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A note on the Hybrid Soil Moisture Deficit Model v2.0

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Abstract

The Hybrid Soil Moisture Deficit (HSMD) model has been used for a wide range of applications, including modelling of grassland productivity and utilisation, assessment of agricultural management opportunities such as slurry spreading, predicting nutrient emissions to the environment and risks of pathogen transfer to water. In the decade since its publication, various *ad hoc* modifications have been developed and the recent publication of the Irish Soil Information System has facilitated improved assessment of the spatial soil moisture dynamics. In this short note, we formally present a new version of the model (HSMD2.0), which includes two new soil drainage classes, as well as an optional module to account for the topographic wetness index at any location. In addition, we present a new Indicative Soil Drainage Map for Ireland, based on the Irish Soil Classification system, developed as part of the Irish Soil Information System.

Keywords

Areas of natural constraint • drainage • model • soil moisture • trafficability

Introduction

In temperate maritime climates, soil moisture dynamics are drivers of the evolution of agricultural systems. The number of days when soil has excess moisture, known as field capacity (FC) days, determines the type of agricultural system used, with specific influence on herbage growth, herbage utilisation, farm operations and environmental sustainability (Schulte *et al*., 2012). The European Commission now recognises FC days as a bio-physical criterion that defines a natural constraint for agriculture in Europe (Jones *et al*., 2013).

FC days can be either measured *in situ* at the field/soil profile scale or modelled as a function of the temporal pattern of soil moisture deficit (SMD), which in turn can be computed from meteorological variables and soil properties. Schulte *et al*. (2005) combined existing Teagasc and Met Éireann SMD models into the 'hybrid soil moisture deficit' or HSMD model, which is a simple mass-balance calculation to predict SMD from precipitation, evapotranspiration and drainage. Precipitation and evapotranspiration were taken and computed, respectively, from observed weather data or numerical weather prediction (NWP) model output using the Penman–Monteith equation (Allen *et al*., 1998) and drainage was modelled as a function of one of the three drainage classes calibrated using empirical experimental data. These calibrations showed that poorly drained soils are those that remain wetter than FC for multiple days following winter rainfall events, moderately drained soils carry water in excess of FC during winter rainfall events, but return to FC on the first dry day, whilst well-drained soils never carry soil water in excess of FC. This calibration of drainage is described in detail by Schulte *et al*. (2005).

In recent evaluations of the HSDM model to test its suitability for operational deployment, Kerebel *et al*. (2013) demonstrated strong relationships between HSMD output and field observations of topsoil (to 30 cm depth) volumetric water content, whilst Doody *et al*. (2010) concluded that the HSDM model outperformed two alternative soil moisture models in predicting overland flow events.

The main use of the HSMD model has been by Met Éireann to provide weekly reports on SMD conditions throughout the Republic of Ireland (see www.met.ie/agmet/default.asp). It has also been cited in more than 50 scientific publications, for a variety of applications, including farm-scale modelling of grassland productivity and utilisation (Fitzgerald *et al*., 2008), assessment of agricultural management opportunities such as slurry spreading (Lalor & Schulte, 2008; Kerebel *et al*., 2013), understanding spatio-temporal dynamics of water movement through the unsaturated travel zone (e.g. Vero *et al*., 2014) as well as predicting nutrient emissions to the environment (e.g. Doody *et al*.,

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2010; Fenton *et al*., 2011) and risks of pathogen transfer to water (Samadder *et al*., 2010). A detailed review was presented by Schulte *et al*. (2012).

These applications of the HSMD model have been associated with a number of developments and modifications that have resulted in parameterisation beyond the three soil drainage classes originally described. In order to ensure consistent use of the model in the future, there was an urgent need to formally develop a new version of the model (HSMD2.0). Therefore, the first objective of this work was to review recent modifications to HSMD model and integrate these into HSMD2.0.

For application at larger scales, an indicative drainage map was presented by Schulte *et al.* (2006), based on the assignment of soil associations of the General Soil Map (Gardiner and Radford, 1980) to each of the three drainage classes, using expert judgement. The General Soil Map has now been superseded by the Irish Soil Information System. This digital soil resource now includes a new Irish soil classification system that is fully correlated to the World Reference Base (Reidy *et al*., 2014); a harmonised third-generation soil map of associations at 1:250,000 scale (Creamer *et al*., 2014, Simo *et al*., 2014); and a digital soil information system (http://soils.teagasc.ie) (Hallett *et al*., 2014).The new soil classification system includes subgroups, which allow for the more objective assignment of drainage classes to the principal soil series of each association, based on the diagnostic features of the subgroup to which they belong, as catalogued in Table 2. Diagnostic features are field-based descriptions that describe the main soil forming and management characteristics associated with a particular soil subgroup (Láng *et al*., 2013). The key diagnostic features relating to drainage status in Irish soils are 'gleyic' and 'stagnic'. Gleyic denotes water saturation in a soil profile as a result of a fluctuating watertable, whereas the stagnic feature indicates saturation because of the presence of a slowly permeable layer in the soil. Therefore, the second objective of this note is to present an Indicative Soil Drainage Map for Ireland at the 1:250,000 scale, based on soil associations.

Materials and Methods

Model development

In the decade since its publications, the HSDM model has been adapted to allow accurate prediction of soil water conditions for scenarios or soil types for which it was not originally calibrated. These include

- Calibration of the HSDM model for tillage on excessively drained soils (Premrov *et al*., 2010);
- Calibration of a new drainage class with drainage characteristics in between those of poorly drained and moderately drained soils (Fitzgerald *et al*., 2008). This requirement was also recognised by Kerebel *et al*. (2013) who suggested calling this 'imperfectly drained' soil;
- The development of a topographic wetness index (TWI) model component, for use in locations that receive water not only from precipitation but also from adjacent land areas through overland flow, interflow or groundwater elevation events (Lewis and Holden, 2012). The influence of landscape position is captured in their model by modifying the drainage rate (variable *Drain*) depending on the calculated TWI:

$$SMDt_t = SMD_{t-1} - Rain_t + ET_t + [Drain_t / Y] \quad (1)$$

where SMD_t is soil moisture deficit on day t (mm), SMD_{t-1} is the deficit on the previous day (mm), $Rain_t$ is the daily rainfall (mm day^{-1}), ET_t is the daily actual evapotranspiration (mm day^{-1}), $Drain_t$ is the amount of water moved by percolation or overland flow (mm day^{-1}) and Y is modifier derived from TWI observations by Lewis and Holden (2012) (Table 1). This modification can be applied to moderately, imperfectly and poorly drained soils but not to well-drained soils, as the variable *Drain* is by definition set to infinity for this soil class.

We have now formally included these three additions into the HSMD2.0 model, using the methodologies and calibrations of the original scientific publications, as listed. Table 3 presents the resulting changes to the model parameters for each of the drainage classes.

Table 1. Topographic wetness index (TWI) value categories and Y values for modification of $Drain_t$ in the HSMD2.0 model, based on Lewis and Holden (2012).

TWI Value Category	Y value
<7	0.8
≥ 7 and < 8	1
≥ 8 and < 11	5
≥ 11	10

In addition, we have taken the opportunity to adjust an emerging property of the original HSMD model through adjustment of the time interval for moderately drained soils: the daily time step of the original HSMD model required an arbitrary decision whether the computed SMD value referred to the start or the end of the day. In the original version of the model, moderately drained soils were 'forced' to return to FC at the *start* of the first dry day following a winter rainfall event. However, subsequent model employment has suggested that this results in largely similar behaviour (and predictions) for moderately drained and well-drained soils. For the HSDM2.0 model, this arbitrary choice has been reversed: moderately drained soils are now forced to return to FC at the *end* of the first dry day following a winter rainfall event.

Table 2. Categorisation of taxonomic soil subgroups into drainage classes, based on the diagnostic criteria listed.

Drainage category	Diagnostic rules
Excessive	Dominance of sandy loam and sandy textural classes within association
Well	No mottling, no full argic/spodic horizon present
Moderate	Mottling 40–80 cm with no organic matter accumulation, but argic or spodic may be present
Imperfect	Mottling 40–80 cm AND some organic matter accumulation and argic/spodic horizon present (at least a score of 1 in either category)
Poor	Mottling within 40 cm argic/spodic horizon causing stagnation

Table 3. Changes in the model parameters in HSDM2.0, as compared to the original values in the first HSDM.

Drainage class	Original Parameter Values	Change in Parameter Values	Topographic Wetness Module
Excessive	N/A	SMD_{max} = 50mm SMD_c = 0mm	N/A
Well	SMD_{max} = 110mm SMD_c = 0mm $Drain_{max}$ = ∞	No change	N/A
Moderate	SMD_{max} = 110mm SMD_c = 10mm $Drain_{max}$ >10mm	*SMD* = 0 at the *end* of the first dry day following a winter rainfall event, or $SMD(t) = SMD(t-1) + Et_a$, whichever is greater.	
Imperfect	N/A	$Drain_{max}$ = 3mm day^{-1}	Reduce *Drain* by a factor Y (Table 1)
Poor	SMD_{max} = 110mm SMD_c = 10mm $Drain_{max}$ = 0.5mm	No change	

Indicative soil drainage classification

Following the methodology developed by Simo *et al*. (2015), each soil subgroup in the new Irish Soil Classification System (Creamer *et al.*, 2014) was assigned a score of 1 for the diagnostic features 'gleyic' and 'stagnic', if the evidence of saturation occurs within 40 cm of the surface horizon and thus defined the great group to which the subgroup belongs. These soils were designated as poorly drained. Where saturation is evident between 40 cm and the lower profile boundary (80 cm), the diagnostic feature defines the subgroup, rather than the great group, and was, therefore, recorded as 0.5. These latter soils required additional diagnostic features to allow for designation to either the moderately drained or imperfectly drained category. Imperfectly drained soils required the diagnostic feature of organic matter accumulation to be scored as 0.5 or greater and scores of at least 1 for either the additional diagnostic feature 'argillic' (clay eluviation from the topsoil to a lower horizon) or 'spodic' (enrichment of a lower horizon with Fe/Al sesquioxides leached from the horizon above), as defined by Creamer *et al.* (2014). By contrast, moderately drained soils do not have any organic matter accumulation but may score 0 or 0.5 for the spodic or argic features. Where no evidence of waterlogging occurs, the feature is recorded as 0. Subsequently, soils with a score of 0.5 or less for organic matter, spodic or argillic features were designated as well drained. Finally, excessively drained soils were considered those associations that are dominated by soils that have a loamy sand or sand texture.

Results

Figure 1 demonstrates the differences between the outputs of the original HSMD model (Figure 1a) and the new HSMD2.0 model presented in this paper (Figure 1b) for the year 2013. In first instance, Figure 1 demonstrates that the predictions for well-drained, moderately drained and poorly drained soils do not differ significantly between the two versions of the model. This means that for these drainage classes, future predictions of HSMD2.0 will be consistent – and can be compared with – historic predictions made by the original HSMD model. A notable exception is that in the new version, moderately drained soils reach FC (SMD = 0) one day after well-drained soils following wet periods. This means that moderately drained and well-drained categories no longer behave identically in the new version.

In addition, Figure 1b shows that the predicted SMD of the new imperfectly drained category falls consistently between poorly drained and moderately drained soils and, therefore, has a unique 'behaviour' that justifies the allocation of this new drainage class. Furthermore, it is obvious that the new category of excessively drained soils shows identical dynamics to well-drained soils during the winter months, but much lower SMD values during the summers. This counterintuitive pattern is explained by the fact that excessively drained soils have a maximum SMD (SMD_{max}) of 50 mm, as opposed to 110 mm for well-drained soils, reflecting the reduced water-holding capacity of the former (Premrov *et al*., 2010).

a

b

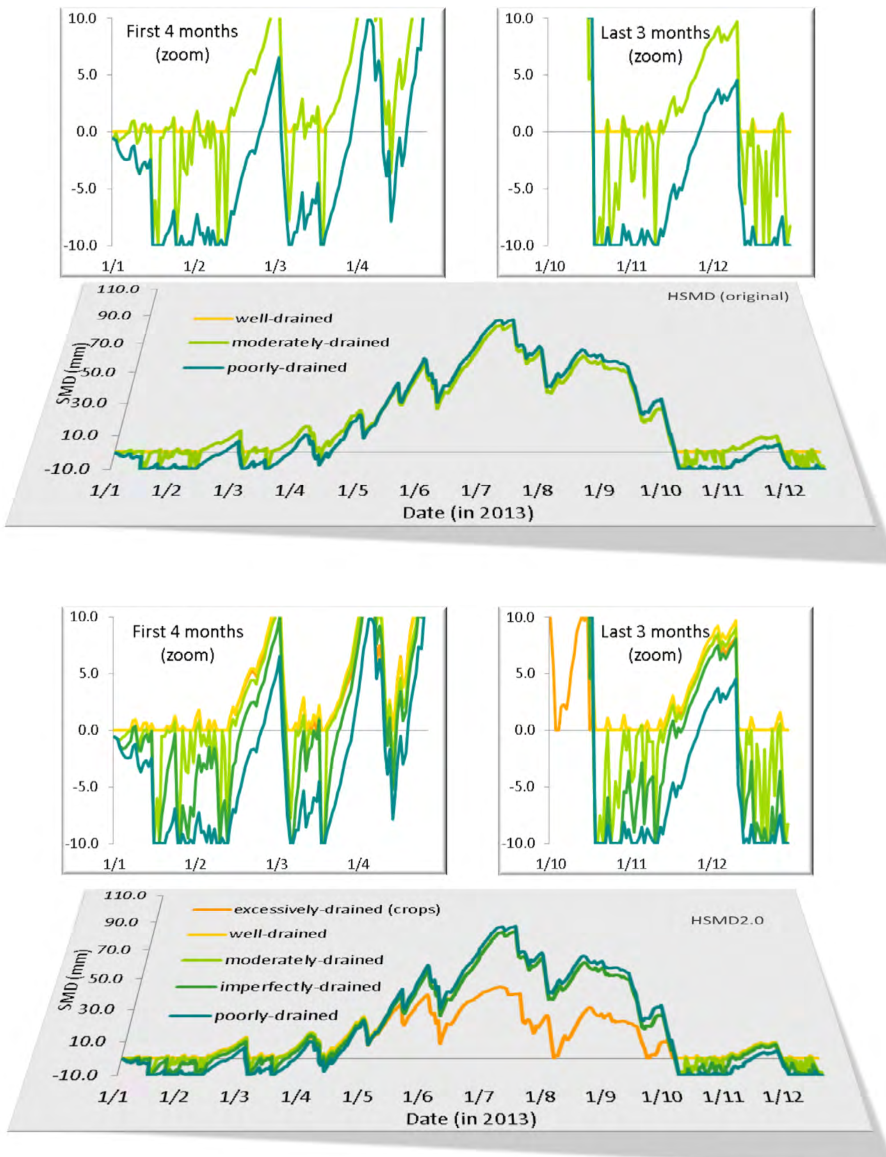

Figure 1. A comparison of the model outputs of (a) the original HSMD model and (b) the HSMD2.0 using weather data for Johnstown Castle for the year 2013.

Figure 2 shows the evolution of the Indicative Soil Drainage Map for Ireland. The new version (Figure 2b) replaces the earlier version presented in Schulte *et al*. (2006) (Figure 2a) and is publically available as a vector map.

Discussion

The inclusion of the imperfectly drained soil category means that the HSDM2.0 model can now discriminate more precisely the temporal soil moisture dynamics of contrasting soils. Heretofore, soils were classified as poorly, moderately or well drained, and the original HSMD version computed an identical number of FC for the latter two categories. Table 4 shows that this has changed in the new HSMD2.0 version: not only does it discriminate successfully between well-drained and moderately drained soils, the insertion of the new imperfectly drained category now allows for a gradient of FC days to be assigned to a specific location, rather than a binary allocation.

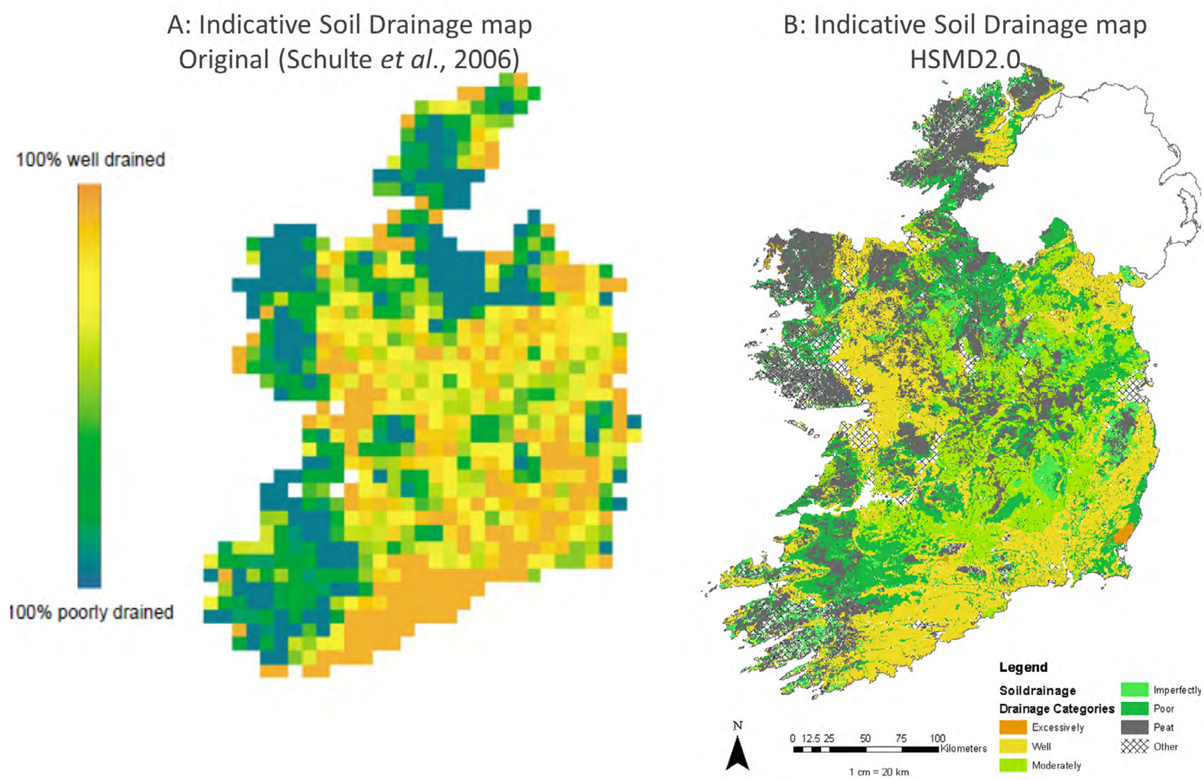

Figure 2. Evolution of the Indicative Soil Drainage Map. (a) The original map by Schulte** et al. **(2006). (b) The new map is based on the diagnostic features of the principal soil series in each soil association.

Table 4. Difference in applied model outputs (number of FC days during 2013 in Johnstown Castle) between the original HSMD and HSMD2.0

Drainage Class	#FC days (Johnstown Castle, 2013)	
	Original	HSMD2.0
Excessive	N/A	79
Well	72	72
Moderate	72	104
Imperfect	N/A	121
Poor	152	152

In this context, the Indicative Soil Drainage Map now facilitates the assessment of *spatial* dynamics of SMD, in addition to the *temporal* dynamics to which assessments were limited heretofore. It must be emphasised that the 1:250,000 scale of the Indicative Soil Drainage Map only allows for visualisation of the dominant drainage class within each association. As a result, this map should not be used for the allocation of drainage classes to point data, which by necessity requires in-field visual assessment such as the methodology developed by Kerebel and Holden (2013), which will now need to be updated to include the imperfectly drained category. However, the Indicative Soil Drainage map does permits planning of field work and generalised spatial interpretation of data and will ensure a consistent initial application of HSMD2.0.

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