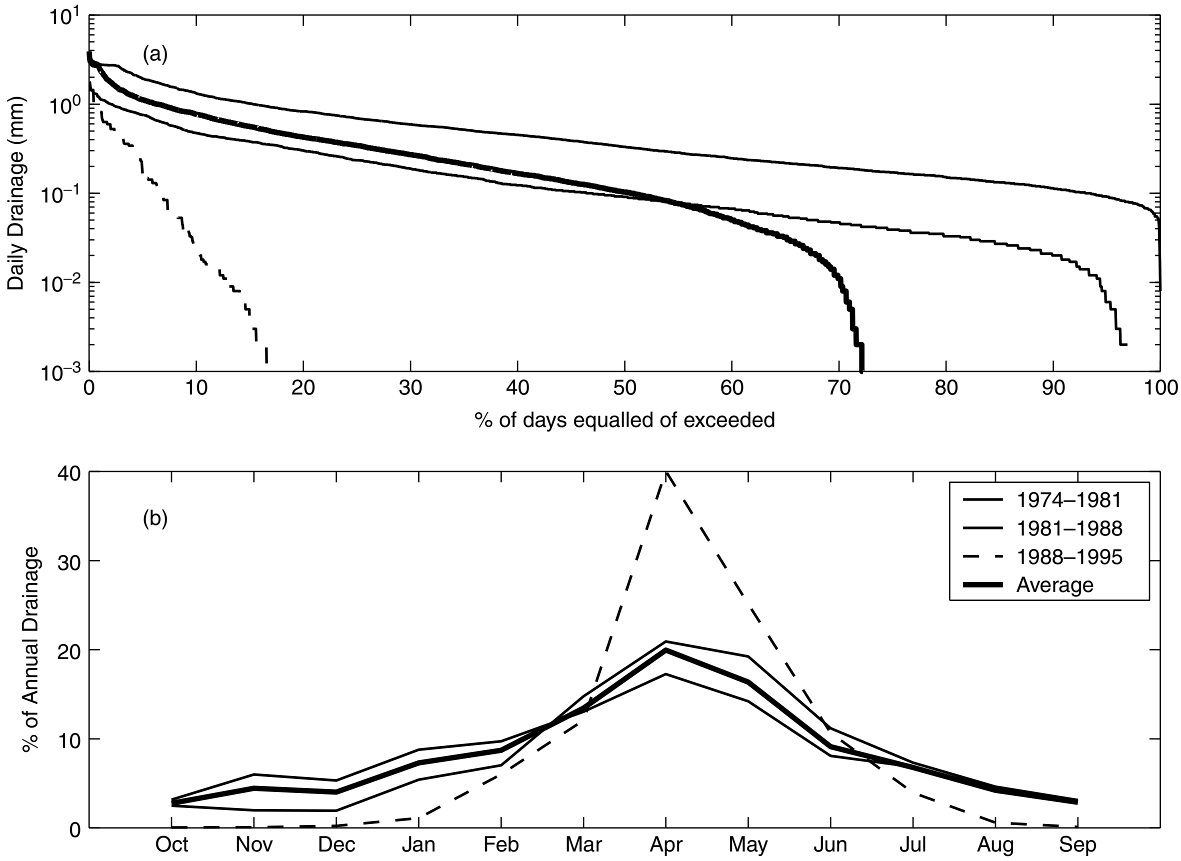


Figure 3. (a) Drainage duration curves and (b) drainage regimes for early (1974–81), intermediate (1981–88) and late (1988–95) growth stages. Average signatures for 1974–95 are also shown

The dynamic impact of vegetation upon the hydrology of the lysimeter is incorporated in terms of its impact upon evapotranspiration and interception losses, which are significantly variable between forested and non-forested sites. Evapotranspiration (the sum of bare soil evaporation E_{bs} and plant transpiration E_t) is assumed to remove soil moisture at a rate equal to the potential rate E_p, linearly scaled to account for the relative moisture content of the soil, which is similar to the method used in many other water balance models (e.g. Chiew and McMahon, 1991; Calder, 1992; Beverly *et al.*, 1999). Bare soil evaporation and plant transpiration components are explicitly incorporated, since the relative contribution of each to total evapotranspiration will change significantly as vegetation grows. For simplification, the permanent wilting point is assumed to represent the lower threshold for both evaporative processes, which allowed an effective porosity and field capacity (determined by subtracting the permanent wilting point moisture content from their actual values) to be used in modelling (Farmer *et al.*, 2002). Bare soil evaporation is considered to remove soil moisture only from the portion of the soil not shaded by vegetation cover, and is calculated as

$$E_{bs} = (1 - C_v)E_p \frac{S}{S_b} \tag{5}$$

where C_v is the percentage vegetation cover, and S_b denotes the soil moisture capacity at saturation (i.e. soil moisture content equal to soil porosity ϕ). The remaining vegetated portion of the soil is subject to plant transpiration E_t:

$$E_t = C_\nu E_p \alpha \tag{6}$$

where α is the plant stress coefficient, given by

$$\alpha = \begin{cases} \dfrac{S}{S_{fc}} & \text{for} \quad S \leq S_{fc} \\ 1 & \text{for} \quad S > S_{fc} \end{cases} \tag{7}$$

which assumes that plant water uptake (hence transpiration) is limited only by demand at soil moisture contents above (or equal to) field capacity.

Daily precipitation P is considered to infiltrate the soil completely within the time step in which it falls, with the exception of the portion intercepted by vegetation surfaces c_i, such that daily interception is given by

$$E_i = c_i P \tag{8}$$

For simplicity in model parameterization, interception loss is regarded as a separate, additional evaporative loss term in the water balance, and is not considered to impact transpiration.

The simplest possible parameterization of this model framework is initially trialled. Two types of refinement to the model are then implemented, based upon identified weaknesses in the model's ability to replicate the behaviour of important drainage signatures. The first refinement seeks to improve the description of soil water partitioning, and the second refinement attempts to improve the description of water input to the soil system. In all cases, linear and non-linear forms of each model are assessed, and a daily time step is used, which corresponds to the resolution of the primary model input (i.e. meteorological data) and validation data (i.e. drainage measurements).

Single-layer capacitance model (Model 1)

The simplest parameterization of the framework described is to represent the soil as a single 'bucket', extending over the total depth of the lysimeter. Daily evapotranspiration and drainage are calculated on the basis of the preceding day's storage, such that the explicit form of Equation (1) for this non-linear model version is

$$S^t = S^{t-1} + (1 - c_i^t)P^t - (1 - C_\nu^t)E_p^t \left[\frac{S^{t-1}}{S_b}\right] - C_\nu^t E_p^t \left[\frac{S^{t-1}}{S_{fc}}\right] - \left[\frac{S^{t-1} - S_{fc}}{a}\right]^{1/b} \tag{9}$$

(where $b = 1$ and a is replaced with t_d for the linear model version). The superscripts $t - 1$ and t denote the previous and current time steps respectively.

Parameter values used in linear and non-linear implementations of the Model 1 series model (as well as those for subsequent models) are summarized in Table I. Soil porosity was determined by gravimetric analysis of soil samples. Field capacity and permanent wilting point were evaluated as the moisture content corresponding to soil water potentials of −33 kPa and −1500 kPa respectively, and obtained from soil moisture characteristic curves derived from laboratory analysis of multiple soil samples. Values are comparable to those quoted by Dingman (1994) and Rawls *et al.* (1992) for sands.

Drainage parameter values were obtained from the best fit of chosen drainage recessions. For a linear bucket, t_d is obtained by fitting chosen recessions to the expression

$$D = D_0 \exp\left(\frac{-t}{t_d}\right) \tag{10}$$

Table I. Parameter value set used in modelling

Parameter	Symbol	Value	Source
Linear model			
Drainage parameter	t_d	100 days	Recession fit to Equation (10)
Non-linear model			
Drainage parameter	a	90 days^b mm^{1-b}	Recession fit to Equation (11)
Drainage parameter	b	0·6	Recession fit to Equation (11)
Model 1 series			
Porosity[a]	ϕ	0·349	Soil sample analysis
Field capacity[a]	θ_{fc}	0·073	Soil moisture characteristic
Lysimeter depth	L	4300 mm	Measurement
Initial interception	I_{init}	5%	Estimated value
Maximum interception	I_{max}	39%	Dingman (1994)
Maximum cover	$C_{v,max}$	90%	Assumed value
Time until maximum canopy closure	d_{mcc}	5000 days	Leersnijder (1992) (approx. 16 years old)
Model 2 series (additional to Model 1)			
Bare soil evaporation zone of influence	L_{BSE}	300 mm	Assumed value
Time until root zone intercepts base (4300 mm)	d_{rzi}	8500 days	Assumed (corresponding to root penetration to 4 m by 1995)
Model 3 series (additional to Model 2)			
Critical temperature	T_{crit}	1·5 °C	Magdeburg meteorological data
Degree day factor	B	2·5 mm day^{-1} °C^{-1}	Bras (1990)
Snow albedo	A	0·65	Bras (1990)

[a] Effective values, relative to a permanent wilting point volumetric water content of 0·024.

where D_0 denotes the initial drainage value (i.e. at $t = 0$). Parameters for a non-linear bucket model are obtained by fitting chosen recessions with the expression (Wittenberg and Sivapalan, 1999)

$$D = D_0 \left[1 + \frac{(1-b)D_0^{1-b}}{ab} t\right]^{1/(b-1)} \tag{11}$$

Equations (10) and (11) are obtained by solution of the differential forms of Equations (3) and (4) respectively for some initial drainage D_0 and assuming that evapotranspiration and precipitation have a negligible impact upon recessions (i.e. are negligible or equivalent in magnitude), such that

$$\frac{dS}{dt} = -D \tag{12}$$

Fits to Equation (10) are reasonable, but typically underestimate peak drainage and overestimate residual drainage. This indicates that t_d is effectively increasing over the recession, and therefore suggests that a non-linear assumption may be more realistic (Wittenberg, 1999). Indeed, although peak magnitudes are still underpredicted, fits to Equation (11) are superior to those for Equation (10), although derivation of optimum values for a and b is complicated by the additional degree of freedom; it is necessary to restrict values for b to between 0·4 and 0·6 to achieve fitted values for a that produce reasonable drainage values for the quantities of excess storage ($S - S_{fc}$) generated in modelling the lysimeter system.

The hydrological impact of growing vegetation is parameterized in the model by variable values of rainfall interception percentage I and vegetation cover percentage C_v, which are properties of the canopy. No direct measurements of canopy properties were taken during the study period, and relevant values for time variability in canopy properties for a growing pine stand could not be obtained from literature. For parsimony, parameter values are therefore assumed to grow linearly from some initial value (I_{init} and $C_{\text{v,init}}$) to a maximum value ($I_{\max}$ and $C_{\nu,\max}$) at the time when maximum canopy closure is achieved (d_{mcc}). The PINOGRAM pine growth area model of Leersnijder (1992) predicts that maximum canopy dimensions are achieved within 15 years for a stand with a slightly higher density (10 000 trees ha^{-1}) to the pre-thinning density at the study site (8530 trees ha^{-1}), and so it is assumed that canopy parameter values reach their maxima in a 16 year old stand (i.e. by 1988) in this study. An annual average value of interception percentage for mature European pine stands of 39% is used (Dingman, 1994), but documented maximum percentage vegetation cover values were unavailable, and so an assumed value of 90% is used. An arbitrary initial value for interception is used for the initial 2 year old stand at planting, with sensitivity analysis confirming that model output is insensitive to the exact value used. The correlation between interception and vegetation cover is assumed to be non-variable with growth, such that the initial value for percentage vegetation cover is given by

$$C_{\text{v,init}} = I_{\text{init}} \frac{C_{\nu,\max}}{I_{\max}} \tag{13}$$

The daily growth rates for interception percentage and vegetation cover percentage are given by

$$\Delta I = \frac{I_{\max} - I_{\text{init}}}{d_{\text{mcc}}} \tag{14}$$

and

$$\Delta C_\nu = \Delta I \frac{C_{\nu,\max}}{I_{\max}} \tag{15}$$

respectively.

Growth of the stand was interrupted twice by thinning (in 1982 and 1993), with stand density in trees per hectare being decreased to approximately 80% of pre-clearing values in both cases. It is assumed that this results in a commensurate step-reduction in canopy property values, and otherwise has no impact upon the linear growth assumption (i.e. dI and dC_ν are unaffected).

Multiple-layer capacitance model (Model 2)

The single-bucket model effectively implies that bare soil evaporation and root water uptake (hence transpiration) act throughout the 4·3 m profile. In reality, the effects of bare soil evaporation are restricted to the near-surface soil, and plant transpiration removes water from the root zone, which increases as the *P. sylvestris* stand grows. Zones of evaporative influence are more adequately represented by applying a multiple-layer capacitance model, in which the soil profile is divided into three layers; (1) the uppermost layer (constant thickness) is subject to bare soil evaporation and plant transpiration; (2) the middle layer (variable thickness, increasing as the roots grow) is subject to plant transpiration only; (3) the base layer (variable thickness, decreasing with root growth) is not subject to evapotranspiration processes. Water in excess of field capacity in a given layer drains (percolates) into the underlying layer according to Equation (3) or (4). Drainage from the base layer constitutes actual drainage, for water balance purposes. The water balance can be expressed by the following system of equations (non-linear model version), where numerical subscripts denote layer numbers:

$$S_1^t = S_1^{t-1} + (1 - c_{\text{i}}^t)P^t - (1 - C_\nu^t)E_{\text{p}}^t \left(\frac{S^{t-1}}{S_{\text{b}}}\right) - C_\nu^t E_{\text{p}}^t \left[\frac{\min(S_1^{t-1}, S_{\text{fc1}})}{S_{\text{fc1}} + S_{\text{fc2}}}\right] - \left(\frac{S_1^{t-1} - S_{\text{fc}}}{a_1}\right)^{1/b} \tag{16}$$

$$S_2^t = S_2^{t-1} - C_\nu^t E_{\text{p}}^t \left[\frac{\min(S_2^{t-1}, S_{\text{fc2}})}{S_{\text{fc1}} + S_{\text{fc2}}}\right] + \left(\frac{S_1^{t-1} - S_{\text{fc}}}{a_1}\right)^{1/b} - \left(\frac{S_2^{t-1} - S_{\text{fc}}}{a_2}\right)^{1/b} \tag{17}$$

$$S_3^t = S_3^{t-1} + \left(\frac{S_2^{t-1} - S_{\mathrm{fc}}}{a_2}\right)^{1/b} - \left(\frac{S_3^{t-1} - S_{\mathrm{fc}}}{a_3}\right)^{1/b} \tag{18}$$

No physical measurements of plant roots were made at the study site. Tensiometer readings from a 3 m depth since 1995 indicate a progressive drying of the deeper soil profile, which suggests that roots have extended to this depth or beyond by this time. The root zone is assumed to reach the lysimeter base by 1997 (i.e. $d_{\mathrm{rzi}} = 8500$), although the model output is insensitive to variations in this value of 5 years or more. For consistency with canopy parameter growth, the mean root zone thickness (below the bare soil evaporation layer) is also considered to grow linearly from some initial thickness $L_{\mathrm{rz,init}}$, at a rate given by

$$\Delta L_{\mathrm{rz}} = \frac{L - (L_{\mathrm{BSE}} + L_{\mathrm{rz,init}})}{d_{\mathrm{rzi}}} \tag{19}$$

where L_{BSE} denotes the bare soil evaporation layer thickness, which is assumed to be 300 mm for the sandy lysimeter soil. Root zone growth is not considered to be impacted by thinning events. Since the initial influence of plant transpiration is small (i.e. while C_ν is small), any small value for the initial thickness of the second soil layer can be used without significantly influencing model predictions (confirmed by sensitivity analysis), and a value of 10 mm is used. Similarly, model predictions are insensitive to the value of L_{BSE} used.

No set of drainage parameter values can make a multiple-layer model drain in exactly the same way as a single-layer model. Since the drainage parameter is conceptually related to an average travel time, its value is assumed to be proportional to layer thickness such that, for soil layer i:

$$t_{\mathrm{d}i} = \max\left(\frac{L_i}{\sum L} t_{\mathrm{d}}, 1\right) \quad \text{or} \quad a_i = \max\left(\frac{L_i}{\sum L} a, 1\right) \tag{20}$$

where values must exceed unity to ensure that calculated drainage does not exceed the excess storage in each layer. A control simulation, in which multiple layers are used, but where evaporative processes are assumed to impact the entire soil profile (as per the single-layer model), indicates that the modification of the single-layer model to a multiple-layer model has a negligible impact upon predicted drainage behaviour, *per se*. Therefore, any difference in predicted drainage behaviour between corresponding multiple-layered models and single-layered models can be considered as a true impact of the improved incorporation of evaporative zones of influence, rather than an artefact of using a different parameterization for drainage behaviour.

Multiple-layer capacitance model with snowfall (Model 3)

Snowpack formation and snowmelt introduces an additional lag between precipitation and infiltration, which will impact the timing of drainage generation. If snowfall is an important component of winter precipitation, explicit incorporation of snow processes may be required to capture sub-annual drainage behaviour adequately.

Without on-site data relating to daily precipitation form, precipitation is assumed to fall as snow below some critical temperature T_{c}, and will accumulate in a surface snowpack (S_{s}). The simplest empirical method for estimating snowmelt from the snowpack is the degree-day or temperature-index method (Dingman, 1994); snowmelt occurs when atmospheric temperatures exceed some critical temperature (assumed to equal T_{c} for parsimony; Eder *et al.*, 2003) at a rate given by

$$\Delta S_{\mathrm{s}} = B(T - T_{\mathrm{c}}) \tag{21}$$

where B (mm day^{-1} °C^{-1}) is termed a degree-day factor.

Potential evapotranspiration estimates derived for a soil or vegetated surface are likely to overestimate potential evaporation from a snow surface, due to the relatively high albedo of a snow surface relative to a soil or vegetation surface (Leydecker and Melack, 2000). Snow albedo A is used in the model as an evaporation scaling factor, such that evaporation from the snowpack is given by

$$E_s = (1 - A)E_p \tag{22}$$

Interception of snowfall will be considered to operate identically to rainfall interception, given that interception percentages obtained from literature relate to total precipitation, without specification of precipitation form. Studies in North American and Russian forests suggest between 25 and 45% of seasonal snowfall is intercepted and sublimated, and therefore lost to interception (Pomeroy *et al*., 1998); the assumed interception percentage used in this study (39% at maturity) is within this range.

Precipitation form data were not collected at Colbitz. Therefore, 1974–95 daily precipitation, temperature and precipitation classification data from the nearby Magdeburg meteorological station was used to estimate a critical temperature value suitable to the site. Annual snowfall predictions corresponded to measured values when a value of 1·5 °C was used, which is within the range of −2 to +4 °C obtained by Braun (1985) for German climates. As the precipitation classification record is imperfect (i.e. no proportioning estimates are given for days classified as 'mixed form'), the true value may be ±2 °C this value. Daily atmospheric temperature measurements obtained from Magdeburg will be used in modelling, since no local measurements were made.

An average melt coefficient of 2 mm day^{-1} °C^{-1} (Bras, 1990) will be assumed. Although known to vary with snow density and snow age, a constant value for snow albedo will also be used for simplicity.

Model evaluation

Models are primarily evaluated by comparison of predicted and observed drainage signatures, such as the drainage duration curve and drainage regime (and dynamic trends in these signatures), rather than by their ability to replicate drainage time-series, *per se*. Statistical correlations between the magnitude and timing of predicted and observed drainage are also evaluated. The drainage ratio R_D assesses the ability of the model to predict the average magnitude of drainage accurately, with a value of unity indicating perfect agreement:

$$R_D = \frac{E[D_{pred}]}{E[D_{obs}]} \tag{23}$$

where $E[D_{pred}]$ and $E[D_{obs}]$ denote the expected values of daily predicted and observed drainage respectively. Correlation coefficients between observed and predicted drainage time-series, at annual, monthly and daily time scales, are also used to assess the ability of the model to replicate the timing of drainage at different scales:

$$\rho = \frac{\mathrm{cov}(D_{obs}, D_{pred})}{\sqrt{\mathrm{var}(D_{obs})\ \mathrm{var}(D_{pred})}} \tag{24}$$

Higher values indicate a higher agreement between the observed and predicted drainage datasets in terms of patterns of variability from mean drainage values, with a value of unity indicating complete agreement. The correlation coefficient between observed and predicted drainage regimes ρ_{reg} is similarly determined.

RESULTS

Both linear (Model 1L) and non-linear (Model 1NL) versions of the single-layer model successfully replicate the observed long-term trend in annual drainage (Figure 4). Patterns of inter-annual variability in drainage are reasonably well captured, as indicated by ρ_a values greater than 95% in both versions of the single-layer model

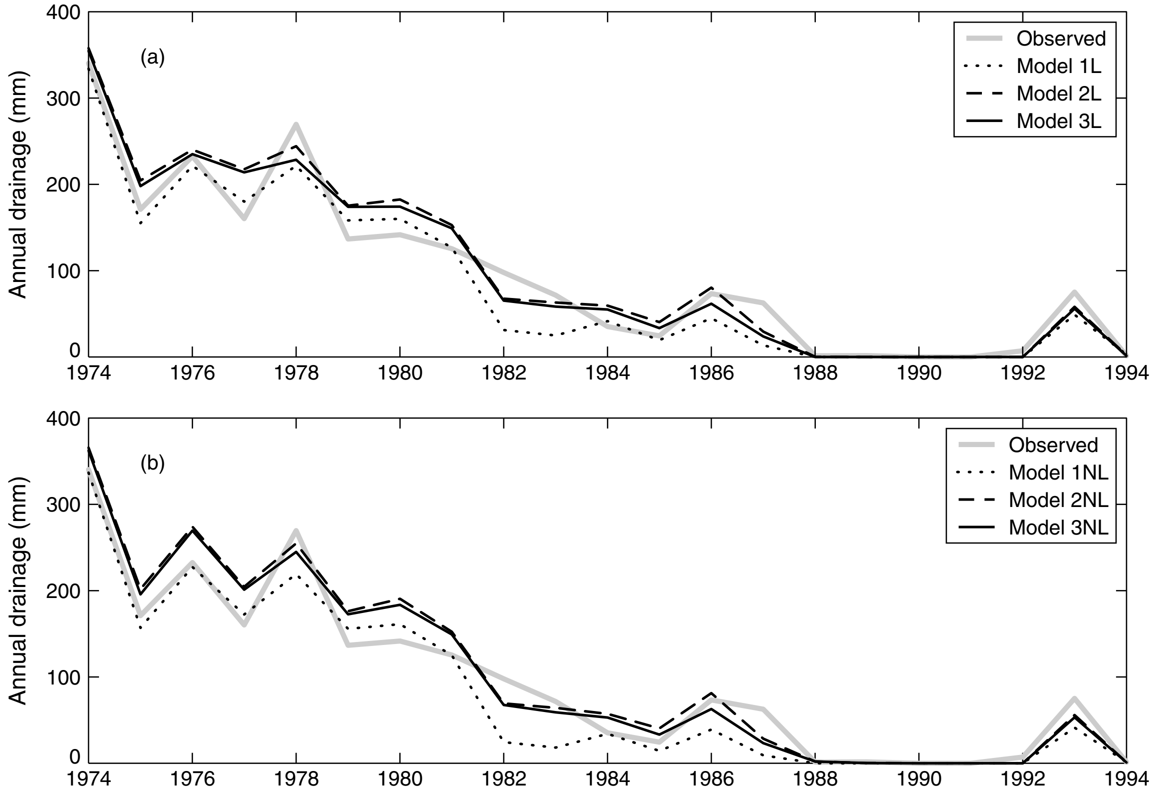


Figure 4. Annual drainage time-series predictions for (a) linear and (b) non-linear model versions, using October–October hydrological year

Table II. Evaluation statistics for all models; annual (ρ_a), monthly (ρ_m) and daily (ρ_d) correlations, drainage ratio R_D and regime correlation ρ_{reg}, as defined in Model evaluation section

	ρ_a	ρ_m	ρ_d	R_D	ρ_{reg}
Model 1L	0·969	0·775	0·707	0·879	0·642
Model 1NL	0·966	0·771	0·702	0·856	0·542
Model 2L	0·975	0·844	0·776	1·072	0·861
Model 2NL	0·979	0·835	0·771	1·094	0·731
Model 3L	0·972	0·851	0·787	1·026	0·921
Model 3NL	0·978	0·887	0·830	1·052	0·843

(Table II), although there is a noticeable underprediction during the intermediate growth phase (1981–88), which results in the underprediction of average drainage magnitude (i.e. $R_D < 1$).

Drainage regimes are skewed, overpredicting the drainage contribution from the first half of the hydrological year, i.e. October to March (Figure 5). Drainage duration curves indicate that the single-layer models overpredict the frequency of moderate magnitude (i.e. 0·3–1 mm) daily drainage events and underpredict the frequency of low-magnitude drainage events (Figure 6). Peak daily drainage magnitudes are also underpredicted, although to a lesser extent by the non-linear model.

Predicted dynamic trends in the drainage regime and drainage duration curve are almost identical for both model versions, with linear model predictions given in Figure 7. The drainage duration curve produces the

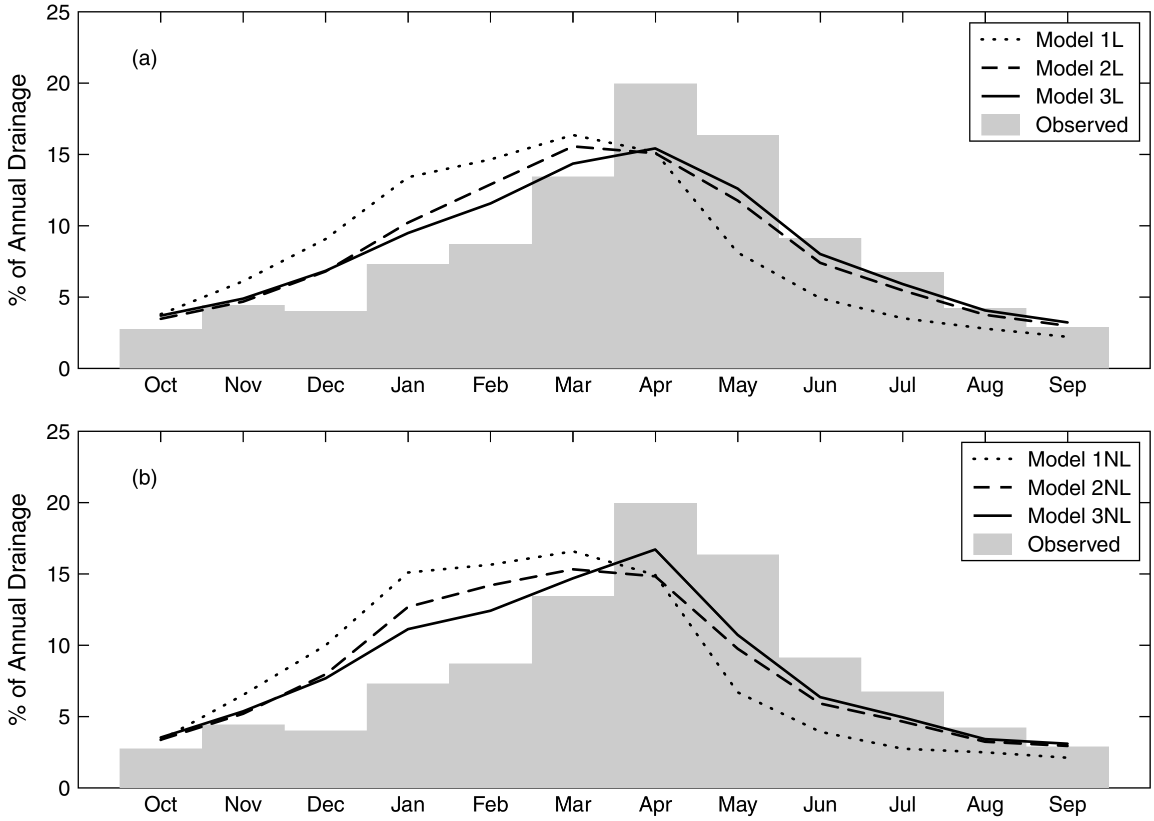
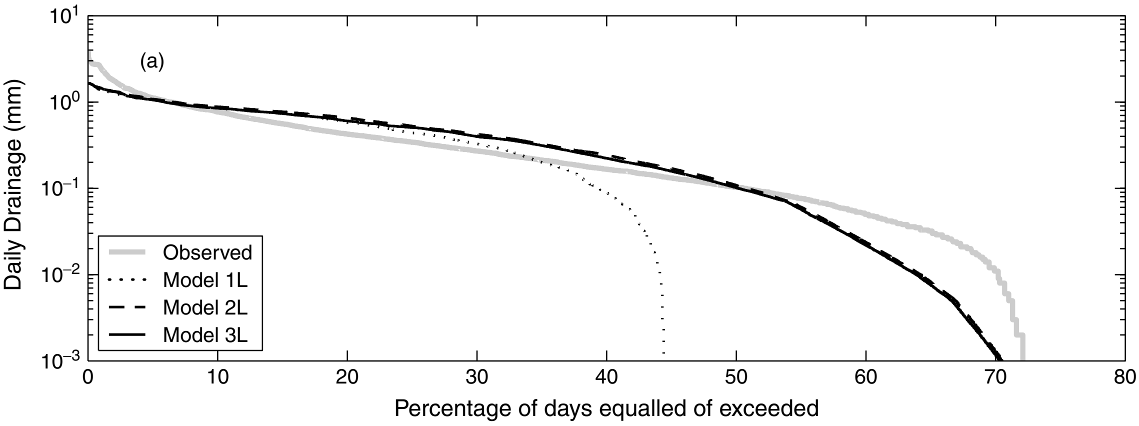


Figure 5. Average drainage regime predictions for (a) linear and (b) non-linear model versions

correct dynamic trend of decreasing curve length and decreasing average daily drainage magnitude with time, although curve lengths and large-magnitude daily drainages are systematically underpredicted. Predicted regimes replicate the observed decrease in the length of the 'drainage season' as vegetation grows, as shown in Figure 3, but with systematic errors in the timing of season commencement and cessation and the within-season pattern. These systematic errors reflect the deviations between predictions and observations evident in their respective parent curves (i.e. Figures 5 and 6).

The ability of both versions of the model to capture the basic long-term drainage behaviour suggests that the simple linear growth assumption used is sufficient for modelling the impact of vegetation *growth* upon hydrology, although this does not preclude the possibility that shortcomings in model predictions at sub-annual time scales are a result of the way in which vegetation, rather than vegetation growth, was itself incorporated. For example, the annual average loss percentage used for interception loss may be adequate for annual and greater time scales, but at smaller time scales the interception loss will be functional upon variability in rainfall and evaporation properties at these scales. More importantly, it also suggests that a single-storage capacitance model is sufficient for predicting annual and inter-annual drainage behaviour in a growing pine stand. Model refinements may be implemented if further improvement is required in long-term predictions, or if accurate predictions are required at sub-annual time scales.

Refinement using a downward approach examines the ability of the current model basis to generate important signatures, and attempts to explain discrepancies in terms of inadequate process description or parameterization, which can then be incorporated into subsequent modelling. For Model 1L, in the absence of infiltration and evaporation (i.e. drainage as the only source/sink), the drainage duration curve will have a



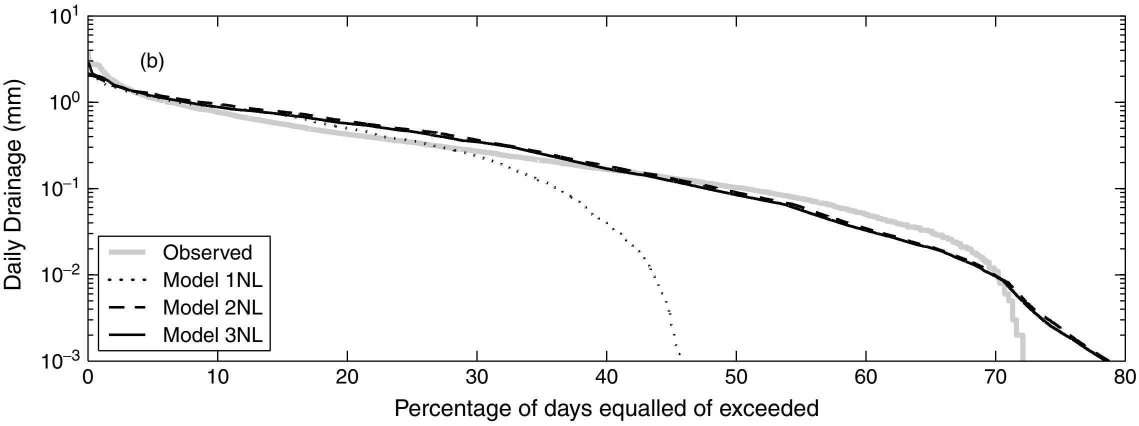


Figure 6. Drainage duration curve predictions for (a) linear and (b) non-linear model versions

linear (on the log–linear axes used) negative gradient, with a magnitude dependent upon the magnitude of t_d. Behaviour for Model 1NL is similar, but with a decreasing (rather than constant) negative gradient with increasing exceedence probability. Drainage events act to decrease the magnitude of the negative gradient, whereas evaporative losses act to increase the magnitude of the negative gradient, relative to this.

The drainage duration curve intercept is functional upon the magnitude of the largest soil moisture excess occurring during the simulation (which is controlled by precipitation and soil parameter values), and upon the drainage parameter value, and therefore cannot be altered for a given precipitation record without calibration of parameter values or a re-conceptualization of drainage behaviour. It is reasonable, therefore, to conclude that, if the drainage parameter value is assumed to be correct, then the length of the drainage duration curve (i.e. the percentage exceedence value corresponding to zero daily drainage; approximately 72% for observed data) is strongly influenced by the relative strength of evaporative processes. By assuming that evaporative processes operate over the complete soil profile, the Model 1 series overestimates the impact of bare soil evaporation (in reality, restricted to the near-surface profile) and plant transpiration (restricted to the root zone). Throughout most of the simulation period, a base soil layer below the depth of root exploration will exist that is not subject to evaporative forcing. The expected reduction in evapotranspiration resulting from proper incorporation of evaporative zones of influence should increase the incidence of low-magnitude daily drainage, thereby lengthening the drainage duration curve, increasing the persistence of drainage into summer (thereby improving regime predictions) and increasing cumulative drainage prediction (hence R_D).

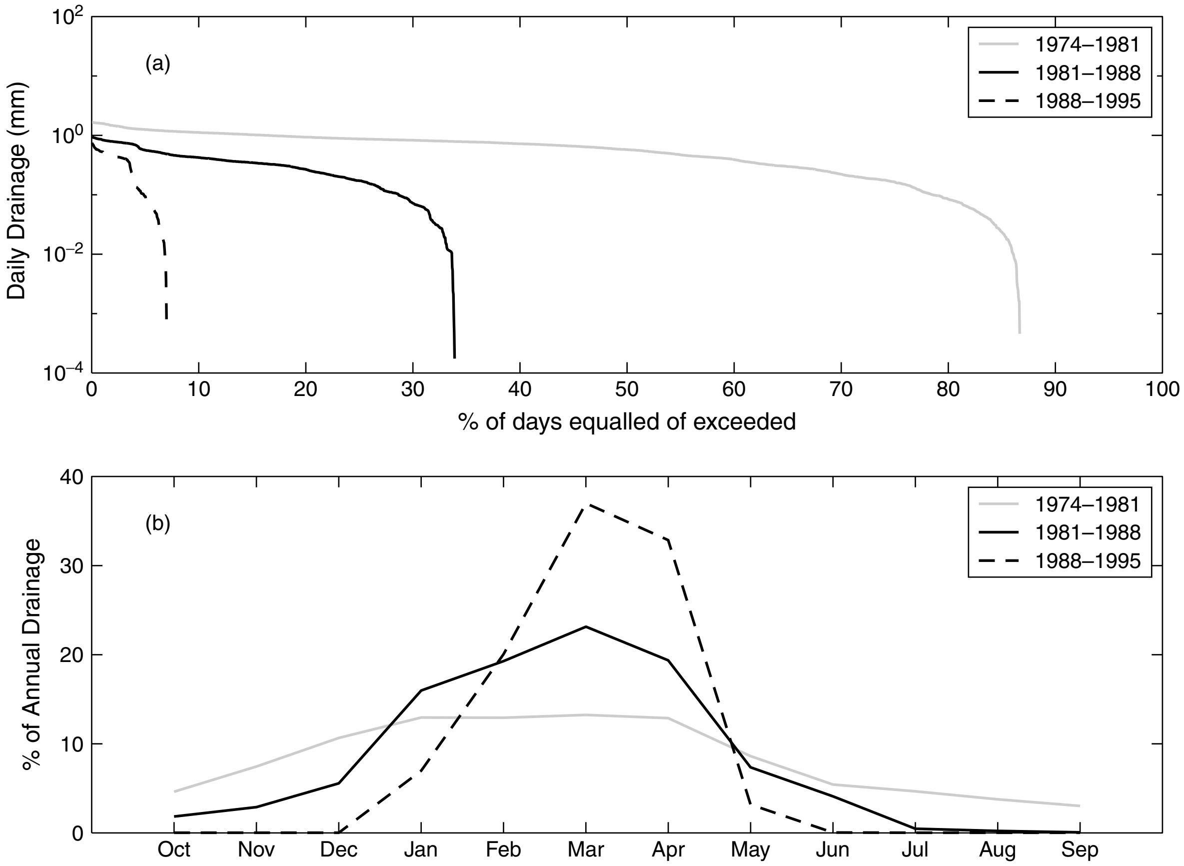


Figure 7. Predicted (a) drainage duration curves and (b) drainage regimes for early (1974–81), intermediate (1981–88) and late (1988–95) growth stages using Model 1L

The multiple-layer model versions (Model 2L and Model 2NL) do, indeed, produce improvements in the prediction of the drainage duration curve length, drainage regime and drainage ratio. Drainage duration curve length is predicted to within a few percent of observed length by the linear model, whereas the non-linear model overpredicts the length. Improvement to the intermediate growth phase (1981–88) drainage duration curve (shown for Model 2L in Figure 8a) is especially significant, and is also evident by the improvement in predictions of the annual drainage time-series during the corresponding period, which is no longer systematically underpredicted (Figure 4). Some improvement in predicted drainage timing is evident in overall (and individual growth phase) drainage regimes and regime correlation values ρ_{reg}. Snowfall, snowpack formation and snowmelt will result in a delay between winter precipitation and infiltration (hence delaying excess soil moisture generation and drainage), which may explain the remaining discrepancy between predicted and observed drainage regimes.

With the exception of monthly and daily correlations for the non-linear model, which show a moderate improvement, the incorporation of snow processes in Model 3L and Model 3NL has, at best, a minor impact upon improving the prediction of drainage behaviour. Correction of the overprediction of late winter drainage contribution, in particular, is not as significant as expected.

Average predicted annual snowfall is approximately 70 mm (i.e. roughly 10% of annual precipitation), which is reasonable for this region of Germany. The predicted onset of snowfall typically occurs in late November or early December and continues as late as early April, and is interspersed by significant rainfall events—all

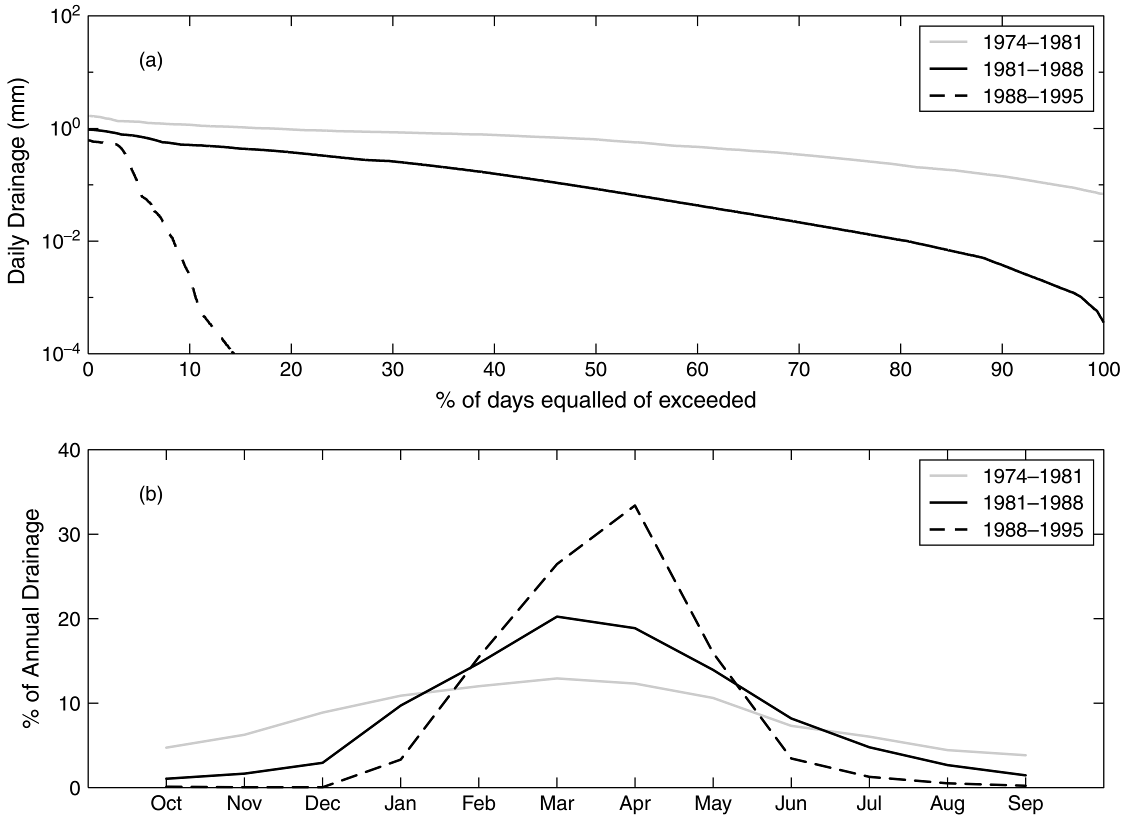


Figure 8. Predicted (a) drainage duration curves and (b) drainage regimes for early (1974–81), intermediate (1981–88) and late (1988–95) growth stages using Model 2L

of which is also in good agreement with the existing precipitation record from Magdeburg. Even when the occurrence of snow is exaggerated (i.e. by using a critical temperature of 4 °C; equivalent to 140 mm year^{-1} annual average snowfall), model output is found to be largely insensitive to variability in snow parameter values. Given this, the failure of snow incorporation to impact significantly on the model results suggests that the influence of snow upon drainage is minor, rather than process description being inadequate.

SENSITIVITY AND UNCERTAINTY ANALYSIS

An analysis of the sensitivity of model output to variability in model parameters is an effective means of determining the relative importance of different processes upon drainage generation. Although there is generally some level of uncertainty associated with all parameter values used in modelling, the level of confidence that can be placed in the model is mostly dependent upon the degree of uncertainty associated with parameters to which the model output is found to be sensitive.

Sensitivity was assessed by comparison of the evaluation statistics obtained using the standard parameter value set for Model 3L against those obtained by varying parameter values individually by ±50% arbitrarily (noting that sensitivity to T_{crit} was instead assessed using a range of ±2·5 °C, and that sensitivity to a was evaluated using Model 3NL, by necessity). Sensitivity was expressed in terms of the average percentage deviation in evaluation statistic values (Table III).

Table III. Average deviation in R_D and ρ_{reg} associated with sensitivity and uncertainty analyses. Sensitivity analysis was conducted using a ±50% variation in parameter values, and uncertainty analysis using stated ranges (equivalent percentage range in brackets). Noteworthy values in bold

Parameter	Sensitivity analysis (±50%)		Uncertainty analysis		
	R_D	ρ_{reg}	Range	R_D	ρ_{reg}
ϕ	**18**	1	0·403–0·341 (8%)	3	0
θ_{fc}	**24**	4	0·057–0·089 (16%)	**10**	2
t_c	**12**	**14**	65–135 (35%)	6	**9**
a	**15**	**14**	70–110 (22%)	5	**11**
d_{mcc}	**41**	2	4000–6000 (20%)	**17**	1
d_{rzi}	**14**	2	7000–10 000 (12%)	4	0
I_{max}	**23**	2	29–49 (26%)	**13**	1
$C_{v,max}$	**37**	2	75–100 (28%)	**10**	0
I_{init}	4	0			
T_{crit}	7	4			
B	2	1			
A	3	1			
L_{BSE}	2	0			

Prediction of drainage magnitude R_D is sensitive to variability in soil, vegetation and drainage parameters, but insensitive to snow parameters. Sensitivity to porosity and field capacity is a consequence of their role in scaling potential evaporation to obtain estimates of actual bare soil evaporation and transpiration respectively. Sensitivity to field capacity also relates to its role as a storage threshold, which strongly influences overall drainage magnitude. The sensitivity of the model to numerous vegetation parameters reflects the strong impact of interception and the dynamic variability of evapotranspiration partitioning between bare soil evaporation and plant transpiration as vegetation grows upon predicted drainage magnitude. The effect of drainage parameter value variability (t_d and a) upon average drainage magnitude relates to the impact that these parameters have in determining the partitioning of excess water between drainage and evapotranspiration.

Drainage timing correlations (ρ_d, ρ_m and ρ_a) are insensitive (percentage deviations $<5\%$) to variability in all parameters other than the non-linear drainage parameter a, and are therefore not shown. Sensitivity to a (with deviations of 13% for ρ_m and 23% for ρ_d) is an obvious consequence of the impact of the drainage parameter upon the 'routing' of excess water, with larger values resulting in a smoother drainage response with smaller peak magnitudes.

Uncertainty analysis was conducted on parameters to which model output was sensitive (i.e. if resultant variability in any evaluation statistic in the sensitivity analysis exceeded 10%), noting that uncertainty ranges for all model parameters are less than the 50% variability used in sensitivity analysis. Soil parameter uncertainty was taken from measurements of scatter between individual samples, and the simulation results of Leersnijder (1992) were used to estimate uncertainty in the timing of canopy closure (d_{mcc}). Variations in fits to Equations (3) and (4) for individual drainage recessions were used to assess uncertainty in t_d and a respectively. Arbitrary large uncertainty ranges are used for the remaining parameters in the absence of measured uncertainty. Results (along with the ranges used) are given in Table III.

Results of the uncertainty analysis indicate that confidence in the prediction of long-term drainage behaviour will be most readily improved by a more detailed determination of vegetation parameter values, and their growth. This may also facilitate refinement of the linear growth assumption presently used, which may improve annual predictions during the growth phase (in particular). A more rigorous determination of drainage parameter values will also improve confidence in predictions of drainage magnitude and timing.

The impact of combined parameter uncertainty upon drainage prediction is assessed by Monte Carlo analysis; 1000 simulation simulations were performed, in which all parameter values were randomly evaluated (using the uncertainty ranges given in Table III, and with a uniform probability assumption) for each simulation. Figure 9 illustrates the resulting variability in the predicted annual drainage time series and drainage regime for Model 3L, with Model 3NL producing similar results. For both model versions, observed annual drainage falls within a plus/minus one standard deviation range of predictions for most years of the simulation. The difference between observed and predicted regimes, however, cannot be accounted for by parameter uncertainty, which suggests that the model is deficient for predictions at the sub-annual scale.

The most significant source of model uncertainty relates to parameters contained within the initial (Model 1 series) modelling basis, rather than in subsequent amendments. Since additional uncertainty associated with model amendment is negligible, the decision to retain these amendments can be made purely by weighing their cost, in terms of additional complexity (i.e. additional costs of computation and data acquisition), against the resulting improvement to model predictive ability. Given that the magnitude of uncertainty associated with R_D exceeds the magnitude of the improvement associated with the addition of snow processes, for example, the additional cost of incorporating snow processes (i.e. the additional parameters T_{crit}, B and α, and the additional requirement of daily temperature data) may be considered as unjustified. The improvement to the regime correlation ρ_{reg} when snow is incorporated, however, does exceed model uncertainty; incorporation of snow may, therefore, be justified if the prediction of sub-annual drainage patterns is a priority.

GENERAL DISCUSSION

The initial single-layer model (Model 1) proved sufficient for modelling the long-term impact of vegetation growth upon drainage generation. This illustrates the dominant role of climate and basic soil properties

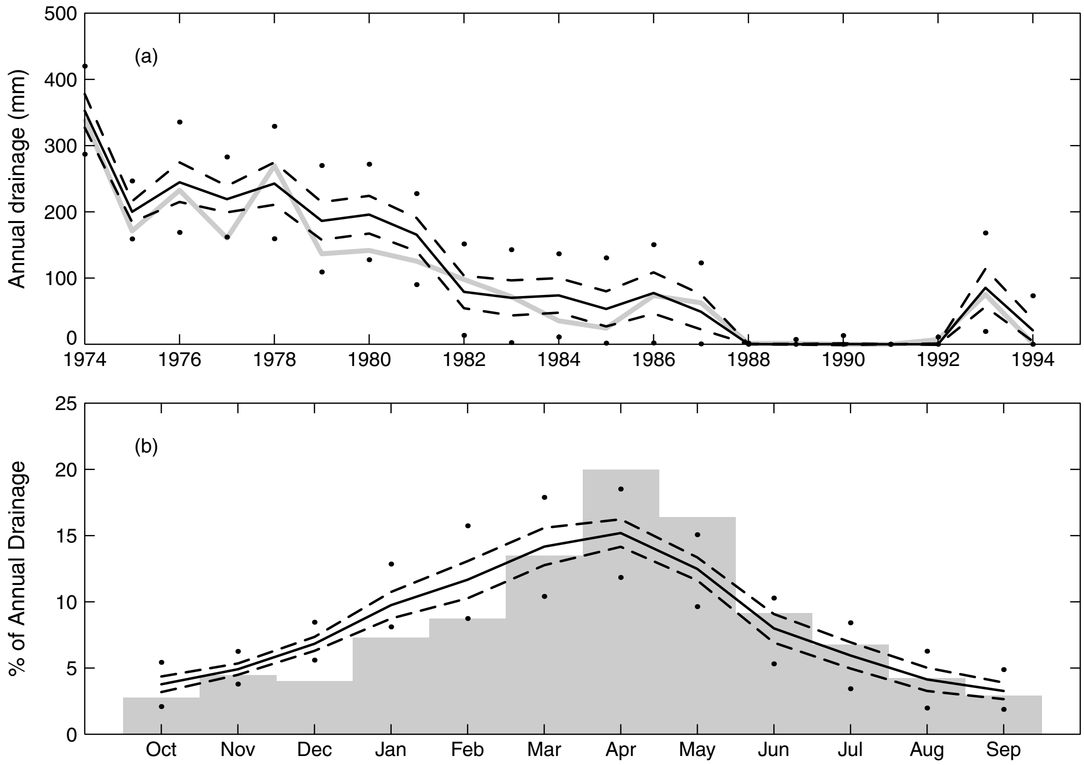


Figure 9. Variability in Model 3L predictions of (a) annual drainage time-series and (b) drainage regime, obtained via Monte Carlo analysis. The solid line denotes the average prediction, dashed lines are the plus/minus one standard deviation bounds, and dots correspond to the maximum and minimum predicted values for 1000 simulations

(regulated by variable vegetation properties) in determining long-term water balance behaviour, as suggested by the work of Milly (1994) and others. Expansion to a multiple-layered model (Model 2), with explicitly defined zones of evaporative influence, improved the closeness of fit between observed and predicted annual drainage, most significantly during the intermediate growth phase (1981–88). The improved prediction of low-magnitude drainage by the multiple-layered model also produced improvements in the prediction of sub-annual drainage timing (Figure 5), which was further improved by the incorporation of snow processes. Improvements at sub-annual time scales are, however, relatively minor, with a significant systematic error evident in the prediction of monthly and daily drainage timing. Given that these errors exceed predictive uncertainty, they indicate either the failure of the present model to incorporate one or more hydrological processes important at sub-annual time scales, or else the inadequate incorporation of an existing process.

An important limitation of the capacitance approach for the modelling of short-term drainage behaviour is its inability to account explicitly for the lag between excess moisture generation at the soil surface and drainage generation at the soil base, which is dependent upon the unsaturated hydraulic conductivity and thickness of the soil. Since unsaturated hydraulic conductivity decreases with decreasing soil moisture content, the magnitude of this lag will increase as plant water usage increases with vegetation growth, which is supported by observed drainage data (Christoph Hinz, unpublished data). It is hypothesized that a majority of the discrepancy between predicted and observed drainage regimes is caused by this unaccounted lag.

The lack of field data pertaining to drainage in many applications has meant that it is, by necessity, overlooked in model testing and validation. Thus, simple capacitance approaches are often used for simulating the drainage component of catchment water balance (e.g. Sivapalan *et al*., 1996), with most of the effort being directed towards improving model predictions that can be more readily validated, e.g. overall catchment runoff. Where the drainage contribution to overall catchment runoff is significant, however, the findings of this study suggest that the predictive ability of these models at sub-annual time scales is inherently limited, especially in applications with deep soils. A more conceptually correct *de facto* drainage modelling basis, for use when field measurements are unavailable (and hence validation cannot be performed), is required to overcome this limitation. A multiple infiltration–redistribution front approach is perceived as the next step in the downward approach to model development, since this explicitly accounts for the position of drainage fronts within the soil system, and hence the lag between excess water generation near the surface and base drainage. Development of a multiple infiltration–redistribution front model applicable to a water balance application (i.e. variable, deterministic precipitation) is currently in progress, using the event-based model of Ogden and Saghafian (1997) and rectangular redistribution model of Indelman *et al*. (1998) as a theoretical basis.

CONCLUSIONS

The ability of simple models to replicate long-term (annual and inter-annual) trends in drainage, as well as the resulting dynamic trends in hydrological signature curves, associated with vegetation growth has been successfully demonstrated. In applications where annual drainage simulation is sufficient, the findings of this study demonstrate that efforts towards improving *a priori* estimates of critical soil and vegetation parameters are of more benefit than increasing model complexity if model accuracy and confidence are to be maximized.

In applications that require daily or monthly drainage estimates, the study has identified an important inadequacy in the timing of predicted drainage when capacitance modelling approaches are used. A conceptual model basis that accounts for the physical delay between excess moisture generation at the soil surface (following infiltration) and the resulting drainage at the soil base is required to overcome this inadequacy.

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