Review

A review of rainfall interception modelling

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SUMMARY

This paper is a review of physically-based rainfall interception modelling. Fifteen models were selected, representing distinct concepts of the interception process. Applications of these models to field data sets published before March 2008 are also analysed. We review the theoretical basis of the different models, and give an overview of the models' characteristics. The review is designed to help with the decision on which model to apply to a specific data set. The most commonly applied models were found to be the original and sparse Gash models (69 cases) and the original and sparse Rutter models (42 cases). The remaining 11 models have received much less attention, but the contribution of the Mulder model should also be acknowledged. The review reveals the need for more modelling of deciduous forest, for progressively more sparse forest and for forest in regions with intensive storms and the consequent high rainfall rates. The present review also highlights drawbacks of previous model applications. Failure to validate models, the few comparative studies, and lack of consideration given to uncertainties in measurements and parameters are the most outstanding drawbacks. Finally, the uncertainties in model input data are rarely taken into account in rainfall interception modelling.

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Introduction

Rainfall interception is the process by which gross rainfall falling onto vegetative surfaces is subsequently redistributed. The rain that hits plant surfaces is temporarily retained and, ultimately, either evaporates into the atmosphere (interception loss) or makes its way to the ground either by falling as drops (drip) or by flowing down branches and stems (stemflow). The rain that does not hit a plant surface is called free throughfall and, together with drip, is often referred to as throughfall (David et al., 2005). Throughfall and stemflow together are referred to as net rainfall. Interception loss depends strongly on the timing and intensity of rainfall, the vegetation structure and the meteorological conditions controlling evaporation during and after rainfall (Rutter et al., 1975; Ward and Robinson, 1990; Dingman, 2002; Brutsaert, 2005).

Rainfall interception is recognized as a hydrological process of considerable importance in water resource management, but also in the context of climate change (Arnell, 2002). This is especially true for forest stands, where annual interception loss commonly amounts to a quarter or more of total rainfall (Dingman, 2002). Evaporation rates of intercepted water are much higher for forest than for short vegetation, because forest has markedly higher aerodynamic conductance. Unlike short vegetation, evaporation rates of intercepted water from tall vegetation thus greatly exceed transpiration rates under identical conditions because there is no physiological control by the plants. Hence, interception loss can be regarded as a substantial net addition to transpiration (Rutter, 1967; Stewart, 1977; Calder, 1979). Evaporation of intercepted rainfall contributes significantly to the differences in water use found for different vegetation types (Calder, 1990). The various components of the rainfall interception process have been measured and modelled for many vegetation types, with a special emphasis on forest stands. Interception measurement studies have been extensively reviewed, the most recent examples being by Crockford and Richardson (2000), Dunkerley (2000), Levia and Frost (2003, 2006) and Llorens and Domingo (2007). However, a comprehensive review of interception modelling studies has not yet been published. The present attempt is motivated first and foremost by the widely recognized importance of rainfall interception models for predicting the effects of climate and land-cover changes on water resources. Apart from allowing extrapolation of measurement results in space as well as time, interception models also provide insights into the mechanisms of the interception process (David et al., 2005).

The first attempt to conceptually model interception loss was by Horton (1919, also reproduced by Gash and Shuttleworth, 2007). However, until the 1970s, interception loss was predicted using empirically-derived relationships with gross rainfall. These relationships emphasized a species-dependent character of the interception process. Classic examples are the equations by Merriam (1960) and Zinke (1967). A major drawback of empirical models is that, as they are highly data set-specific, they cannot be confidently applied where conditions are distinctly different, particularly in terms of rainfall regime and vegetation type (Massman, 1983; Dingman, 2002). The first conceptual model, after Horton's work, to describe interception as a process driven by evaporation was put forward in the early 1970s by Rutter et al. (1971). The complete version of the model, with an added stemflow component, soon followed (Rutter et al., 1975). At present, well over 15 physically-based interception models exist.

The objective of this paper is to provide a review of physically-based interception modelling that addresses not only the models themselves, but also their application to field data sets. In the next two sections, a general description of the models is followed by a comparison of key model features. The following section concerns the model applications, and the final section addresses the main limitations in current process descriptions and the principal gaps in model assessment.

Selection of interception models and their applications

The Scopus data base (www.scopus.com) was searched using various combinations of the terms 'rainfall', 'interception', 'partitioning' and 'model(ling)'. From the over 200 bibliographic references found, nearly 80 scientific articles published in SCI journals before March 2008 were retained for this review.

The retained articles were screened for interception models that were not included in a preliminary listing of models previously compiled by the authors. Given the importance of interception loss for tall plants, only the models that explicitly address the interception loss component were retained for this review. Thus, the models of Ploey (1982), Bussière et al. (2002) and Castro et al. (2006) were disregarded because they covered just a part of the interception process and did not model the evaporation; the model proposed by Kozak et al. (2007) was not included because it is explicitly designed for short vegetation. The Groen and Savenije (2006) model, though an interesting approach, was not included in the review, either, as it extends rainfall interception to all wetted surfaces (canopy, understorey, forest floor, litter and soil). Of the most recent models, published after 2005, only that of Murakami (2007) is fully addressed in the review *sensu stricto*, but those of Groen and Savenije (2006) and Wang et al. (2007) are considered in the final section.

In all, 15 physically-based models were selected, to represent distinct conceptualizations of the interception process, published before 2008. Ten models are designated as 'original models', and five as significantly 'improved' variants of these original models. In chronological order of publication, the original models are the following: Rutter (Rutter et al., 1971, 1975), Gash (1979), Massman (1983), Mulder (1985), Calder one-layer (Calder, 1986), Liu J. (Liu, 1988), Liu S. (Liu, 1997), Xiao (Xiao et al., 2000), Zeng (Zeng et al., 2000) and Murakami (2007). In the same order, the 'improved' models are the following: Sellers and Lockwood (1981), sparse Gash (Gash et al., 1995), Calder two-layer (Calder, 1996), sparse Rutter (Valente et al., 1997) and van Dijk and Bruijnzeel (2001a).

The 15 models under review can be divided into two main groups. The first group deals with the interception of rainfall drops using probability distribution, whereas the second group deals with the redistribution of rainfall volume using a mass balance equation. This first group is restricted to two models, the Calder one- and two-layer models. The remaining models can be further sub-divided according to whether they employ a continuous, running water balance approach or, instead, an analytical solution to this approach. Following the first exponents of both approaches, the former models will be referred to here as Rutter-type models and the latter as Gash-type models (Table 1).

Table 1
Principal characteristics of reviewed models. I = interception loss, Tf = throughfall, Sf = stemflow.

Model	Input temporal scale[a]		Output variable			Number of parameters	Layers	Spatial scale	Reference
	Rainfall	Meteorological	I	Tf	Sf				
Rutter-type									
Rutter	Hourly[b]	Hourly[b]	x	x	x	7	1	Stand	Rutter et al. (1971)
Sellers and Lockwood	Hourly	Hourly	x	x		$2 + 4 \times n$[c]	Multiple	Stand	Sellers and Lockwood (1981)
Massman	10 min	10 min	x	x		4	1	Stand	Massman (1983)
Liu J.	Daily	Not clear	x			$4 + 2 \times n$[c]	Multiple	Stand	Liu (1988)
Liu S.	Hourly[d]	Hourly[d]	x			3	1	Stand	Liu (1997)
Xiao	Hourly[d]	Hourly[d]	x	x	x	14	Multiple	Tree	Xiao et al. (2000)
Rutter sparse	Hourly[b]	Hourly[b]	x	x	x	5	1	Stand	Valente et al. (1997)
Gash – type									
Gash	Hourly[d]	Hourly	x	x	x	4	1	Stand	Gash (1979)
Mulder	Daily	Daily	x			2	1	Stand	Mulder (1985)
Gash sparse	Hourly[d]	Hourly	x	x	x	4	1	Stand	Gash et al. (1995)
Zeng	Hourly	Hourly[e]	x			3	1	Stand	Zeng et al. (2000)
van Dijk and Bruijnzeel	Daily	Hourly	x	x	x	7	1	Stand	van Dijk and Bruijnzeel (2001a)
Murakami	Hourly[f]	Hourly[g]	x			4	1	Stand	Murakami (2007)
Calder stochastic	Hourly[b]	Hourly[b]	x			6	1	Stand	Calder (1986)
Calder two-layer	Hourly[b]	Hourly[b]	x			16	2	Stand	Calder (1996)

[a] Minimum to meet the model's requirements.
[b] High resolution of calculations.
[c] *n* number of layers.
[d] Or daily or event.
[e] From hourly to yearly.
[f] And daily.
[g] Not necessary if *E* rate obtained from regression.

The five improved models involve modifications to the corresponding original models that are all related to vegetation stand characteristics, in particular to the spatio-temporal variation in them. Three types of modification can be discerned, i.e. those concerning the vegetation's horizontal structure (open or sparse vs. closed stands), its vertical structure (multi-layer vs. single-layer) and its temporal variation (dynamic vs. static cover).

Model descriptions

Original models

Rutter et al. (1971) were the first to present a conceptual, physically-based model. The Rutter model represents the interception process by a running water balance of rainfall input, storage and output in the form of drainage and evaporation. Since drainage and evaporation rates both depend on the amount of water stored in the canopy, they vary throughout the event. Rutter et al. (1975) developed the model's definitive version by adding a stemflow module, in which a fraction of the rainfall input is directly diverted to a compartment comprising the trunks. Early applications of Rutter-type models were made by Calder (1977) and Gash and Morton (1978).

Subsequent Rutter-type models were proposed by Massman (1983), Liu (1988), Liu (1997) and Xiao et al. (2000). The Massman model differs from the Rutter model in its drainage and evaporation equations (see " Model comparison"). A fundamental difference of the Liu (1988) model from the other Rutter-type models is that it includes multiple canopy layers and, thus, progressive wetting of the canopy as water 'falls' from one layer to the other. Very recently, the Liu J. model was developed further to deal with heterogeneous canopies (Liu and Liu, 2008). The Liu S. model was explicitly designed to minimize data input requirements. It differs from the Rutter model in the way it deals with trunk interception and canopy wetting (Liu, 2001). The Xiao model was developed for estimating interception from single trees. It differs from the other Rutter-type models in that it covers the three-dimensional canopy architecture and thus requires special canopy architecture parameters.

Almost a decade after the original Rutter model was developed, Gash (1979) put forward the first analytical interception model, providing a simplified solution to the Rutter model. The Gash model represents rainfall input as a series of discrete storms that are separated by intervals sufficiently long for the canopy and stems to dry completely – this assumption is possible because of the rapid drying of forest canopies. Each individual storm is then divided into three subsequent phases – canopy wetting-up, saturation and drying. This separation emphasizes the relative importance of the climate against plant structure. For the first two of these phases, the actual rates of evaporation and rainfall are replaced by their mean rates for the entire period being modelled.

Subsequent Gash-type models were developed by Mulder (1985) and, much more recently, by Zeng et al. (2000) and Murakami (2007). The first two models maintain the original three storm phases, but introduce modifications. The Mulder model uses distinct evaporation rates for wet conditions (phases 1 and 2) and dry conditions (phase 3), whilst the Zeng model takes into account the statistical characteristics of rainfall input. Unlike the other models, the Murakami model does not distinguish different storm phases. It derives evaporation rates from observed rainfall data and, to this end, also explicitly deals with splash droplet evaporation.

Calder (1986) developed a distinct model of the interception process that is conceptually very different from Rutter- and Gash-type models. The Calder model employs Poisson probability distribution to determine the number of raindrops that strike the canopy and are retained by it. The stored canopy water is then removed by evaporation or, whenever the storage threshold is exceeded, routed to the ground as drainage.

Improved models

The sparse versions of Gash and Rutter models were proposed by Gash et al. (1995) and Valente et al. (1997), respectively, to adjust the original model formulations to forest stands with significant open spaces between the tree canopies. At the same time, some minor corrections were introduced. A crucial change is that in the sparse versions the evaporation rate from wetted surfaces

is no longer calculated for the entire plot area, but only for the area that is covered by the canopy. This change overcame a poor boundary condition in the original models whereby the modelled canopy failed to wet up beyond a certain degree of sparseness. Both model versions provide similar results for closed canopies, as the sparse versions converge to the original models when the canopy cover approaches unity.

van Dijk and Bruijnzeel (2001a) adapted the sparse Gash model for vegetation whose characteristics change markedly during the growing season. The key amendment of the van Dijk and Bruijnzeel model is the use of time-variant model parameter values. In their study (van Dijk and Bruijnzeel, 2001b) calculated these parameter values as functions of the Leaf Area Index as it changes during the crop cycle.

Model variants accommodating multiple vegetation layers were developed by Sellers and Lockwood (1981) for the Rutter model; and by Calder (1996), for the Calder one-layer model. Both multi-layer models determine storage and drainage for each of the vegetation layers individually. In the Sellers and Lockwood model, this involves assessing the evaporation rate of each layer on the basis of the Penman–Monteith equation (Monteith, 1965). In the Calder two-layer model, the kinetic energy of the throughfall drops falling on the lower layer is a key element in assessing changes in the layer's storage and drainage.

Model comparison

Ten model characteristics were chosen to convey the essential differences between the selected models (Table 1). These characteristics can be divided into two groups. Those that concern model structure and processes are taken up first, and those that concern model input, parameters and output are analysed afterwards.

Model structure and processes

Spatial extent

All but one of the selected models predict interception loss at the spatial scale of individual vegetation stands, whereas the Xiao model deals with individual trees. The 'sparse' models divide the stands into one part with a uniform closed canopy and an open part without any canopy. In contrast, the remaining models treat the stands as homogeneous intercepting areas.

Canopy drainage

Canopy drainage is explicitly represented in eight of the models. Two main approaches can be distinguished. The Rutter original and Massman model estimate drainage as a function of time that is based on empirical relationships, whereas the other models (the Rutter sparse, both Gash models, Mulder, Xiao and Calder two-layer models) treat drainage as an integral part of the canopy water balance.

The Rutter model computes drainage by multiplying an empirically-based drainage rate by a coefficient that relates drainage rate to canopy storage. Drainage in the Rutter model can therefore continue after rainfall has ceased. Massman (1983) proposed a different approach, in which drainage rate depends directly on rainfall intensity. The sparse Rutter model uses a more straightforward drainage formulation than the original model, thereby avoiding the above-mentioned empirical parameter. It involves determining the difference between the canopy's storage and its storage capacity, and converting any surplus storage directly into drainage. Thus, unlike the original Rutter model, in the sparse variant drainage automatically stops as soon as the rainfall ends. The Xiao model stands out amongst the other models in that it takes rainfall angle

of incidence and leaf inclination as important factors affecting drainage.

Though Calder (1986) did not explicitly include drainage in his one-layer model, he admitted that estimating it from canopy storage would improve model results. The model's follow-up, two-layer version does in fact include drainage, representing it as the falling of drops from the upper layer. The improved model ignores drainage after cessation of rainfall, but just for practical reasons, i.e. because it is not a significant part of the interception process.

Maximum wet canopy evaporation rate

Evaporation of intercepted rain from canopy and/or stems is calculated by means of the Penman–Monteith formulation (Monteith, 1965) in almost all the 15 models. Only the Massman, Murakami and Xiao models do not follow this approach. It is generally acknowledged that setting the canopy resistance in this equation to zero provides a good approximation of the evaporation rate from a completely wet canopy (Gash et al., 1980), which is normally referred to as 'maximum wet canopy evaporation rate'. The Xiao model uses the adapted Penman (1948) equation rather than the equation modified by Monteith. Massman (1983) developed an alternative formulation that overcomes the high data input requirements of the Penman–Monteith equation. However, it has received little attention. The two key assumptions underlying Massman's equation are that: (i) thermal diffusivity is constant over the entire tree canopy depth and (ii) the Bowen ratio and other micrometeorological parameters can be appropriately averaged over the duration of a rainstorm. As highlighted by the author himself, this equation is especially suited to forest stands that have deep canopies with fairly large temperature gradients.

The Murakami model is exceptional in employing observed, rather than modelled, wet evaporation rates. The author argues that the Penman–Monteith equation does not take into account evaporation from splash droplets, and thus ignores an important process, particularly for climates typified by intense storms with high rainfall rates. An obvious drawback of this approach is its empirical nature.

Pre-event canopy and stem storage

Canopy and stem storage compartments are assumed to be empty at the onset of each storm in all analytical models (excepting the Mulder model) and in the two Calder models. In other words, generally for the Gash-type and Calder models individual storms have, by definition, a fully-closed water balance. The running water balance approach makes the Rutter-type models, in this respect, less restrictive.

Model input, parameters and output

Input temporal resolution

The Massman model is exceptional in that it requires rainfall data with a temporal resolution of 10 min as opposed to the hourly or daily rainfall values required by the 14 other models (Table 1). The sparse and original Gash models and the Liu S. model may equally use event-wise rainfall data as input. In all models except three, if the meteorological input data are used to estimate evaporation rates, their requirements are the same as the minimum requirements for temporal resolution of the rainfall data (Table 1). These exceptions are the van Dijk and Bruijnzeel and two Gash models, which require meteorological records with a higher temporal resolution than the rainfall records. It should be pointed out that the mean wet-canopy evaporation rate required for the storm-based models can be obtained from a regression of interception on rainfall, thereby removing the requirement for meteorological data.

Table 2

Parameters used in the reviewed models. Values in the columns reflects the number of required parameters within each parameter type.

Parameters related to	Parameter	Rutter-type models							Gash-type models						Calder models	
		Rutter et al. (1971, 1975)	Sellers and Lockwood (1981)	Massman (1983)	Liu J. (1988)	Liu S. (1997)	Rutter sparse (Valente et al., 1997)	Xiao et al. (2000)	Gash (1979)	Mulder (1985)	Gash sparse (Gash et al., 1995)	Zeng et al. (2000)	van Dijk and Bruijnzeel (2001a)	Murakami (2007)	Calder (1986)	Calder (1996)
Water storage	Max depth of canopy storage					1		1						1	1	3[abc]
	Canopy storage capacity	1	1	1			1	1	1	1	1	1	1			
	Water storage[d]				1											
	Specific storage				1								1			
	Leaf wetted area coefficient		1													
	Trunk storage capacity	1							1				1			
Canopy structure	Canopy cover				1		1				1	1	1	1		3[e]
	Free throughfall coefficient	1	2[f]	1		1		1	1	1			1			
	Branch, stem, leaf or total area index		1[f]		2[f]	1		2					1	1		
	Number of elemental surfaces														1	1
	Average leaf surface							1								
	Surface area density			1												
	Leaf inclination angle							2						1		
	Stem inclination angles							2								
	Normal and effective stem and crown projection area							4								
Water partitioning	Drip parameters			2												
	Canopy drainage coefficient	2	1[f]													
	Drainage partitioning coefficient						1				1					
	Stemflow partitioning coefficient	1							1				1			
	Fraction of rain striking top layer															1
	Fraction of shed rain from the top layer striking bottom layer															1
Other	Number of drops														1	
	Mean number of drops retained per element														1	
	Max number of drops retained per element														1	1[g]
	Mean raindrop volume														1	2[h]
	Characteristic volume[i]															3
	Parameters governing kinetic dependence of Cm Cmax as a function of volume															
	Threshold of rainfall intensity											1				
	Constant between Et/Ec	1					1									

[a] For zero kinetic energy drops.

[b] Achievable for the two-layer formulation with zero kinetic energy drops incident on the top layer.

[c] Achievable for the two-layer formulation with non-zero kinetic energy drops incident on the top layer.

[d] In unit volume of canopy.

[e] And for the top and bottom layer.

[f] Referred to the n layer.

[g] For non-zero kinetic energy drops.

[h] For zero and non-zero kinetic energy drops.

[i] Of drops falling from vegetation.

Model parameters

The total number of model parameters varies considerably from model to model (Table 1). In the case of the single-layer models, the number varies from 2 to 7, and in the case of the multi-layer models, from 8 to 16 for stands comprising two layers. The model parameters themselves are shown in Table 2, where they are grouped in four main categories. A selection of these parameters - i.e. those that are common to most of the models – will be addressed in more detail in the following paragraphs.

All 15 models include some parameter representing the storage of intercepted rain in the canopy or, to be more specific, the threshold amount of rain that can be stored in the canopy. The analogous designations of this storage threshold are misleading, because its exact definition may differ significantly between models. For example, in the original and sparse Rutter and Gash models, it is defined as the minimum amount of intercepted rain that is necessary to saturate the canopy, whereas in the Calder one-layer model it is defined as the maximum number of drops that can be retained by any canopy element, multiplied by the drops' mean volume. It may also be misleading that the canopy storage parameter may apply to different parts of the vegetation stand. For example, it refers to the entire plot area in the case of the original Rutter and Gash models, but, in the case of the models' sparse variants, only to the part of the plot covered by the canopy or, in the case of the Liu J. model, to a unit volume of canopy. Further information on the canopy storage parameter is given by Klaassen et al. (1998).

The 15 models also all include a parameter describing the structure of the canopy (Table 2). The bulk of the Rutter- and Gash-type models employ the free throughfall coefficient to partition the throughfall, but in the sparse versions the canopy cover fraction is used to partition the evaporation. In practice, however, this distinction is often ignored with the free throughfall coefficient being determined as (1 – canopy cover fraction). The two Calder models stand out because they require a parameter that describes the number of elemental surface areas per unit of ground area. Conceptually, this parameter is highly specific to the Calder models, but the existing applications of the Calder model generally derive its value from the Leaf Area Index (LAI). This same LAI is also used in applications of the Liu J., Liu S., Sellers and Lockwood, and van Dijk and Bruijnzeel models.

Model output variables

Half of the selected models predict throughfall and stemflow as well as interception loss (Table 1). In the models that do not explicitly model throughfall and stemflow, the water balance equation can be used to estimate at least net rainfall (i.e. throughfall + stemflow).

Model applications

The selected articles were analysed individually for a series of key features concerning the application of the 15 interception models to field data sets. These key features are: (i) the model(s) tested; (ii) the country, region, climate and vegetation type studied; (iii) the duration of the modelling period; (iv) the method of estimating the maximum evaporation rate; (v) model validation and success.

For obvious reasons, climate and vegetation type need to be standardized. To this end, Köppen's climate classification (McKnight and Hess, 2000) was used and six physiognomically-based vegetation types were distinguished (rainforest, conifers, hardwoods, mixed conifer and hardwoods, shrubs, crops). The length of the modelling period was standardized to five classes (less than or equal to 1, 3, 6 or 12 months, and more than 1 year). Two types of model assessment were recognized, depending on

whether or not separate data sets were used for calibrating the model(s) or optimizing model parameter values. In the case of separate data sets, the model is designated as 'calibrated and validated'. Model success is defined here as the absolute difference between predicted and observed interception loss. In several of the reviewed articles (Table 3), this measurement was not given in the original papers and could not be calculated from the figures shown. In these instances, model success was simply given as unspecified or as under- or over-estimated. In the other cases, model error is classified in eight numerical and five qualitative groups. Whilst the former are given with a table (see Appendix), the latter are as follows: bad (error > 30% of measured interception loss); fair (10% < error ⩽ 30%); good (5% < error ⩽ 10%); very good (1% < error ⩽ 5%); extremely good (error ⩽ 1% < error). If applicable, model error refers to the results of model validation rather than calibration, and to the best of multiple results.

Overview

As shown in Fig. 1, the bulk of the selected model applications involve the original and sparse Gash models (69 cases) and, to a lesser extent, the original and sparse Rutter models (42 cases). The Mulder model was applied in four studies; the remaining 10 models have received even less attention (Fig. 1 and Table 3). In view of these numbers, it was decided to limit the more detailed review of the application studies in the next section to the two versions of the Gash and Rutter models.

Three-quarters of the model applications are about equally divided between three of the vegetation types, i.e. rainforest, conifer and hardwood stands. Not surprisingly, however, there are clear geographical differences in the study of the various vegetation types (Fig. 2). Modelling studies in Central and South America and in Asia have clearly focused on rainforests, whilst those in Europe and Africa have concentrated on conifers and crops, respectively. In North America, research attention has been divided more evenly between shrubs, conifers and hardwoods.

Europe has seen a larger number of model applications than the other geographic regions (Fig. 2). This may be because most of the 15 models were developed at European research institutes. In contrast, comparatively few application studies deal with Africa or Central and South America, which as expected coincides with a general tendency in scientific research.

Rutter and Gash model applications

As mentioned before, the two variants of the Gash model have been tested together more often than the Rutter model variants (69 vs. 42 instances; see Appendix, Table 4). This difference is more accentuated in the case of the sparse variants, with 41 sparse Gash applications against only six sparse Rutter applications. The much lower application of the sparse Rutter model than the sparse Gash model contrasts strongly with the roughly similar numbers of applications of the original variants (Gash: 28; Rutter: 36). The difference in publication dates of the sparse versions (Gash et al., 1995; Valente et al., 1997) does not offer a satisfactory explanation. What may have happened, however, is steady abandonment of the running-balance approach in favor of the simpler analytical approach, possibly motivated by the satisfactory results obtained with the original Gash model. Furthermore, the use of a regression between rainfall and interception to derive evaporation rate can make application of the Gash model possible in places where only rainfall data are available – often an attractive option for sparsely instrumented watersheds. The numerous applications of the Gash model derived from regression, even if this was not intended by Gash (1979), support this argument (see Table 4).

Table 3
Complete list of applications. R–Rutter models, G–Gash models, M–Mulder model, L–Liu S. model, C–Calder models, SL–Sellers and Lockwood model.

| In-text reference	R	G	M	L	C	SL	Country	Region	Conifer	Hardwood	Mixed	Shrub	Agriculture	Rainforest
Aboal et al. (1999)	x	x					Spain	Canary Island		x				
Asdak et al. (1998)	x	x					Indonesia	Centr. Kalimantan						x
Bigelow (2001)	x						Costa Rica			x				
Bringfelt and Lindroth (1987)	x						Sweden	Northern	x					
Bryant et al. (2005)		x					USA	Georgia	x	x	x			
Calder et al. (1986)	x				x		Indonesia	W Java						x
Carlyle-Moses and Price (1999)		x					Canada	Ontario		x				
Carlyle-Moses and Price (2007)		x		x			Mexico	Sierra Madre			x			
Cooper and Lockwood (1987)						x	–	–						
Cuartas et al. (2007)	x	x					Brazil	Central Amazonas						x
Davie and Durocher (1997)	x						Simulated data							
Deguchi et al. (2006)		x					Japan	Central		x				
van Dijk and Bruijnzeel (2001b)		x					Indonesia	Java					x	
Dolman (1987)		x	x				Netherlands	Coastal		x				
Domingo et al. (1998)	x						Spain	S–E				x		
Dykes (1997)		x					Brunei	N–W						x
Eltahir and Bras (1993)	x						Simulated data							
Gash and Morton (1978)	x						UK	East Anglia	x					
Gash (1979)		x					UK	East Anglia	x					
Gash et al. (1980)	x	x					UK	Wales,Scotland	x					
Gash et al. (1995)		x					France	S–W	x					
Gash et al. (1999)	x						Portugal	Central	x					
Germer et al. (2006)		x					Brazil	Rodonia						x
Hall et al. (1996)	x				x		Sri Lanka	Upper Mahaweli						x
Herbst et al. (2006)		x					UK	S England		x				
Holscher et al. (2004)		x					Costa Rica	Talamanca						x
Hormann et al. (1996)		x					Germany	North		x				
Hutjes et al. (1990)		x	x				Ivory Cost							x
Jackson (2000)		x					Kenya	Nairobi					x	
Jetten (1996)	x						Guyana	Georgetown		x				
Kozak et al. (2007)						x	US						x	
						x	Australia						x	
Lankreijer et al. (1993)		x	x				France	S–W	x					
							Netherlands	Central		x				
Lankreijer et al. (1999)		x					Sweden	Uppsala			x			
Link et al. (2004)		x					USA	Pacific N–W	x					
Liu (1997)				x			USA		x	x				
Llorens (1997)		x					Spain	pre–Pyrenees	x					
Lloyd et al. (1988)	x	x					Brazil	Manaus						x
Lockwood (1990)						x	–							
Lockwood (1992)						x	–							
Loescher et al. (2005)	x						Costa Rica	Puerto Viejo						x
Loustau et al. (1992)		x					France	Bordeaux	x					
Mulder (1985)			x				Netherlands	Castricum	x					
Murakami (2007)		x					Japan	Eastern	x					
Navar and Bryan (1994)		x					Mexico	Gulf Mexico				x		
Navar et al. (1999b)		x					Mexico	Gulf Mexico				x		
Navar et al. (1999a)		x					Mexico	Gulf Mexico				x		
Pearce et al. (1980)	x	x					UK	Norfolk	x					
Pearce and Rowe (1981)		x					New Zeland	South Island						x
Price and Carlyle-Moses (2003)		x					Canada	Ontario		x				
Pypker et al. (2005)		x					USA	Pacific N–W	x					
Rao (1987)		x					India			x				
Rowe (1983)		x					New Zeland	South Island		x				
Rutter et al. (1971)	x						UK		x					
Rutter et al. (1975)	x						UK		x					
Schellekens et al. (1999)	x	x					Puerto Rico	Loquillo						x
Schellekens (2000)	x						Puerto Rico	Luquillo						x
Sraj et al. (2008)		x					Slovenia	S–W		x				
Tallaksen et al. (1996)	x						Norway	Oslo	x					
Tani et. al. (2003)	x						Malasia							x
Valente et al. (1997)	x	x					Portugal	Central	x	x				
Wallace and McJannet (2006)		x					Australia	N Queensland						x
Wallace and McJannet (2008)		x					Australia	N Queensland						x
Whelan and Anderson (1996)	x						UK	Devon	x					
Whitehead and Kelliher (1991)	x						New Zeland	Rotorua	x					
Zeng et al. (2000)	x						Brazil	Central Amazon						x
							France	Les Landes	x					
Zhang et al. (2006)		x					China	Central–S	x	x				
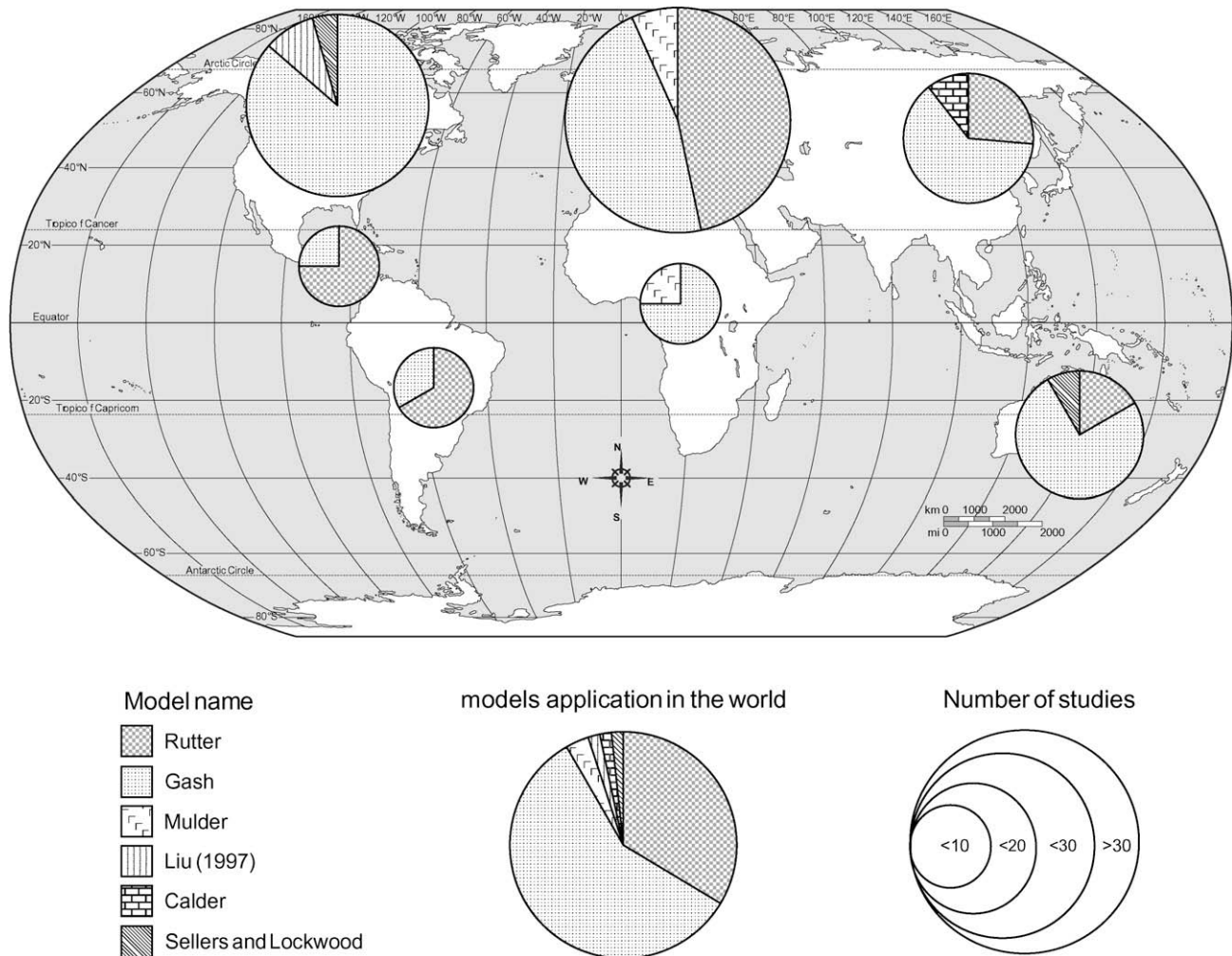
Fig. 1. Model applications in the world. Gash, Rutter and Calder model refers to the original and improved versions. Only applications with real data were considered.

Almost four-fifths of 111 Gash and Rutter applications either specify or allow the computation of the above-mentioned error in predicted interception loss. The quantitative performance of Gash and Rutter model applications is summarized in Fig. 3, which shows four of the five classes of quantitative error ('extremely good' and 'very good' were merged). Special attention is given to the model applications whose validation uses independent data sets (which, interestingly, are all studies of more than one year). In one case – that of the entire set of sparse Gash model applications – the four error classes reveal marked differences in the number of applications. A similar tendency toward very good results can also be observed for the 'validation' subset of sparse Rutter model applications, but its reduced sample size advises extra caution.

However, measurement errors are not usually taken into account in the discussion of modelling performance. Because interception is measured as the relatively small difference between gross and net rainfall, even small errors in these measurements can result in high relative errors in interception loss (Fig. 4). For instance, if gross rainfall and throughfall are both measured with 2.5% accuracy but interception loss is 15% of gross rainfall, one should expect an error of some 22% in the measured interception loss (Fig. 4). This is an important consideration when assessing the performance of models, as even quite large differences between predicted and observed interception loss can be less than the expected measurement error, limiting the conclusions that

can be drawn. In the next two sections, the results obtained with the Rutter and Gash models will be analysed in more detail by comparing the two original models as well as the original and sparse variants of the Gash model. The other two possible comparisons are less interesting due to the above-mentioned, restricted number of sparse Rutter applications.

Rutter original versus Gash original

Thirty-five percent of the total number of original Rutter model applications did not specify the error obtained. However, all the original Gash applications indicated the error obtained. For both models, 6% of applications did not give a numerical estimate of the magnitude of the error.

However, fewer than 40% of these original model applications were validated with independent data sets. For these applications the number of very good performances (up to 5%) were similar for both models, which was maintained for the other levels of goodness (Fig. 3). The similarities between the two models' applications are also found in the type of climate to which the models were mainly applied, which for both models is temperate, except that the Rutter model was more frequently used in tropical rainforest climates than the Gash model. The general similarities are also reflected in the vegetation types most frequently studied. The difference is that the Rutter model was applied predominantly in coniferous species, whereas the Gash model, as mentioned above, was applied in coniferous and hardwood species, too.
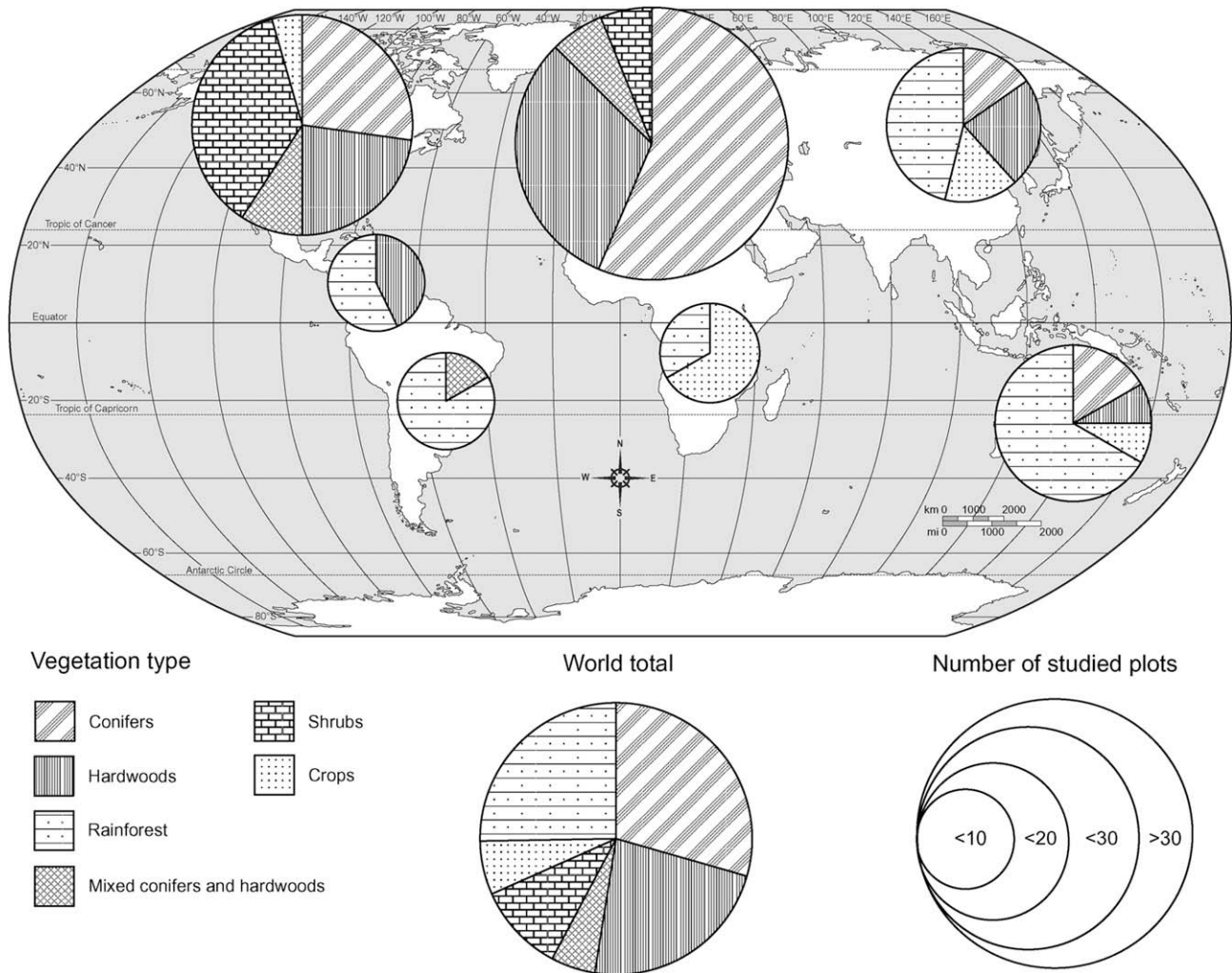
Fig. 2. Distribution of model applications among principal vegetation types.

Gash original versus Gash sparse

Some interesting trends can be drawn out from a comparison between Gash original and sparse model applications. As might be expected, the Gash sparse model gives better results than the original version in terms of modelling error, and more than 76% of the model applications resulted in errors below 10%, with an important contribution of model performances with errors under 5% (51% of the applications), whereas for the Gash original model the figure was 27%. As stated above, the latter model has a marked number of applications with errors higher than 30% (23% of cases).

Gash models had only 32% and 26% (original and sparse versions, respectively) of validated applications. For these applications the number of very good performances (below 5%) was higher for the sparse version (5 and 2 applications, respectively). The numbers of applications with results at the other levels of goodness are similar for both models (Fig. 3).

The better performance of the Gash sparse model may be due to the conceptual changes introduced in this version, but may also be caused by many of the applications not being duly validated, particularly those with the best results. It should also be mentioned that the original version has mainly been applied to temperate climates, whereas the sparse version has been applied mainly to tropical climates, also with good results. It is important to highlight the high number of Gash sparse model applications in semi-arid climates – a consequence of the sparse vegetation characteristic of this climate.

Discussion and conclusions

Comparison of the models that takes into account their structure and functioning was possible, but the decision as to which model is most suited to each situation must still be a decision for the modeller. The first part of this study provides theoretical information about the models that may help decide on which model to use for a specific data set and gives an overview of the models' characteristics. The second part summarizes the experiences of the models' performance and poses some interesting questions for debate.

The main and most obvious point is that several models are used very little, or in other words, three models dominate, which suggests their greater success than the other models. So, what are the causes of the limited use of certain models? Why have some simple models (e.g. the Mulder model) been abandoned? Is the Gash model fashionable and if so, why? Will the measurements' availability continue to be the most important limit for model application?

We believe that the limited use of certain models is either due to their parameter requirements (e.g. Calder two-layer model), which are not commonly or easily obtained, or to the techniques for obtaining the parameters being unusual. Moreover, if many parameters are needed to satisfy a more exhaustive description of the interception process, these are usually empirical and
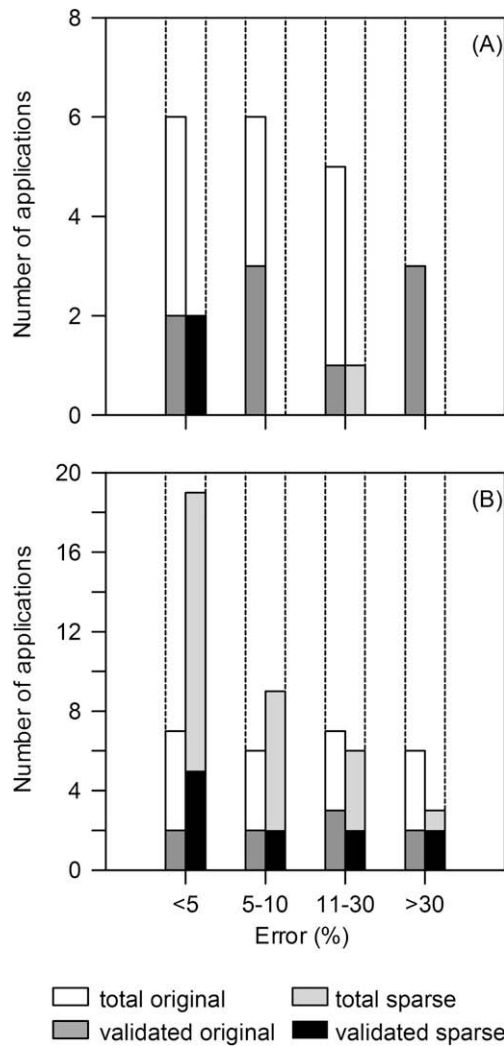
Fig. 3. Errors obtained in Rutter(A) model and Gash (B) model applications.

Fig. 4. Total percentage error in measured interception loss as a function of e2/e1, the ratio between error in measurements of throughfall (e2) and gross rainfall (e1), and measured interception loss (given as percentage of gross rainfall %Pg).This graph was made assuming a measurement error in Pg of 2.5% (e1=0.025), neglecting stemflow and considering that gross rainfall and throughfall are independent measured variables. Total percentage error in measured interception loss can then be calculated as $\frac{e_1\sqrt{1+(1-\%Pg)^2\times(e_2/e_1)^2}}{\%Pg}$.

site-specific. Other limits for model application are that the model was only published recently (e.g. the Zeng model), or the specific vegetation type for which the model is developed (the van Dijk and Brujinzeel model). However, the main factor influencing the decision on model use is its ease of use, e.g. the workload and the costs, in terms of parameter requirements, data input, low conceptual and programming complexity – the Gash models have all these. This may be why the Gash sparse model was used so often.

One way to overcome the problem of the limited use of certain models would be to develop a user-friendly software package for the more computationally demanding models or for models that require higher programming skills. Such a facility would increase their distribution among the scientific community. A high number of published applications encourages re-use of a model and comparison with new data. This in turn provides more information about possible drawbacks of the model and aspects which need improvement. The application of new models, however well described they are and however good their results, is always more difficult when there is little information available.

In practical terms, the lack of data with high temporal definition and the great number of parameter requirements prevent the general use of most of the models reviewed. Although an accurate description of the interception process at a point scale for monitored plots is possible and may be efficient, the extrapolation of results for large areas involves significant errors, particularly if the
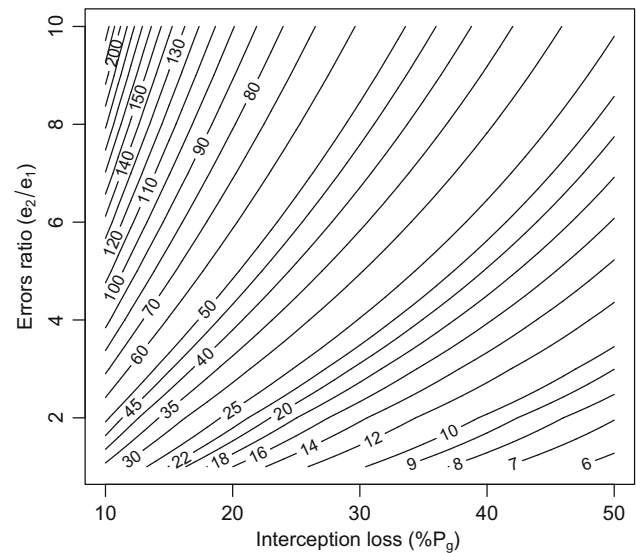
physical parameters that control the interception at a single location are assumed constant in space (Eltahir and Bras, 1993) and no rainfall variability is included. This difficulty appears as a need for subgrid parameterization of heterogeneous processes in General Circulation Models (GCM). The rainfall distribution must be spatially distributed to avoid the GCM unrealistically spreading any rainfall over the whole grid square to give low rainfall over the whole square rather than the patterns of storms which occur in reality (see Dolman and Gregory, 1987; Eltahir and Bras, 1993; Eltahir and Bras, 1994; Wang et al., 2007). Failure to account for the sub-grid variation of rainfall rate results in overestimation of interception loss. Modelling rainfall interception over large areas whilst taking into account both the physical nature of the process and the spatial variability of vegetation cover and climate, without significant simplifications and uncertainties of measurements, remains a problem. Nevertheless, interception models, especially the Rutter and Gash models, have been recently used as interception subroutines in more complex hydrological models (e.g. Finch, 1998; Ewen et al., 2000; van der Salm et al., 2007) and nearly all GCM SVAT models now use some sort of interception model that is conceptually similar to the Rutter model.

The search for new approaches to modelling increases the understanding of the process and should allow new models to include more detailed processes such as the vertical and spatial variability of interception loss at a point scale (e.g. Bassette and Bussière, 2005; Kozak et al., 2007; Liu and Liu, 2008). There are also new approaches whose objective is to simplify the modelling of this process while keeping some conceptual background. Groen and Savenije (2006) is an example of this last approach. They disregard the short temporal scale of data and propose an analytical equation for monthly interception loss estimation, which may be a very useful tool in catchment studies. Another example is that of Wang et al. (2007), who attempted to describe and estimate global interception loss by using a sub-grid of rainfall and canopy-storage variability. Although it was possible to validate the model with published data on field measurements of interception loss for different locations over the world, it was difficult to obtain good results for tropical and extra-tropical areas together.

The applications encountered in this review show the need for more vegetation-type testing. Deciduous and mixed forests require more studies, given their importance in middle latitudes and seasonal change; and the recent work by Herbst et al. (2008) which has shown the counter-intuitive result that the seasonal change in their canopy characteristics might affect interception loss less than expected. More effort to model the interception process in very sparse forests and isolated trees should also be made. In this type of vegetation, not only should the influence of rainfall incident angle and the spatial variability of throughfall be taken into account (Xiao et al., 2000; David et al., 2005), but the usual methodology of calculating the evaporation rate during wet canopy conditions (the Penman–Monteith equation) should be re-evaluated. Recent work by Pereira et al. (2009a,b), has shown the potential for a simple Dalton equation (Dalton, 1802) and tree-based approach to modelling very sparse forests. It remains an open question as to when the use of one-dimensional models like the Penman–Monteith equation is no longer valid in these conditions and what is the effect of forest sparseness on the enhancement of turbulence and evaporation. In other words, we need to evaluate the limit of the assumption in sparse models that the overall evaporation reduces linearly in proportion to the canopy cover.

One of the reasons for the few studies of shrubs and crops is that evaporation from wet canopies is clearly a net water loss for forests, but not so for short vegetation (David et al., 2005). Shrubs also gained little attention, perhaps due to the difficulty of water flow measurement techniques (Dunkerley, 2000). However, the existing studies of this type of vegetation show that, despite the structural differences between shrubs and forest, interception models can be applied in shrubs with equal success (Domingo et al., 1998).

The recent work by Murakami (2006, 2007) raises the intriguing idea that evaporation from splash droplets is a missing process in interception modelling. This omission would be particularly problematic in tropical areas with intensive storms and high rainfall rates. More studies on this subject are needed.

A further unresolved issue is the question of enhanced evaporation of intercepted rainfall close to coasts. Here, according to van Dijk and Bruijnzeel (2001b), the one-dimensional Penman–Monteith equation may fail due to advection of warm maritime air. This implies horizontal temperature gradients, which to our knowledge have not been observed at the same time as the other necessary measurements. More comprehensive data are needed to establish whether the Penman–Monteith equation fails under these circumstances, or whether the high rates of interception sometimes observed at coastal sites have another explanation (e.g.Bruijnzeel and Wiersum, 1987; Dykes, 1997).

The present review also reveals some of the drawbacks to model applications: inadequate validation of the models, the few comparative studies and the uncertainties of measurements and parameter variability are the main problems. The validation of the model should be the prime point in a model assessment, as it provides objective information about the model's performance. However, this is not done or not mentioned in many of the reviewed papers. This lack impedes evaluation of the models' application. The reliability of non-validated models is low and their results are not easily comparable with validated models. Comparative studies would also enrich the modelling exercise, especially when two different approaches are compared. This study found fewer examples of this kind of paper than expected (under 20%).

Finally, the uncertainties in model input data and parameter values are rarely taken into account during interception modelling. They should be, as they may provide insights into the quality of the model's performance and be useful in the model's result interpretation.

Acknowledgements

Appendix

Table 4.

Table 4

Complete list of Rutter and Gash model applications. Error ranges: $1 - (\leqslant 1\%)$, $2 - (1 < \ldots \leqslant 5\%)$, $3 - (5 < \ldots \leqslant 10\%)$, $4 - (10 < \ldots \leqslant 15\%)$, $5 - (15 < \ldots \leqslant 20\%)$, $6 - (20 < \ldots \leqslant 25\%)$, $7 - (25 < \ldots \leqslant 30)$, 8 – over 30%, 9 – under-estimated, 10 – over-estimated, –unspecified.

Author	Model	Period of study	Climate	Error range	Evaporation rate method	Calibration validation	Species
Aboal et al. (1999)	Rutter	⩽12 Months	Mediterranean	–	Penman–Monteith	No	Laurel forest
	Gash	⩽12 Months	Mediterranean	2	Penman–Monteith	No	Laurel forest
Asdak et al. (1998)	Rutter	⩽12 Months	Tropical monsoon	3	Penman–Monteith	No	Logged tropical forest
	Rutter	⩽12 Months	Tropical monsoon	3	Penman–Monteith	No	Unlogged tropical forest
	Gash	⩽12 Months	Tropical monsoon	8	Penman–Monteith	No	Logged tropical fores
	Gash	⩽12 Months	Tropical monsoon	3	Penman–Monteith	No	Unlogged tropical forest
	Gash sparse	⩽12 Months	Tropical monsoon	3	Penman–Monteith	No	Logged tropical fores
	Gash sparse	⩽12 Months	Tropical monsoon	3	Penman–Monteith	No	Unlogged tropical forest
Bigelow (2001)	Rutter sparse	⩽12 Months	Tropical wet and dry	9	Penman–Monteith	No	Cedrela odorata
	Rutter sparse	⩽12 Months	Tropical wet and dry	9	Penman–Monteith	No	Cordia alliodora
	Rutter sparse	⩽12 Months	Tropical wet and dry	9	Penman–Monteith	No	Hyeronima alchorneoides

Table 4 (continued)

Author	Model	Period of study	Climate	Error range	Evaporation rate method	Calibration validation	Species
Bringfelt and Lindroth (1987)	Rutter	>1 Year	Continental	8	Penman–Monteith	Yes	Pinus sylvestris
Bryant et al. (2005)	Gash sparse	>1 Year	Humid subtropical	1	Penman–Monteith	No	Pinus taeda and Pinus echinata
	Gash sparse	>1 Year	Humid subtropical	3	Penman–Monteith	No	Pinus palustris
	Gash sparse	>1 Year	Humid subtropical	2	Penman–Monteith	No	Mixed hardwood
	Gash sparse	>1 Year	Humid subtropical	2	Penman–Monteith	No	Quercus berberidifolia
	Gash sparse	>1 Year	Humid subtropical	3	Penman–Monteith	No	Quercus alba, P. echinata P.palustris
Calder et al. (1986)	Rutter	>1 Year	Tropical monsoon	–	Penman–Monteith	No	Rainforest
Carlyle-Moses and Price (1999)	Gash	⩽6 Months	Continental	4	Empirical regression	No	Quercus rubra and Acer saccharum
	Gash sparse	⩽6 Months	Continental	2	Empirical regression	No	Quercus rubra and Acer saccharum
Carlyle-Moses and Price (2007)	Gash sparse	>1 Year	Temperate	8	Empirical regression	No	Pinus pseudostrobus, Q.canbyi, Q.laeta
Cuartas et al. (2007)	Gash sparse	> 1 Year	Tropical monsoon	5	Penman–Monteith	No	Rainforest
	Rutter	> 1 Year	Tropical monsoon	9	Penman–Monteith	No	Rainforest
Deguchi et al. (2006)	Gash sparse	> 1 Year	Humid subtropical	2	Empirical regression	No	Quercus serrata
van Dijk and Bruijnzeel (2001b)	Gash sparse	⩽6 Months	Tropical rainforest	3	Empirical regression and optimization	No	Agrosystem
	Gash sparse	⩽12 Months	Tropical rainforest	1	Empirical regression	No	Agrosystem
Dolman (1987)	Gash	>1 Year	Temperate	3	Empirical regression	No	Quercus rubra
Domingo et al. (1998)	Rutter	⩽12 Months	Semi-arid	–	Penman–Monteith	Yes	Anthylis cytisoides
	Rutter	⩽12 Months	Semi-arid	–	Penman–Monteith	Yes	Retama sphaerocarpa
Dykes (1997)	Gash sparse	⩽6 Months	Tropical rainforest	1	Empirical regression	No	Various evergreen species
Gash and Morton (1978)	Rutter	> 1 Year	Temperate	3	Penman–Monteith	Yes	Pinus sylvestris
Gash (1979)	Gash	> 1 Year	Temperate	2	Penman–Monteith	No	Pinus sylvestris
Gash et al. (1980)	Rutter	> 1 Year	Temperate	5	Penman–Monteith	Yes	Picea sitchensis, Pinus sylvestris
	Gash	> 1 Year	Temperate	5	Penman–Monteith	Yes	Picea sitchensis, Pinus sylvestris
Gash et al. (1995)	Gash	⩽12 Months	Temperate	8	Penman–Monteith	No	Pinus pinaster
	Gash sparse	⩽12 months	Temperate	–	Penman–Monteith	No	Pinus pinaster
Gash et al. (1999)	Rutter	⩽1 Month	Mediterranean	7	Penman–Monteith	No	Pinus pinaster
	Rutter sparse	⩽1 Month	Mediterranean	4	Penman–Monteith	No	Pinus pinaster
Germer et al. (2006)	Gash sparse	⩽6 Months	Tropical wet and dry	–	Not specified	No	Rainforest
Hall et al. (1996)	Rutter	⩽6 Months	Tropical rainforest	2	Penman–Monteith	No	Rainforest
Herbst et al. (2006)	Gash	> 1 Year	Temperate	4	Penman–Monteith	Yes	Hedgerows
Holscher et al. (2004)	Gash	⩽12 Months	Tropical rainforest	4	Empirical regression	No	Various evergreen species
Hormann et al. (1996)	Gash	> 1 Year	Maritime temperate	8	Other	No	Fagus sylvatica
Hutjes et al. (1990)	Gash	⩽6 Months	Tropical rainforest	8	Penman–Monteith and regression	No	Various evergreen species
Jackson (2000)	Gash sparse	> 1 Year	Semi-arid	2	Penman–Monteith	No	Agroforestry system
	Gash sparse	> 1 Year	Semi-arid	2	Penman–Monteith	No	Agroforestry system
Jetten (1996)	Rutter	⩽6 Months	Tropical rainforest	4	Penman–Monteith	No	Evergreen forest
	Rutter	⩽6 Months	Tropical rainforest	4	Penman–Monteith	No	Mixed forest
Lankreijer et al. (1993)	Gash	⩽6 Months	Temperate	4	Penman–Monteith and regression	No	Quercus rubra
Lankreijer et al. (1993)	Gash	⩽12 Months	Temperate	2	Penman–Monteith and regression	No	Pinus pinaster

Table 4 (continued)

Author	Model	Period of study	Climate	Error range	Evaporation rate method	Calibration validation	Species
Lankreijer et al. (1999)	Gash sparse	⩽3 Months	Continental subarctic	10	Penman–Monteith	No	Sparse mixed forest
	Gash	⩽3 Months	Continental subarctic	10	Penman–Monteith	No	Closed mixed forest
Link et al. (2004)	Gash sparse	> 1 Year	Maritime temperate	2	Penman–Monteith and regression	Yes	Pseudotsuga menziesii Tsuga heterophylla Thuja plicata
Llorens (1997)	Gash	> 1 Year	Mediterranean	3	Penman–Monteith and regression	Yes	Pinus sylvestris
Lloyd et al. (1988)	Rutter	> 1 Year	Tropical rainforest	2	Penman–Monteith	Yes	Rainforest
	Gash	> 1 Year	Tropical rainforest	2	Penman–Monteith	Yes	Rainforest
Loescher et al. (2005)	Rutter	> 1 Year	Tropical rainforest	–	Penman–Monteith	No	Rainforest
Loustau et al. (1992)	Gash	> 1 Year	Temperate	3	Penman–Monteith and regression	No	Pinus pinaster
Murakami (2007)	Gash sparse	> 1 Year	Maritime temperate	1	Empirical regression	No	Japanese cypreses
Navar and Bryan (1994)	Gash	⩽6 Months	Semi-arid	1	Empirical regression	No	Shrubs
Navar et al. (1999b)	Gash sparse	> 1 Year	Semi-arid	3	Empirical regression	Yes	Shrubs
	Gash sparse	> 1 Year	Semi-arid	4	Empirical regression	Yes	Shrubs
	Gash sparse	> 1 Year	Semi-arid	8	Empirical regression	Yes	Shrubs
	Gash sparse	> 1 Year	Semi-arid	8	Empirical regression	Yes	Shrubs
	Gash sparse	> 1 Year	Semi-arid	5	Empirical regression	Yes	Shrubs
	Gash sparse	> 1 Year	Semi-arid	1	Empirical regression	Yes	Shrubs
Navar et al. (1999a)	Gash sparse	> 1 Year	Semi-arid	1	Empirical regression	Yes	Shrubs
Pearce and Rowe (1981)	Gash	> 1 Year	Temperate	3	Empirical regression	No	Various evergreen species
Pearce et al. (1980)	Rutter	> 1 Year	Temperate	3	Penman–Monteith	Yes	Pinus sylvestris
	Gash	> 1 Year	Temperate	2	Penman–Monteith	Yes	Pinus sylvestris
Price and Carlyle-Moses (2003)	Gash sparse	⩽6 Months	Continental	4	Penman–Monteith	No	Quercus rubra, Acer saccharum
Pypker et al. (2005)	Gash	⩽6 Months	Maritime temperate	2	Empirical regression	No	Pseudotsuga menziesii
Rao (1987)	Gash	> 1 Year	Tropical monsoon	3	Penman–Monteith	No	Cashew trees
Rowe (1983)	Gash	> 1 Year	Temperate	3	Empirical regression	Yes	Nothofagus spp.
Rutter et al. (1971)	Rutter	> 1 Year	Temperate	–	Penman–Monteith	No	Pinus nigra
Rutter et al. (1975)	Rutter	> 1 Year	Temperate	3	Penman–Monteith	No	Pinus nigra
	Rutter	> 1 Year	Temperate	2	Penman–Monteith	No	Pseudotsuga menzesii
	Rutter	> 1 Year	Temperate	2	Penman–Monteith	No	Picea abies
	Rutter	> 1 Year	Temperate	1	Penman–Monteith	No	Carpinus betulus
	Rutter	> 1 Year	Temperate	5	Penman–Monteith	No	Quercus robur
Schellekens et al. (1999)	Rutter	⩽3 Months	Tropical	9	Penman–Monteith	No	Tabonuco type forest
	Gash	⩽3 Months	Tropical	9	Penman–Monteith	No	Tabonuco type forest
Schellekens (2000)	Rutter	⩽3 Months	Tropical	–	Penman–Monteith	No	Tabonuco type forest
Sraj et al. (2008)	Gash sparse	⩽12 Months	Mediterranean	3	Empirical regression	No	Decidous mixed forest
	Gash sparse	⩽12 Months	Mediterranean	2	Empirical regression	No	Decidous mixed forest
Tallaksen et al. (1996)	Rutter	> 1 Year	Continental subarctic	3	Penman–Monteith	Yes	Picea abies
Tani et. al. (2003)	Rutter	> 1 Year	Tropical rainforest	–	Penman–Monteith	No	Rainforest
Valente et al. (1997)	Gash sparse	> 1 Year	Mediterranean	2	Penman–Monteith	Yes	Eucalyptus globulus
	Gash sparse	> 1 Year	Mediterranean	2	Penman–Monteith	Yes	Pinus pinaster
	Rutter sparse	> 1 Year	Mediterranean	2	Penman–Monteith	Yes	Eucalyptus globulus
	Rutter sparse	> 1 Year	Mediterranean	2	Penman–Monteith	Yes	Pinus pinaster
	Gash	> 1 Year	Mediterranean	8	Penman–Monteith	Yes	Eucalyptus globulus

(continued on next page)

Table 4 (continued)

Author	Model	Period of study	Climate	Error range	Evaporation rate method	Calibration validation	Species
	Gash	> 1 Year	Mediterranean	8	Penman–Monteith	Yes	Pinus pinaster
	Rutter	> 1 Year	Mediterranean	8	Penman–Monteith	Yes	Eucalyptus globulus
	Rutter	> 1 Year	Mediterranean	8	Penman–Monteith	Yes	Pinus pinaster
Wallace and McJannet (2006)	Gash sparse	> 1 Year	Tropical rainforest	3	Penman–Monteith	No	Rainforest
Wallace and McJannet (2008)	Gash sparse	> 1 Year	Tropical rainforest	2	Penman-Monteith, regression and optimization	No	Rainforest
	Gash sparse	> 1 Year	Tropical rainforest	2	Penman-Monteith, regression and optimization	No	Rainforest
	Gash sparse	> 1 Year	Tropical rainforest	3	Penman-Monteith, regression and optimization	No	Rainforest
	Gash sparse	> 1 Year	Tropical rainforest	3	Penman-Monteith, regression and optimization	No	Rainforest
	Gash sparse	> 1 Year	Tropical rainforest	2	Penman-Monteith, regression and optimization	No	Rainforest
	Gash sparse	> 1 Year	Tropical rainforest	–	Penman-Monteith, regression and optimization	No	Rainforest
Whelan and Anderson (1996)	Rutter	⩽3 Months	Temperate	2	Penman–Monteith	Yes	Picea abies
Whitehead and Kelliher (1991)	Rutter	> 1 Year	Temperate	–	Penman–Monteith	Yes	Unthinned Pinus radiata
	Rutter	>1 Year	Temperate	–	Penman–Monteith	Yes	Thinned Pinus radiata
Zeng et al. (2000)	Rutter	> 1 Year	Tropical	–	Penman–Monteith	No	Not specified
	Rutter	> 1 Year	Mediterranean	–	Penman–Monteith	No	Not specified
Zhang et al. (2006)	Gash	⩽12 Months	Tropical monsoon	6	Penman–Monteith and regression	Yes	Cunninghamia Inceolata Pinus masoniana
Zhang et al. (2006)	Gash sparse	⩽12 Months	Tropical monsoon	3	Penman–Monteith and regression	Yes	Understorey of Tropical forest

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