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Predicting the soil moisture conditions of Irish grasslands

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Soil moisture conditions are an important interface between agriculture and the environment, as they impact on the length of the grazing season, grass growth rate and nutrient uptake, and the loss of nutrients to the wider environment. Moisture conditions are conveniently quantified by the soil moisture deficit (SMD) but diverging methods for deriving SMD have been applied in Ireland to date. A simple hybrid model for computing SMD is presented, which accounts for differences in drainage regimes between soil types, and is calibrated for contrasting soil types in Ireland. This hybrid model accurately predicted the temporal patterns of SMD on well-drained and poorly-drained soils. Three soil drainage classes were defined, which satisfactorily describe the differences in drainage between soils.

Keywords: Grasslands; moisture model; soils

Introduction

Soil moisture conditions are an important interface between agriculture and the environment. Temporal patterns in soil moisture conditions impact on both the agronomic management and the environmental performance of Irish farms through a multitude of pathways by regulating soil strength (DeVore-Hansen, 1994) and transport processes (Brady, 1996). Primarily, these temporal patterns largely define the length of the grazing season on livestock farms due to the adverse effects of saturated soil conditions on the trafficability of soils. Land-spreading of artificial fertilisers and animal manure (slurry) is agronomically and environmentally appropriate only at times when soils are

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drier than field capacity. Grass growth rate and hence nutrient uptake by the grass is low when soils are very wet (Brereton and Hope-Cawdery, 1988; Keane, 2001), thus increasing the risk of nutrient and pathogen transport to watercourses and groundwater (McAllister, 1977; Sherwood, 1992; Kurz, 2000) and the risk of nitrogen loss to the atmosphere through denitrification (B.P. Hyde, personal communication).

Significantly low soil moisture contents during the summer also have agronomic and environmental consequences. The reduction in grass growth rate that results from water-stress (Allen *et al.*, 1998) decreases the efficiency of nitrogen-uptake by the grass, which in turn requires fertiliser nitrogen applications during these periods to be reduced accordingly (Coulter, 2001). In addition, both Tyson *et al.* (1997) and Richards (1999) found that large soil moisture deficits during the summer months have a strong, linear impact on nitrate levels found in the groundwater during subsequent months.

Soil moisture conditions are dependent on both weather conditions and soil physical characteristics, and as a result exhibit large spatial and temporal variation between soil types, regions, seasons and years. The accurate prediction of the soil water status of contrasting soil types is an indispensable aid for safe and environmentally acceptable agricultural management.

Soil moisture conditions are commonly quantified by the soil moisture deficit (SMD), i.e. the amount of water (expressed as mm precipitation) required to replenish soil water content to field capacity (Keane, 2001). On the one hand SMD is a poorly defined variable because of a lack of agreement as to the quantification of field capacity, but its practical applicability makes it a useful management tool (e.g. Earl, 1996). SMD can be calculated directly as a soil water mass balance (e.g. Aslyng, 1965; Brereton, Danielov and Scott, 1996; Keane, 2001; Holden and Brereton, 2002). However, various methods are used for the calculation of SMD. For example, two distinct approaches have emerged in Ireland: the model by Brereton *et al.* (1996) (referred to as the Teagasc model) predicts SMD of well-drained soils, on which any water in excess of field capacity is assumed to be instantly drained, while the model employed by Met Éireann (summarised in Keane, 2001), allows water surpluses to accumulate during wet spells, thus predicting SMD of poorly-drained soils. To date, both approaches have generally adopted SMD parameters that were originally established on a soil in Denmark (Aslyng, 1965).

The purpose of this study was to develop a hybrid model that predicts SMD for the top layer (rooting zone) of grasslands on contrasting soil types in Ireland. This hybrid model combines features of the models used by Teagasc (Brereton *et al.*, 1996) and Met Éireann (Keane, 2001), with the guidelines for computing crop water requirements published by the FAO (Allen *et al.*, 1998). The objective was to formulate a predictive model with minimum requirements for input parameters, in order to maximise its practical applicability. Existing process-based models such as CREAMS (Knisel *et al.*, 1980), SOIL (Johnsson *et al.*, 1987) and LEACHN (Wagenet and Hutson, 1992) include far more detailed accounts of soil hydrology (see Feyen *et al.*, 1998 for a review), but are “data-hungry” as a result, which constrains their application for practical purposes.

The hybrid model was calibrated and evaluated for Irish grasslands, using extensive observations of soil water tension on contrasting soil types in Ireland (Diamond and Sills, 2001).

Theory

Soil moisture deficit

Similar to the existing soil moisture models used by Teagasc and Met Éireann, the new hybrid SMD model is a water mass-balance model with a daily time-step, calculating SMD from the cumulative balance of precipitation, evapotranspiration and drainage:

$$SMD_t = SMD_{t-1} - Rain_t + ET_t + Drain_t \quad [1]$$

where SMD_t and SMD_{t-1} are the soil moisture deficits (SMD) on day t and day t–1, respectively (mm), *Rain* is the daily precipitation (mm/day), an input variable of the model, ET_t the daily actual evapotranspiration (mm/day) (Equation 2), and *Drain* equals the amount of water drained daily (mm/day) by percolation and/or overland flow (Equation 5).

Evapotranspiration

The actual evapotranspiration, *ET*, is a function of the potential or reference crop evapotranspiration (ET_0), and the current SMD. Largely based on Aslyng (1965), *ET* is assumed to equal ET_0 when soil moisture conditions are not limiting grass growth, i.e. when the current SMD is between 0 (field capacity) and a critical value SMD_c. When SMD exceeds SMD_c, the grass-leaf stomata close progressively to reduce the transpiration rate. As a result, the actual evapotranspiration will progressively be reduced and be less than ET_0 (Allen *et al.*, 1998). It is commonly assumed that the relationship between *ET* and ET_0 is linear between SMD_c and SMD_{max}, the maximum SMD (Aslyng, 1965; Allen *et al.*, 1998) (Equation 2):

$$ET_t = ET_0 \cdot \frac{SMD_{max} - SMD_{t-1}}{SMD_{max} - SMD_c} \text{ when } SMD_t > SMD_c \quad [2]$$

Aslyng (1965) found SMD_c and SMD_{max} to equal 30 mm and 120 mm, respectively, for the Danish reference soil. Similar values have been used in other studies (e.g. Brereton and Hope-Cawdery, 1988; Brereton *et al.*, 1996; Keane, 2001; Holden and Brereton, 2002). Holden and Brereton (2002) varied SMD_c with topsoil depth to simulate the water buffering capacity of different soils. In the current model, both SMD_c and SMD_{max} are calibrated as site-specific input parameters.

The potential evapotranspiration, ET_0 is calculated according to the FAO Penman-Monteith Equation (Allen *et al.*, 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [3]$$

where ET_0 is the potential evapotranspiration (mm/day), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is the ground heat flux density (MJ m^{-2} d^{-1}), T is the air temperature at 2-m height (°C), u_2 is the wind speed at 2-m height (m/s), e_s and e_a are the saturation and the actual vapour pressures (kPa), respectively, Δ is the slope of the vapour pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}).

Allen *et al.* (1998) present a multitude of approaches to computing the values of these variables from the measured quantities at meteorological stations. The choice of approach depends on the availability of these meteorological observations, the measurement frequency (e.g. hourly or daily), as well as on the required accuracy of the computed potential evapotranspiration. For the current model, ET_0 is calculated from the daily values of precipitation (mm/day), maximum temperature (°C), minimum temperature (°C), global radiation (MJ m^{-2} d^{-1}) and the wind speed at 10-m height (m/s), with latitude (radians) and altitude (m) as site-specific parameters, and assuming that the albedo of the grass crop is 0.23, and the ground heat flux negligible when calculated on a daily basis. For days for which daily global radiation was unavailable, this was estimated from the daily duration of bright sunshine, n (h/day), the daylength, N (h/day) and the extraterrestrial radiation, R_a (MJ m^{-2} d^{-1}), using the Ångstrom formula:

$$Radiation = R_a\left(a + b\frac{n}{N}\right) \qquad [4]$$

in which a and b are country-specific parameters which vary according to local conditions. For the hybrid model, the values $a = 0.18$ and $b = 0.55$ were adopted from Keane (2001). Long-wave radiation was estimated using Allen *et al.* (1998).

Drainage

The amount of water lost from the topsoil through either percolation or overland flow is assumed to be dependent on site-specific characteristics of the soil, and is referred to collectively as drainage. In this model, drainage is characterised by two parameters: the minimum soil moisture deficit, SMD_{min} (mm), and the maximum drainage rate, $Drain_{max}$ (mm/day). In the Teagasc model (Brereton *et al.*, 1996), SMD_{min} was assumed to equal 0, corresponding to field capacity, whereas the model used by Met Éireann (Keane, 2001) assumes SMD_{min} to be –10, thus allowing the soil to saturate beyond field capacity (at which SMD = 0). As a result, SMD, as computed by the Teagasc model, reflects the moisture conditions of well-drained soils that are never saturated (Diamond and Sills, 2001), whereas the Met Éireann model reflects the conditions of poorly-drained soils that can be saturated for considerable lengths of time (Diamond and Sills, 2001).

Based on extensive investigations of soil water regimes by Diamond and Sills (1998, 2001) and Diamond and Shanley (2003), the model presented in this paper defines three soil drainage classes, i.e. poorly-drained, moderately-drained, and well-drained soils. Differences between the hydrological properties of these classes are quantified by calibrating class-specific values for $Drain_{max}$, SMD_{min}, SMD_c and SMD_{max}.

It is assumed that drainage by means of percolation or overland flow only occurs when the soil moisture content exceeds field capacity (SMD < 0). However, it seems unrealistic that drainage can be described satisfactorily by a switch-function. Therefore, it is assumed that the actual drainage rate increases with accumulating soil moisture surplus, from no drainage when the soil is at field capacity (SMD > 0), to maximum drainage when the soil is saturated. Since the precise relationship between the actual drainage rate and SMD is difficult to quantify, the drainage rate *Drain* (mm/day) is described by a simple linear function of SMD when SMD ≤ 0:

$$Drain_t = Drain_{max} \cdot \frac{SMD_{t-1}}{SMD_{min}} \quad \text{when}$$

$$Drain_{max} \le -SMD_{min}$$

and [5]

$$Drain_t = -SMD_{t-1} \quad \text{when}$$

$$Drain_{max} > -SMD_{min}$$

Materials and Methods

The water mass balance equation (Equation 1) for any day is a function of the SMD for the previous day and hence requires an initial value for SMD on “day zero”, i.e. the day before the start of the simulation period. The approach adopted was to start each simulation during a wet period in winter, when SMD was assumed to equal SMD_{min} for each drainage class (see also Diamond and Sills, 2001).

Since SMD cannot be measured directly, the model was calibrated and evaluated against observed soil moisture tension data between 1998 and 2000 (see also Aslyng, 1965), which were available for three sites in Ireland (Diamond and Sills, 2001). Soil moisture tension was closely correlated with soil moisture content; this relationship varies with soil texture and structure (Salter and Williams, 1965; Brady, 1996). The relationship is non-linear and can be quantified using Van Genuchten's model (Van Genuchten, 1980). However, within the range of soil moisture tensions observed in this study (> 500 hPa on one occasion only, and never > 600 hPa), Van Genuchten's curve is close to linear for a wide range of combinations of parameter values, and therefore linear relationships between SMD and soil moisture tensions were assumed for the purpose of model calibration and evaluation.

The sites at which soil moisture tension was measured were:

1. Ballintemple Nursery, Coillte, Co. Carlow (latitude 52° 52'; altitude: 127 m):- Brown Earth, somewhat excessively drained, sandy loam. Records available for the years 1997 to 2000.
2. Clonroche Research Station, Co. Wexford (latitude 52° 27'; altitude 146 m):- Brown Earth, well-drained, loam. Records available for the years 1998 to 1999.
3. Johnstown Castle Research Centre, Co. Wexford (latitude 52° 18'; altitude 54 m):- Gley, poorly drained, loam. Records available for the years 1998 to 2000.

The soils of both Ballintemple and Clonroche were considered to be well-drained, whereas the Johnstown Castle soil was classified as poorly-drained (Diamond and Sills, 2001). The Ballintemple and Johnstown Castle data for the period 1998 to 2000 were used to calibrate the model parameters for well-drained soils and poorly-drained soils, respectively. The Clonroche data of the period 1998 to 1999 were used to independently evaluate the model performance on a well-drained soil. The Ballintemple data for the year 1997 were used to independently evaluate the model during a different time period, i.e. under different meteorological conditions.

Soil moisture tension was not measured on soils classified as moderately-drained, and therefore parameter values for this drainage-class were derived indirectly (see Results and Discussion).

At Ballintemple and Clonroche, daily soil moisture tension was measured from 1 January 1998 until 31 December 2000 by four tensiometers at depths of 15 cm and 30 cm, and three tensiometers at depths of 45, 60, 90 and 120 cm while in Johnstown Castle, soil moisture tension was measured during the same period using four tensiometers at each of these six depths. For further experimental details, see Diamond and Sills (2001).

As the model simulates the soil moisture conditions of the topsoil (i.e. the rooting zone), only the tensions measured at 15-cm depth were considered. Seven-day moving averages were computed and used for calibration and evaluation of the model. In 2000, soil moisture tension at Clonroche displayed a temporal pattern that could not be explained by meteorological conditions and these data were excluded as instrumentally induced artefacts.

Daily observations of precipitation were recorded at each site, this being the weather variable exhibiting the largest spatial variability (Hamilton, Lennon and

O'Donnell, 1988). At Johnstown Castle, daily observations of the remaining weather variables were also available. For Ballintemple, observations made at the Kilkenny synoptic station were used, while for Clonroche, each day the averages of the daily observations made in Kilkenny and Johnstown Castle were used.

The annual precipitation amounts at the three sites are summarised in Table 1, as well as the 20-year average annual precipitation and the maximum and minimum precipitation. At Johnstown Castle, 1999 was the driest year on record since 1981, while 1998 was the second wettest year, with normal precipitation amounts in 2000. Similarly in Ballintemple, both 1998 and 2000 were wet years, falling within the wettest quartile of the 20-year annual rainfall, whereas 1999 was a dry year, within the driest quartile. In Clonroche, the year 2000 was the wettest of the 3 years (within the wettest quartile), with 1998 and 1999 within the wettest and the driest 33-percentiles, respectively.

Calibration procedure

Correlations coefficients were computed for the relationship between the observed soil moisture tension and the predicted SMD. In order to allow for the soil-specificity of the quantitative relationship between these variables, these coefficients were calculated separately for the poorly-drained soil (Johnstown Castle) and the well-drained soil (Ballintemple). Subsequently, both for the poorly-drained soil and the well-drained soil, the parameters SMD_{min}, SMD_c, SMD_{max}, and $Drain_{max}$ were calibrated, by choosing the correlation coefficients as the calibration criterion and maximising these using MS-Excel 2000 Solver, with constraints $SMD_c \geq 0$ and $SMD_{min} \leq 0$. The parameter values of the original Teagasc model and Met Éireann model were used as initial values of the calibrations for the well-drained soil and the poorly-drained soil, respectively. In addition, parameter values represented 10% and 200% of the original values were used as initial values to check the potential existence of local (rather than global) maxima of the correlation coefficients.

Results and Discussion

Calibration

The temporal patterns of the predicted SMD and the observed soil moisture tension (Figure 1) show that SMD prediction closely followed the observed soil moisture tension, with most of the variation between both years and sites accounted

Table 1. Precipitation at the three experimental sites: long-term statistics (20 years) and annual data for the observation period

Precipitation (mm)	Experimental site		
	Johnstown Castle	Clonroche	Ballintemple
Annual mean	1032	1170	1051
Maximum	1197	1358	1189
Minimum	856	994	811
Total for			
1997	–	–	1014
1998	1181	1269	1151
1999	856	1073	995
2000	1110	1292	1153

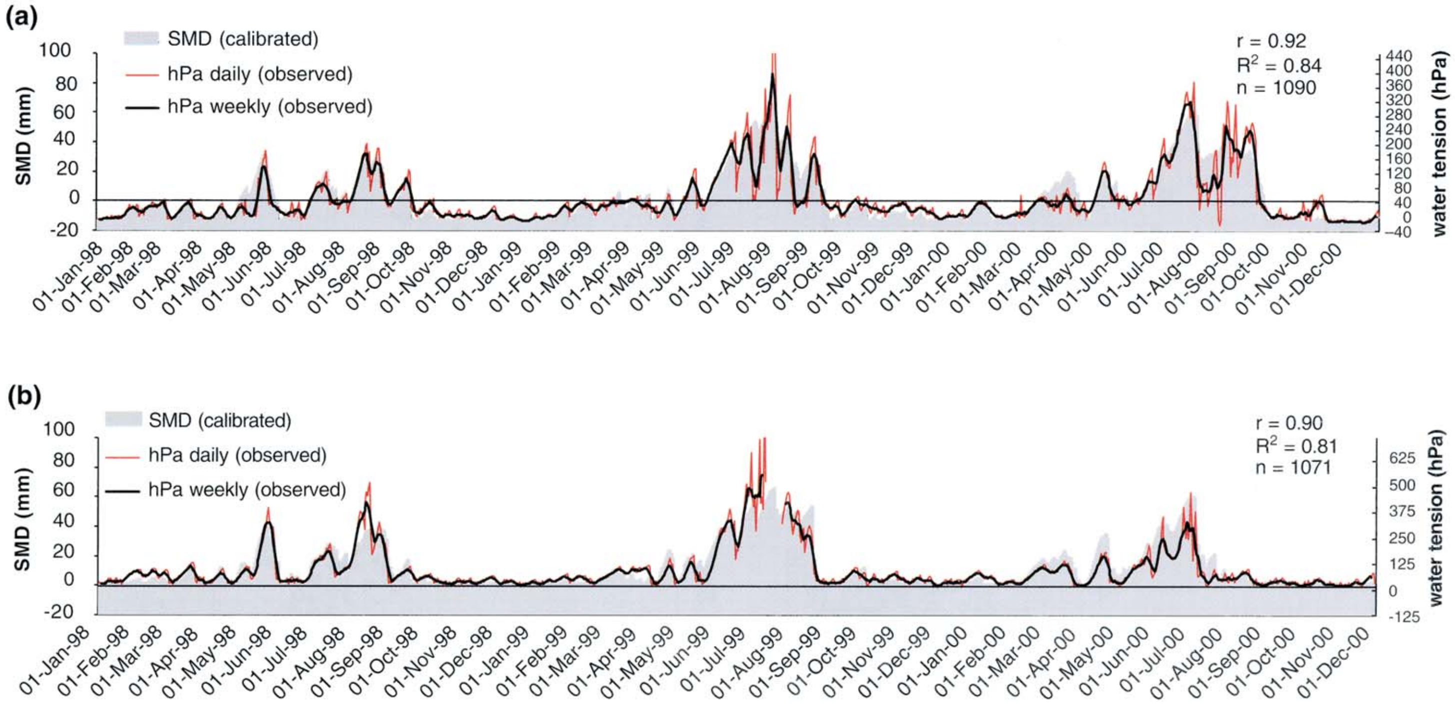

Figure 1: Simultaneous patterns of the calibrated soil moisture deficit (SMD) (mm) (shaded area), and the observed soil moisture tension (hPa) on a daily (red line) and weekly (black line) basis at a) Johnstown Castle (poorly drained) and b) Ballintemple (well drained).

for. In Figure 2, the predicted SMD is directly compared with the observed soil moisture tension for the two different drainage classes.

For both drainage categories, the maximum soil moisture deficit, SMD_{max}, was calibrated as *ca.* 111 mm (Table 2), which is close to the value of 120 mm, found by

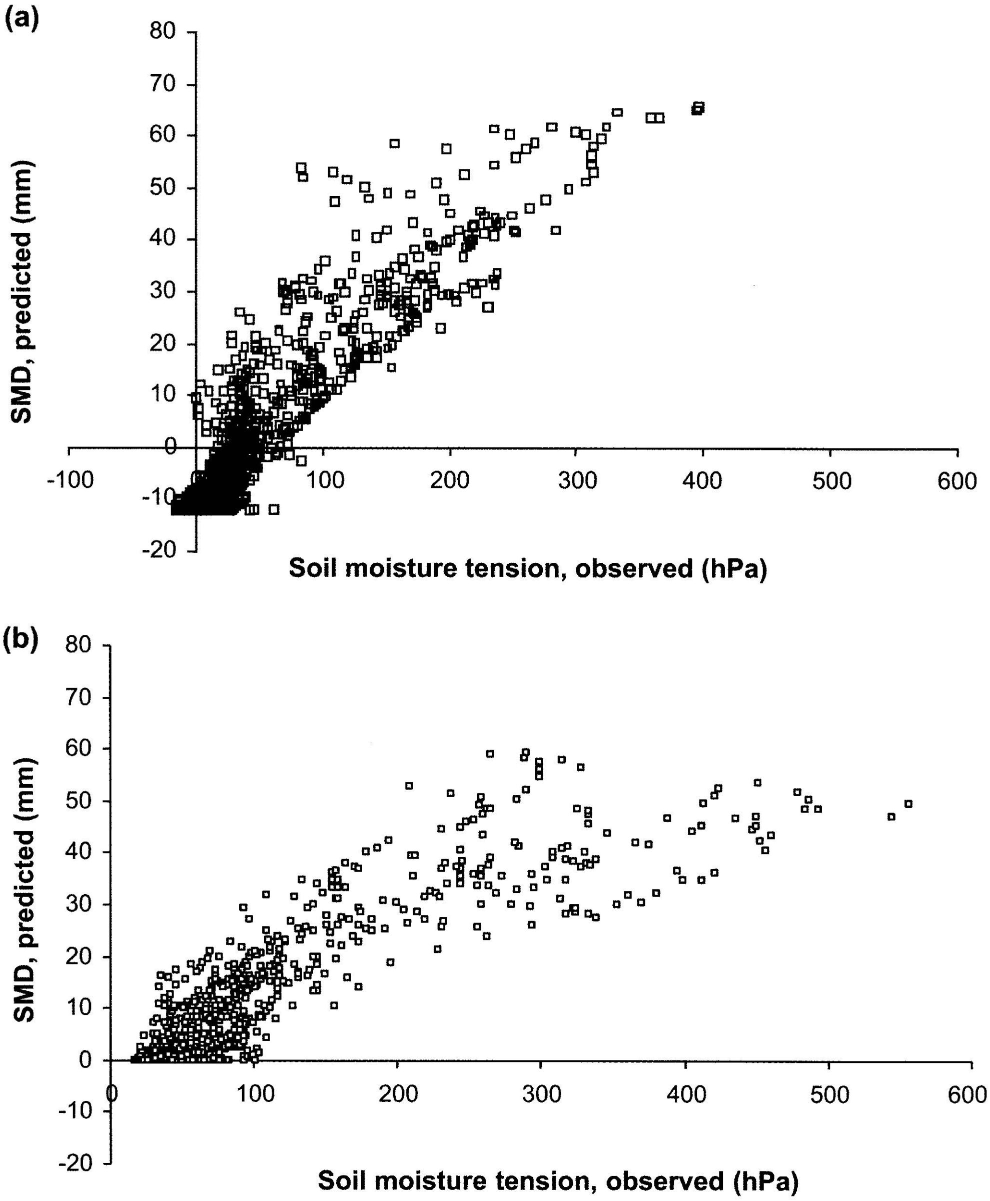

Figure 2: Calibrated soil moisture deficit (SMD) (mm) v. observed soil moisture tension (hPa) at a) Johnstown Castle (poorly drained) and b) Ballintemple (well drained).

Table 2. Calibrated parameter values of the hybrid model, and corresponding parameter values of the Teagasc model (Brereton *et al.*, 1996) and the Met Éireann model (Keane, 2001)

Parameter	Hybrid model		Previous model	
	Well-drained soils	Poorly-drained soils	Teagasc model	Met Éireann model
SMD_{max}	111.0	110.6	120	120
SMD_c	0	9.8	40	30
SMD_{min}	0	–13.3	0	–10
$Drain_{max}$	N/A[1]	0.43	N/A[1]	3.0

[1] The parameter $Drain_{max}$ is not applicable (N/A) where SMD_{min} = 0.

Aslyng (1965) and used by Brereton *et al.* (1996) and Keane (2001) (Table 2). The minimum soil moisture deficits, SMD_{min}, were calibrated as 0 mm for well-drained soils and –13.3 mm for poorly-drained soils, which are similar to the values, 0 and –10 mm, used by Brereton *et al.* (1996) and Keane (2001), respectively.

Since SMD_{min} was calibrated as 0 for well-drained soils, the drainage parameter $Drain_{max}$ did not require calibration for these soils; in fact a minimum SMD of zero implies that drainage will remove any amount of rainfall instantly, thus keeping the soil near field capacity at its wettest. For the poorly-drained soil, $Drain_{max}$ was calibrated as 0.43 mm per day, which is below the value of 3.0 mm per day used by Brereton and Hope-Cawdery (1988) and Keane (2001).

The critical soil moisture deficits, SMD_c, were calibrated as 0 mm and 9.7 mm for well-drained and poorly-drained soils, respectively, which are well below the values of 30 and 40 mm commonly used. This suggests that, at least on these Irish soils, the reduction of the actual evapotranspiration, and hence the onset of water-stress, however mild, commences almost as soon as soils start to dry after wet spells.

Evaluation

The results on model performance, and its use beyond the two sites and the 3 years for which it was calibrated, compared with observed data at Clonroche and Ballintemple are given in Figures 3 and 4. Figures 3a and 4a show that the SMD predicted by the hybrid model closely follows the observed soil moisture tension (R^2 = 0.85; $P < 0.001$) in Clonroche for both the wet year 1998 and the dry year 1999. The model also predicted the SMD patterns in Ballintemple correctly for the year 1997 (Figures 3b and 4b; R^2 = 0.82; $P < 0.001$), during which temporal moisture patterns were distinctly different from those in the years 1998 to 2000, with a very early drought in April, and heavy rainfall events during summer.

Calibration methodology

For the well-drained soil, the parameter values that returned the highest correlation did not depend on the initial parameter values used in the calibration process. For the poorly-drained soil, however, the calibrated parameter values depended on the initial values to some extent, with SMD_{max} ranging from 110 to 129 mm, SMD_c from 2.6 to 12.5 mm, SMD_{min} from –11.1 to –13.3 mm and $Drain_{max}$ from 0.43 to 0.67 mm. Each of the combinations resulted in a correlation coefficient of *ca.* 0.92, indicating a "plateau" of optimum solutions. The highest correlation coefficient was found with the combination of parameter values reported above (Table 2).

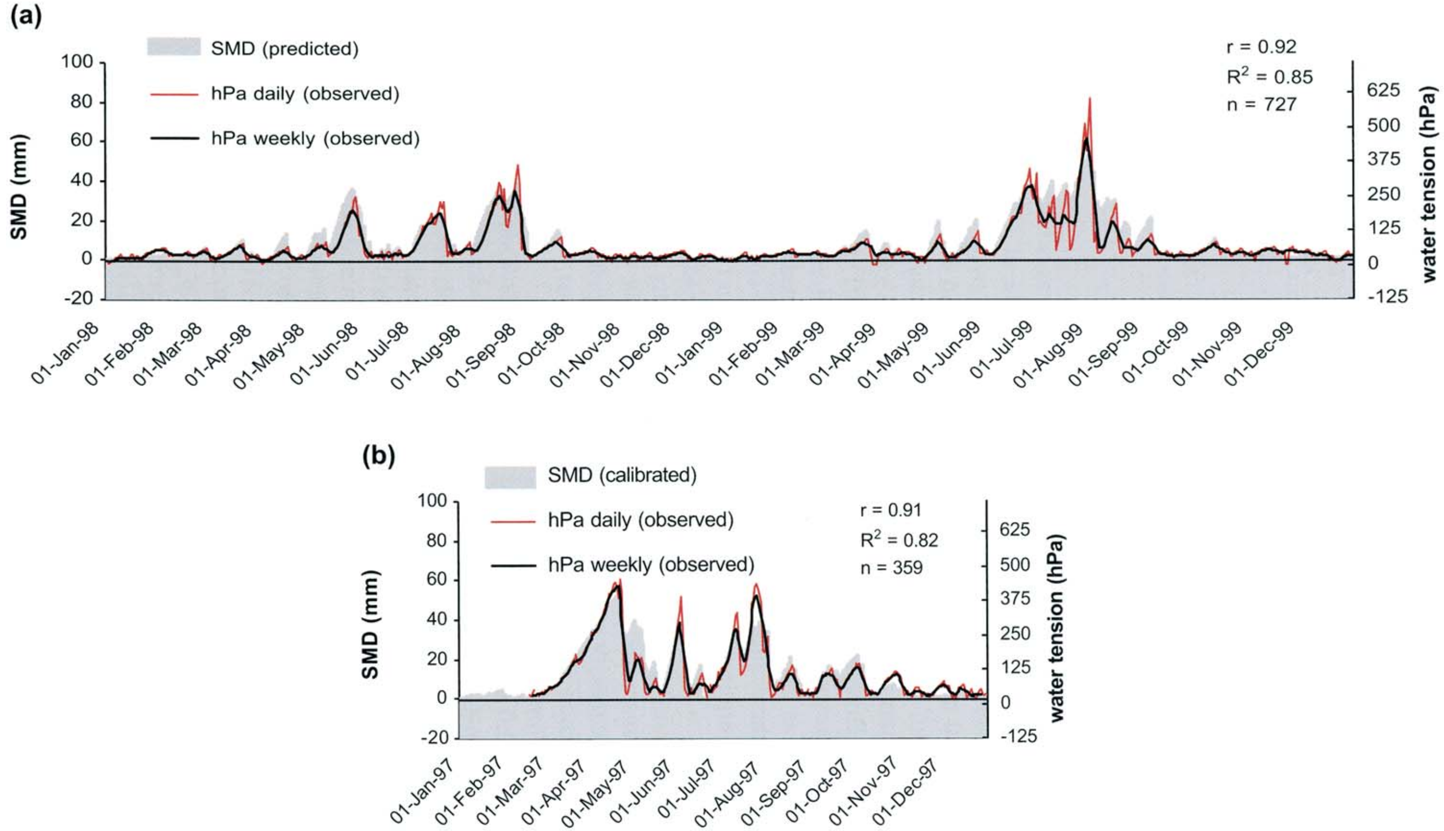

Figure 3: Simultaneous patterns of the predicted soil moisture deficit (SMD) (mm) (shaded area), and the observed soil moisture tension (hPa) on a daily (red line) and weekly (black line) basis at a) Clonroche for the years 1998 to 1999, and b) Ballintemple for 1997.

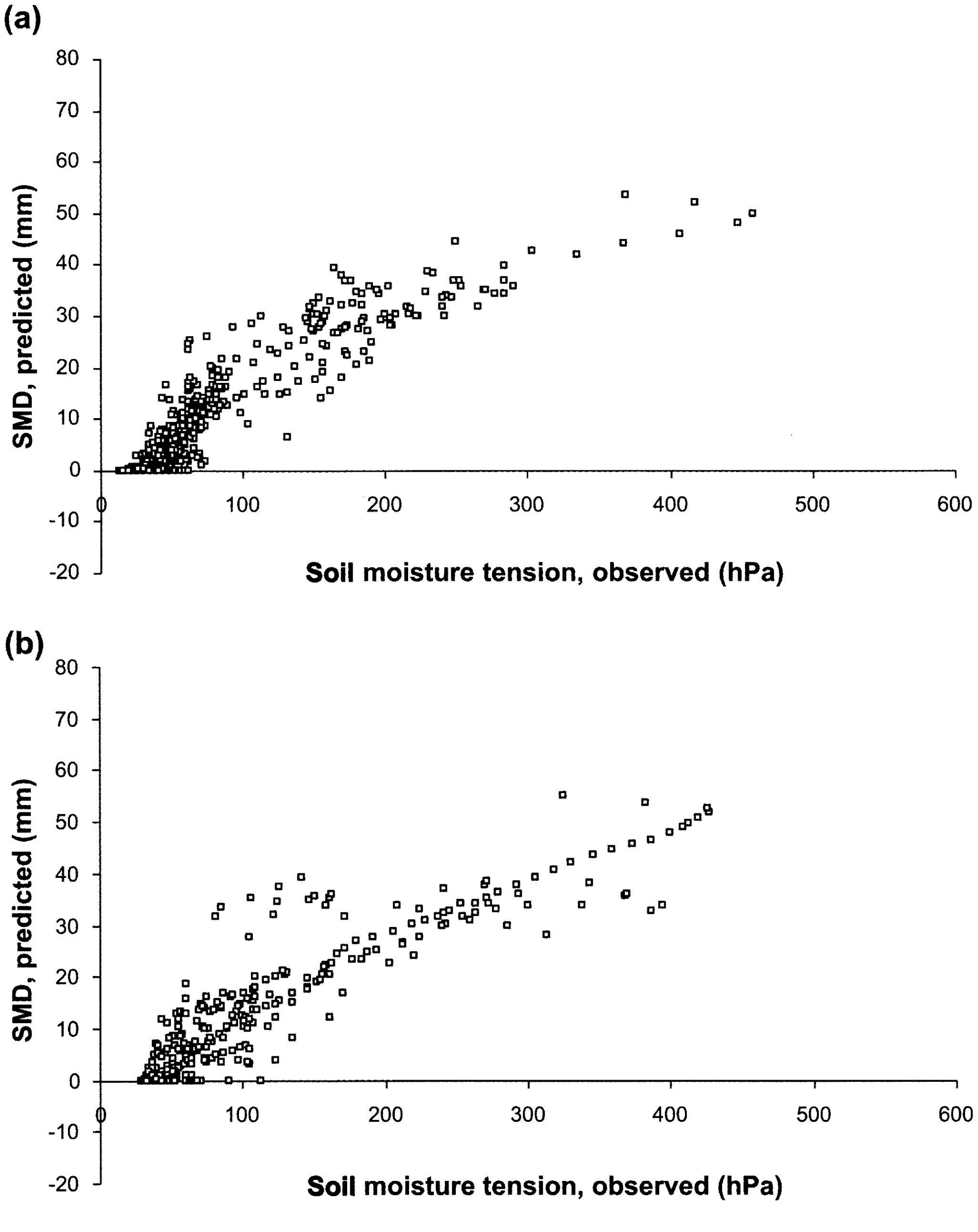

Figure 4: Predicted soil moisture deficit (SMD) (mm) v. observed soil moisture tension (hPa) at a) Clonroche for the years 1998 to 1999, and b) Ballintemple for 1997.

In addition the extent to which the calibration depended on the assumption of a linear relationship between SMD and soil moisture tension was explored. This was done by calibrating the model parameters while assuming the non-linear relationships quantified by Van Genuchten's model (Van Genuchten, 1980). This procedure resulted in parameter values similar to the values derived from the assumed linear relationship, with SMD_{max} = 107 mm and SMD_c = 5.3 mm for well-drained soils, and SMD_{max} = 114 mm and SMD_c = 0 mm for poorly-drained soils. SMD_{min} was reduced to –30 mm for poorly-drained soils. However, the applicability of Van Genuchten's model to calibrate the minimum SMD (at which soils are saturated) is questionable since it was explicitly formulated for unsaturated soils. Moreover, these parameter values did not increase the predictive power of the hybrid model for the test site Clonroche, nor did it increase correlation between model predictions and observed soil moisture tensions in the calibration of the Ballintemple soil, with only a marginal increase for the Johnstown Castle soil (from R^2=0.84 to 0.85).

Sensitivity analysis

In order to further explore the sensitivity of the model performance to the precision with which the parameter values were calibrated, it was subjected to a sensitivity analysis, to establish the consequences of potential under-estimation and over-estimation of the parameter values. For this purpose it was run multiple times to simulate poorly-drained soils, using the weather data of Johnstown Castle for the period 1998 to 2000. During each run, the values of individual parameters were progressively increased from 0% to +400% of their default (calibrated) values. Subsequently, the final values of all parameters were simultaneously increased over the same range. Figure 5 presents the impact of these changes in parameter values on the R^2-values between the predicted SMD and the observed soil moisture tension. The model had a low sensitivity to the parameter values, which means that it is hardly affected by relatively large under-estimates or over-estimates of these parameters. Only under-estimation of SMD_{max} led to a rapid decline in model performance.

Model performance

The insensitivity to the parameter values means that the hybrid model is very robust. Differences between the drainage characteristics of poorly-drained and well-drained soils are accounted for qualitatively, rather than quantitatively; i.e. it is the "qualitative" nature of well-drained soils to immediately drain any water in excess of field capacity, that discriminates their temporal SMD patterns from those found on poorly-drained soils, which do carry water surpluses for prolonged periods each year, in agreement with the observations by Diamond and Sills (2001). This is particularly important for the wider application of the model, as it implies that the model sensitivity has been shifted from the parameter values onto the (more realistic) physical representation of the soil. The relative insensitivity of model performance to quantitative changes in the parameter values means that performance should be good for soils which are qualitatively similar to the soils used in this study (i.e. poorly-drained or well-drained), even when their parameter values differ quantitatively. This was demonstrated by the accurate predictions of the temporal soil moisture patterns in Clonroche, using the parameter values calibrated for Ballintemple. In this light the calibrated parameter values (Table 2) have been generalised (Table 3) for future studies.

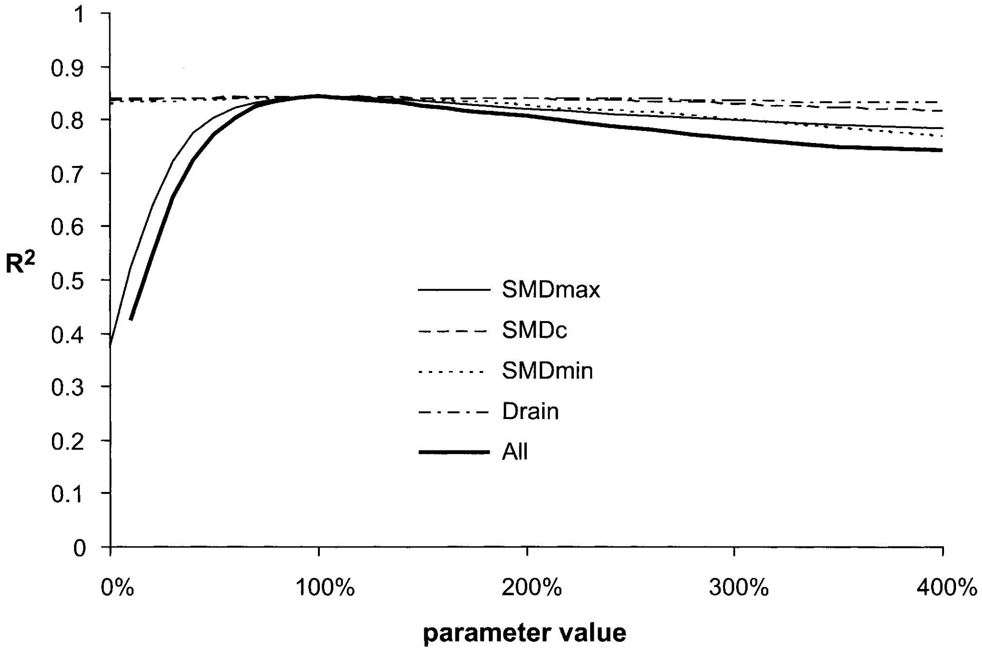

Figure 5: Sensitivity analysis for the hybrid model, predicting soil moisture deficit (SMD) of poorly-drained soils, using weather data of Johnstown Castle for the period 1998 to 2000. Graph shows the effect of relative changes in individual parameter values on R^2-values between predicted SMD and observed soil moisture tension. Bold line shows the effect of changing all parameter values simultaneously.

Differences from old models

The most significant change, resulting from this calibration, has been a substantial reduction of the critical SMD, i.e. the onset of the reduction of the actual evapotranspiration. The impact of this change is illustrated by comparing the reduction of the actual evapotranspiration as predicted by the previous Met Éireann and Teagasc models (red line) and the new hybrid model (black line) for both poorly-drained soils (Figure 6a) and well-drained soils (Figure 6b), respectively, for the period 1998 to 2000, using the weather data of Johnstown Castle. Figure 6a shows that for poorly-drained soils, the new hybrid

Table 3. Generalised parameter values for well-drained, moderately-drained and poorly-drained soils in the hybrid model

Parameter	Soil category		
	Well-drained	Moderately-drained	Poorly-drained
SMD_{max}	110	110	110
SMD_c	0	0	10
SMD_{min}	0	–10	–10
$Drain_{max}$	N/A	>10	0.5

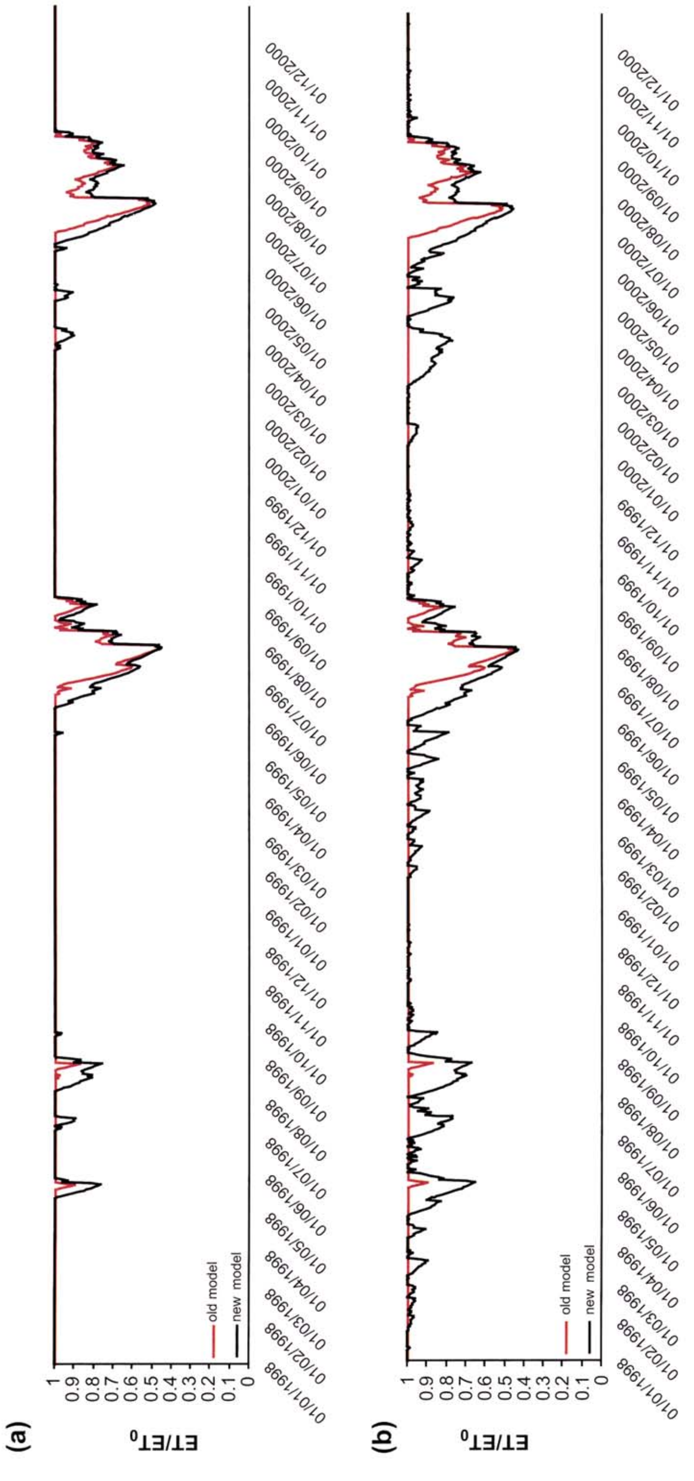

Figure 6: The actual evapotranspiration (ET), expressed as a proportion of the potential evapotranspiration (ET_0), as predicted by the old models and the new hybrid model for the period 1998 to 2000, using Johnstown Castle weather data; a) poorly-drained soils (Met Éireann model: red line; Hybrid model: black line); b) well-drained soils (Teagasc model: red line; Hybrid model: black line).

model predicts the onset of water-stress somewhat earlier than the Met Éireann model. However, water-stress is still predicted to occur only during the summer months. Differences between the hybrid model and the Teagasc model are much more pronounced on well-drained soils (Figure 6b): not only does the new hybrid model predict an earlier onset of water-stress in summer than the old model, it also predicts water-stress, albeit to a much milder extent, much earlier in the season (i.e. as soon as SMD > 0). This would have significant implications for grass growth patterns within and between years.

Drainage class

The drainage rate of well-drained soils is so high that all water in excess of field capacity is drained immediately, resulting in a minimum SMD of 0. By contrast, the drainage rate on poorly-drained soils is so low that, in the absence of high rates of evapotranspiration (winter), it takes a number of days for these soils to drain surplus water, following precipitation. The parameters of the third and intermediate drainage class (moderately-drained soils), could not be calibrated directly. Here we propose to define this drainage class by a maximum drainage rate which is in between the approximately infinite rate of the well-drained soils, and the very low rate of the poorly-drained soils. By assigning a value to $Drain_{max}$ that is in excess of SMD_{min}, this drainage class is defined to encompass those soils that drain any surplus water within a day (Equation 5). In practical terms, this means that these soils may carry water in excess of field capacity, or even be saturated, on wet days during winter, but will return to field capacity again on the first subsequent dry day. As a result, the parameter $Drain_{max}$ does not require calibration, as the drainage rate *Drain* is always equal to the soil moisture surplus on the moderately-drained soils (Equation 5; Table 3).

These definitions of the drainage classes have the distinct advantage that soils can easily be assigned to a class by observation of their hydrological status during winter. These classes are described as follows:

1. Well-drained soils remain at field capacity on wet winter days, even during rainstorm events, and are never saturated.
2. Moderately-drained soils carry water surpluses on wet winter days, and can reach saturation during rainstorm events, but will return to field capacity on the first subsequent dry day.
3. Poorly-drained soils carry water surpluses on wet winter days, and reach saturation during rainstorm events, and remain below field capacity for a number of days, even when no further precipitation occurs.

The drainage classes are related, to an extent, to the texture class of the soils they encompass, with a negative relationship between the maximum drainage rate and the clay content. However, it is worth noting that this relationship is not exclusive. For example, drainage on sandy soils may be impeded by impermeable layers in the sub-soil, while the drainage rate on clayey soils may be increased by artificial drainage pipes.

The current hybrid model does not discriminate drainage through percolation from drainage through overland flow. This requires a quantification of the dependence of these processes on additional, site-specific parameters such as topography.

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