**Evaluation and improvement of the default soil hydraulic parameters for the Noah Land
Surface Model**

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ABSTRACT

Soil hydraulic parameters used in estimating soil water and energy fluxes are included in a lookup table in the Noah Land Surface Model (LSM). The purpose of the study was to examine the Noah default soil hydraulic parameters and compare them to soil measurements across Texas, USA. These default soil parameters were compared to measured soil properties from a soil database including 6,749 soil samples located within and around Texas. Mean differences between measured and default soil parameters were tested using a t-test ($\alpha = 0.05$). To assess the proposed changes to default soil parameters, water retention curves were created using updated parameters and compared to measured soil moisture content at field capacity (θ_{fc}) and permanent wilting point (θ_{wp}). Spatial trends across major land resource areas in Texas were also demonstrated for water retention parameters. Our findings indicate that 95% of the default soil parameters were significantly different from the region-specific measured values. Measured soil water content at air-dry, θ_{wp} , and θ_{fc} are better replacements than default values. Consequent changes in θ_{wp} and θ_{fc} yielded a 35 to 76% decrease in plant available water compared to default. Updated water retention curves showed improved agreement between estimated soil water and measured values in 95% of cases. For three texture classes, the standard deviations of parameters for water retention parameters ranged 30% for the slope of the water retention curve and 65% for saturated hydraulic conductivity. These results indicate the importance of accounting for spatial variability of soil parameters rather than combining these parameters into texture classes alone. The revised parameter table improves modeling of soil hydraulic properties. Ultimately spatially distributed databases of hydraulic soil parameters will better capture variability and spatial structure of soil processes modeled by Noah LSM.

Keywords: Noah land surface model, Soil hydraulic parameter, Pedotransfer function, Soil moisture

1. Introduction

The deterministic land surface properties including soil moisture dominantly influence the surface boundary conditions of the land interacting with the atmosphere (Peters-Lidard et al., 1998; Chen and Dudhia, 2001). Thus, proper parameterization of soil moisture and heat fluxes strongly contributes to realistic initialization of the land surface conditions in mesoscale atmospheric modeling (Quintanar et al., 2008, 2009). This initialization of the land surface is critically important for realistic predictions of changes in weather, air quality, and climate (Chen and Dudhia, 2001; Duan et al., 2001; Ingwersen et al., 2011).

To simulate soil moisture, and consequently heat fluxes, precipitation, and other boundary layer processes, a lookup table with default soil parameters stratified mostly based on the soil textural classes have been frequently used in regional community land surface models (LSMs). An LSM known as Noah was developed jointly by the National Centers for Environmental Prediction (NCEP), Oregon State University (OSU), Air Force Weather Agency (AFWA), and the Hydraulic Research Laboratory (HRL). The Noah LSM is applied increasingly by the atmospheric modeling community in uncoupled and coupled modes with various mesoscale atmospheric models. For example, High-Resolution Land Data Assimilation (HRLDAS) was developed by running the Noah LSM in uncoupled mode (Mitchell et al., 2004; Chen et al., 2007). The Noah LSM was coupled with the NCEP mesoscale Eta model in the past (e.g., Chen et al., 1997; Chen and Mitchell, 1999; Ek et al., 2003), and also with the MM5 model (Chen and Dudhia, 2001), but more recently with the Global Forecast System (GFS, Zhang et al., 2011), the seasonal Climate Forecast System (CFS, Yang et al., 2011) and the regional Weather Research and Forecasting (WRF) model (e.g., Chen et al., 2007; Kumar et al., 2010; Niu et al., 2011). The

spatial resolution of Noah land surface modeling has usually 12- and 4-km grid spacing (e.g., Chen et al., 2007) for soil profiles frequently divided into layers with depths of 0-0.1 m, 0.1-0.4 m, 0.4-1.0 m, and 1.0-2.0 m (Chen and Dudhia, 2001). In both coupled and uncoupled modes, the same default soil parameters are applied during initializing and running the Noah LSM as well as its advanced version Noah-Multiparameterization LSM (Noah-MP, Niu et al., 2011). Consequently, the default soil parameters have far-reaching influence on the outcomes of a range of models and simulations of the land surface at different scales.

1.1. Default soil parameters in the Noah Land Surface Model

The current values of default soil parameter table, called default table in this paper, are presented in Table 1, and their definitions, units, and sources are shown in Table 2. Methods of determination were described for parameters BB, MAXSMC, SATPSI, and SATDK by Cosby et al. (1984), for DRYSMC, SATDW, REFSMC, and WLTS MC by Chen and Dudhia (2001), for F11 by NCEP (2003), and for QTZ by Peters-Lidard et al. (1998) in the 12 USDA soil texture classes. Moreover, seven other categories were identified by Miller and White (1998), Chen and Dudhia (2001), and Kumar et al. (2010). From the general procedures of determining these parameters, a few deviations were observed in the published default table. Some of these deviations or discrepancies are discussed below, but these are discussed in more details by Morgan and Kishné (2013).

Over the last approximately 25 years, the default table has evolved. First, only parameters BB, MAXSMC, SATPSI, and SATDK were published by Cosby et al. (1984) for 11 of the 12 regular USDA soil textural categories, excluding silt (Ek and Mahrt, 1991). In 1997, the table was extended with the following categories existing in the CONUS-SOIL database (Miller and White 1998; White and Miller 1998): Silt, Organic material, Water, Bedrock, and ‘Other’. Later, Chen

and Dudhia (2001) included three new soil parameters, namely REFSMC, WLTS MC, and SATDW. Finally, the parameters DRYSMC, F11, and QTZ were added and three new categories, Playa, Lava, and White sand which made 19 categories in all (Kumar et al., 2010). Although, no reference has been found for the origin of the exact parameter values in the categories of Silt, Organic material, Water, Bedrock, ‘Other (land-ice)’, Playa, and White sand, the following patterns have been observed in the default table.

- Silt has the same values as silt loam, except for REFSMC and QTZ. REFSMC in silt category is the same as in loamy sand and in sandy loam, but different from the values published in Chen and Dudhia (2001).
- Organic material has the same values as loam, except for QTZ.
- Other (land-ice) has the same values as loamy sand, except for REFSMC and QTZ.
- Playa category has the same values as clay category, except for DRYSMC, F11, WLTS MC, and QTZ.
- White sand has the same values as sand, except for QTZ.

1.2. Sensitivity of the Noah LSM to the default soil parameters

In sensitivity analyses, parameter values are usually varied in increments, and the model responses are observed and analyzed to investigate the effects of parameters on model outcomes. For complex models, such as LSMs, interactions between parameters may complicate the identification of individual parameter impacts. Sensitivity of LSMs to certain soil parameters was found to be dependent on multiple conditions, such as model physics, parameterization scheme, climatic conditions (Mitchell et al., 2004; Teuling et al., 2009; Cuenca et al., 1996;

Rosero et al., 2010), and characteristics of sites and regional geographic locations (Bastidas et al., 2006; Hogue et al., 2006; Rosero et al., 2010).

Individual effects of soil parameters on Noah model outcomes have been analyzed by Bastidas et al. (1999, 2006) and Hogue et al. (2006). The study sites were located in Arizona, Oklahoma, Illinois, The Netherlands, Brazil (Bastidas et al., 2006; Hogue et al., 2006), and at the IHOP experimental sites in Oklahoma (Rosero et al., 2010). Model outputs investigated in the sensitivity analyses for Noah have included fluxes of sensible heat, latent heat, and ground heat; ground temperature, and soil water content of the first soil layer (Bastidas et al., 2006; Rosero et al., 2010). In these studies, the examined default soil parameters always included MAXSMC, SATDK, and BB, while other parameters were included sporadically, such as DRYSMC, SATPSI, SATDW, and QTZ. The parameters MAXSMC and BB were commonly found to be the most influential parameters directly affecting the surface soil moisture estimates in various degrees in different Noah schemes. In addition, the parameter SATPSI was also found to be significant in case of using Noah LSM augmented with a phenological modeling scheme (Rosero et al., 2010). The other soil parameters were found significant only through interactions (Bastidas et al., 2006; Hogue et al., 2006; Rosero et al., 2010). The geographical differences in the model outcomes, however, may also originate from differences in the raster input data including the CONUS-SOIL database. In Noah land surface modeling, the gridded soil information of the land surface is provided by using only the top layer of the CONUS-SOIL raster (Miller and White, 1998, White and Miller, 1998). This information of the top layer is used homogeneously throughout the soil profiles. The results from the above studies suggest the need for improving the parameterization of soil properties and processes in the Noah LSM for advanced simulation of water and energy fluxes.

The reason for this study is two-fold. First, atmospheric chemistry transport and meteorological models coupled with the Noah LSM needs to be improved by considering better soil parameter values. Second, increasing amounts of soil data are becoming available through the USDA-NRCS, but the soil parameters in the default table of the Noah LSM have not been updated for more than 25 years. Thus, the need to investigate the agreement of the default table for soils using abundantly measured soil data was the rationale for this study. Specifically, the analysis focused on a soil data set typical for Texas. The hypothesis was that some soil parameters may differ for Texas from the default soil parameters. Therefore, the objectives were (i) to identify default soil parameter values used by the Noah LSM that differ from pertinent soil hydraulic parameter values characteristic for Texas, and (ii) to demonstrate the spatial variability of selected soil parameters across Texas for the same soil texture. Categories of Organic material, Water, Bedrock, 'Other (land-ice), Playa, and White sand, and parameter QTZ are out of the scope of this project because no soil characterization data or insufficient number of samples are available. This paper will be followed by another publication reporting on evaluation of 1-D Noah-MP simulation results with using default and revised soil parameters.

2. Materials and methods

2.1. Study Area

To investigate the default table and its relevance to Texas, soil samples were selected that are characteristic of conditions in the state of Texas and adjacent areas in New Mexico, Oklahoma, Kansas, and Louisiana where major land resource areas (MLRAs) extend across borders. MLRA

units are defined as geographically associated land resource units that are dominated by similar conditions including bedrock and surficial geology, climate, hydrology, physiography, soils, biological resources, and land use (USDA-NRCS, 2006). The study area is depicted in Fig. 1. The area coverage of the MLRAs are listed in Table 3. These 16 MLRA units represent a broad range of geology, geography, hydrology, pedology, and vegetation conditions. The total area of these 16 units covers 1,021,996 km².

2.2. Data description

For Texas and adjacent areas, soil data related to the default soil parameters were obtained from the National Cooperative Soil Survey, National Cooperative Soil Characterization Database (USDA-NRCS) representing readiness by June, 2012 and available online at <http://ncsslabsdatamart.sc.egov.usda.gov/>. Additional data (0.4% of the total) were obtained from the Texas A&M AgriLife Soil Characterization Database, which applies the NRCS procedures for soil characterization and analysis. To fill in missing texture class information in some records, the USDA texture class was calculated from particle size distribution.

Soil records were selected that had measurements of percent clay, percent silt, percent sand; water content at air dry, -1500 kPa (permanent wilting point), and at -33 kPa (field capacity); and soil bulk density measured at -33 kPa (labeled BD from now on). Soil samples were included only from A, B, C, and E horizons. Samples from bedrock, organic horizons, cemented horizons (by carbonates, iron, and gypsum), and highly gypsiferous horizons were excluded because their characteristics are atypical in Texas.

For spatial replicates, when very different spatial replicates were found, one of the records was retained from the data set selected based on similarity to the surrounding samples. The final data set used in the study contained 6,749 soil records from about 850 profiles, summarized in Table 4 (Kishné and Morgan, 2015).

2.3. Revising the default soil parameters

Eight of the ten soil parameters included in the default table were investigated; BB, DRYSMC, MAXSMC, REFSMC, SATPSI, SATDK, SATDW, and WLTS MC, with exception of QTZ and F11. Parameter F11 was not evaluated because of its uncertain definition and unclear role in the Noah codes. QTZ was not evaluated due to missing soils data.

Soil parameter values were determined based on percent clay, silt, sand, bulk density, and soil water content at oven dry, air dry, and -33 kPa matric potential (Table 5). For those parameters that did not have measured values in the database, selected pedotransfer functions (PTFs) were included that are empirically fitted and theoretical models developed for the U.S. (Table 5).

Soil texture is commonly used to characterize the water-holding characteristics of most agricultural soils (Saxton et al., 1986). In addition, soil bulk density is a reliable, widely measured variable in the NRCS database; it was used to estimate porosity (MAXSMC). Other variables, such as organic matter (OM) and mineralogy, are also considered to be influential factors, but were not included in this analysis because of too few data. Pedotransfer functions from two published and widely applied studies, Cosby et al. (1984), and Saxton et al. (1986), have been considered here. Both studies were based on soil samples collected from different regions of the U.S., including a few samples from Texas. The estimation of SATPSI, MAXSMC

and BB values as a function of matric potential (PSI) and water content (SMC) in both studies were based on the model by Brooks and Corey (1964, 1966) and modified by Campbell (1974) referenced by Clapp and Hornberger (1978) as shown in Eq. 1.

$$PSI = SATPSI \left(\frac{SMC}{MAXSMC} \right)^{-BB}. \quad (1)$$

To reduce modeling errors, combining prediction outcomes of various independent models, i.e. multimodel simulations, have been suggested and used (e.g., Guber et al., 2006; 2009; Guber and Pachepsky, 2010), however, calibration and choosing the appropriate weights for each pedotransfer functions are challenging, as pointed out by Minasny et al. (2013). Although multimodeling with pedotransfer functions has been shown advantageous, the different model results were not combined in this study because applicability of the model by Saxton et al. (1986) was not valid for large areas of Texas since it excluded samples from areas with great or very small clay, silt, and sand contents. Thus, parameter values estimated by using PTFs of Saxton et al. (2006) are presented only for visual comparison in the figures. In revising the default soil parameters, the means estimated by PTFs according to Cosby et al. (1984) and Chen and Dudhia (2001) were used because they cover the full range of soil conditions in Texas. As indicated before, Table 5 lists all models used for estimating the parameters representing 12 USDA NRCS texture categories. Basic statistics of soil characteristics of all original soil samples, and revised parameters are reported in Kishné and Morgan (2015).

2.4. Testing of significant difference

For testing differences of parameter means grouped by texture category and MLRA, t-tests with 95% confidence levels were applied using MatLab Statistical Tool (version R2012b The MathWorks, Inc). Because normality is required for valid statistical testing of the means, data sets within groups with sample numbers greater than 60, and skew less than 1 and greater than -1, the mean of original values was calculated. For highly skewed data, values were log transformed prior to testing. In some cases, extreme values were identified and truncated to achieve approximately normal distribution. In these cases, the smaller number of samples is indicated in the tables of summary statistics. In cases of log-transformed data, the statistical testing was performed by using log-transformed default parameter values. All results were reported as back-transformed data.

For silt texture class, that is rare in nature, especially in Texas, very little data is available, and too few for conducting statistical testing.

2.5. Evaluating the modified default soil parameters

To check some of the proposed changes to the default soil parameters on the soil water content that is an important output of the LSMs, parameters BB, MAXSMC, and SATPSI were used to estimate water retention functions including soil water content values at field capacity and permanent wilting point rearranging Eq. 1 as it follows,

$$SMC = MAXSMC \left(\frac{PSI}{SATPSI} \right)^{-1/BB}. \quad (2)$$

The means and standard deviations of measured soil water contents and estimated soil water contents based on default and revised soil parameters were compared to measured soil water contents at field capacity and permanent wilting point for the 12 soil texture classes.

2.6. Demonstrating the regional spatial variability of selected soil parameters

The spatial variability of soil parameters are demonstrated in two ways for Texas. First, top soil data with spatial coordinates were presented according to soil texture categories and MLRAs. Because the sample numbers were too few for a spatial statistical analysis, only trends were demonstrated by using means and standard deviations of selected parameters (BB, SATPSI) for three dominant soil texture classes (sandy loam, loam, and clay). Parameters BB and SATPSI were selected due to their significant impacts on Noah model outcomes found in sensitivity analyses studies (Bastidas et al., 2006; Rosero et al., 2010).

Second, raster data of top 5-cm soils from the CONUS-SOIL data set (Miller and White, 1998; White and Miller, 1998) was used to illustrate the spatial variability of parameters BB and SATPSI. Cell-by-cell, these parameters were estimated from percent clay and percent sand, respectively, using relevant models listed in Table 5. The CONUS-SOIL data set was developed based on the first version of the State Soil Geographic Database (STATSGO, USDA NRCS, 1992) to serve regional climate and hydrological models. The soil grid has a spatial resolution of 30 second, and vertically divided into 11 layers down to 2.5 m with uniform layer depths at each grid point. Within each grid cell, aggregated percent clay and percent sand values were computed by weighted averaging the STATSGO map unit components based on the component (%) contributions provided in the STATSGO database (Miller and White, 1998; White and Miller,

1998). The CONUS-SOIL database has been widely applied in numerous atmospheric and land surface models without a change since it was first developed.

3. Results and discussion

3.1. Results of revised soil parameters

For each default soil parameter analyzed, the findings on significantly different means of soil parameters are presented in Table 6. For soils in Texas, the new values of parameter BB were found to be significantly different from the default values for 10 out of 12 texture categories, except clay loam and clay (Table 6). In these two categories, the differences between the default and new values were less than 1% of the default values. The largest variation of parameter BB is in clay soils with average standard deviation of 1.62, 14% of the mean (Fig. 2a), however it is less than the standard deviation published by Cosby et al (1984). Moreover, standard deviations in the other categories are also smaller. Although differences between the default and revised values do not seem too large across texture classes, the differences may still strongly impact the model results of the Noah LSM because of the role of parameter BB as an exponent in the soil moisture release function. The sensitivity analyses study conducted by Rosero et al. (2010) showed a strong dependence of Noah model output on this parameter. Values of BB estimated using by Saxton et al. (1986) are greater than the default and revised values for sandy soils (sand, loamy sand, sandy loam), but smaller for soils with fine texture from silty clay loam through clay. This effect is probably a result of the boundary condition used by Saxton et al. (1986) that

excluded samples with high or very small contents of clay, silt, and sand from the model development.

The revised values of the SATPSI parameter were found to be significantly different from the default table in all texture classes (Table 6). In general, default SATPSI values for silt loam and for silt were rather high compared to the revised values (Fig. 2b). The default values of SATPSI in these classes are greater than the recently estimated values by 90% and 34%, respectively. Thus, a large bias is expected in partitioning precipitation between runoff and infiltration as well as drainage simulations while using the default SATPSI values for areas dominated by silt loam and silt soil. This finding is also supported by the lower SATPSI values in Saxton et al. (1986) which are also 40% and 74% less than the default values in silt loam and silt, respectively. Overall, there is no general trend of revised and SATPSI by Saxton et al. (1986) being larger or smaller than the default values. While the estimates by Saxton et al. (1986) showed a smooth trend of increasing with finer textures, the revised values were similar to the default values in coarse textures, but smaller usually in medium, and larger in fine textures. Representing the air entry potential of the soil, a critical value of desaturation, the estimated values of SATPSI confirm the general trend indicated by Hillel (1998) in that it is the smallest in coarse-textured and well-aggregated soils and tends to be greater in medium-textured or in fine-textured soils. More research is sought to determine if SATPSI estimates calculated based on Saxton et al. (1986) might provide more realistic results than the currently revised values.

Parameter SATDK values were significantly different from the default values in all soil texture categories (Table 6). The greatest difference, more than 20-times, was found in sand. This finding was supported by the values estimated following Saxton et al. (1986) (Fig. 3a). The revised value of parameter SATDK portrays much faster water movement in sandy soils than

what is predicted by the current default parameter value. In Noah-MP, the SATDK value for sand is $4.66 \times 10^{-5} \text{ m s}^{-1}$ deviating from the default value $1.07 \times 10^{-6} \text{ m s}^{-1}$, but it is the same as the value published in Cosby et al. (1984). Our finding of $2.4 \times 10^{-5} \text{ m s}^{-1}$ SATDK supports the trend of much greater SATDK than the default value for sand. Although all values of hydraulic conductivity are different significantly from their corresponding default values, the differences are much less dramatic for finer textured soil than for coarser textured soil.

The revised values for parameter SATDW (Table 6) were estimated from the revised values of parameters BB, MAXSMC, SATPSI, and SATDK using the equations listed in Table 5, resulting in a smaller overall variability of hydraulic diffusivity across textures compared to the default values (Fig. 3b). For sand, the magnitude of revised SATDW is 16 times greater than the default value. In contrast, the revised value of SATDW was 2.4-times less for silt loam than the default value. Parameter SATDW values were significantly different from the default values in all soil texture categories.

The revised MAXSMC values were significantly different for 10 soil textures, excluding loam and silty clay (Table 6). Nonetheless, variation of revised MAXSMC values among textures was rather small, ranging between 0.39 and $0.49 \text{ m}^3 \text{ m}^{-3}$. In addition, the standard deviation was also homogenous (0.021 to $0.033 \text{ m}^3 \text{ m}^{-3}$) and smaller than the ones published by Cosby et al. (1984) in sand, loamy sand, sandy loam, loam, clay loam, and silty clay categories. The revised MAXSMC values were more uniform than the default values and the ones calculated based on Saxton et al. (1986).

Parameter REFSMC values showed coherence within texture classes with standard deviations less than or equal to 6% of average volumetric water content (Fig. 4a). All values were significantly different from the default values in the 11 texture classes examined statistically

(Table 6). The greatest differences were found in the coarser soil textural classes, where the revised REFSMC values were less than the default values by up to $0.24 \text{ m}^3 \text{ m}^{-3}$. The average measured REFSMC values in loamy sand, sandy loam and silt are 62%, 44% and 10% less, respectively, than the corresponding default values, although those deviate from the original values (0.283 , 0.312 , $0.360 \text{ m}^3 \text{ m}^{-3}$, respectively) published by Chen and Dudhia (2001). Consequently the use of the current default values of REFSMC may contribute to strong overestimation of plant available water primarily in coarse-textured soils.

Values of revised WLTS MC showed significant differences between the mean WLTS MC values by texture from the default values (Table 6). The magnitudes of the differences were rather small in sandy soils but increased across texture classes up to a more than two-fold increase for fine-textured soil (Fig. 4b). Soil water content at permanent wilting point is used in Noah land surface modeling as the lower threshold for calculating potential plant available water content, i.e. the difference between REFSMC and WLTS MC, and the total available water content, i.e. the difference between MAXSMC and WLTS MC. Thus, its impact on model outcomes is usually stronger in calculating water stress for stomatal conductance for transpiration, hence latent heat flux.

The revised parameter DRYSMC values were significantly and consistently smaller than the default values (Table 6) that are the same as the corresponding WLTS MC values (Chen and Dudhia, 2001). The revised parameter values reflect that soils could dry to a lower threshold (air dry) which is less than the WLTS MC. In the Noah LSM, using DRYSMC instead of WLTS MC as the lower threshold in the direct evaporation calculation would increase total available water contents for direct evaporation in all texture classes.

In consequence that total available and potential plant available water contents are estimated in Noah land surface modeling based on MAXSMC, REFSMC, and WLTSMC as described above, the changes in these parameters would yield changes in total available and potential plant available water content estimates as illustrated in Fig. 5a and Fig. 5b, respectively. Due to changes in both MAXSMC and WLTSMC, total available water contents are 35-76% lower than predicted by default parameter values (Fig. 5a) for all classes except sand as discussed above. Similarly, changing REFSMC and WLTSMC strongly decreases potential soil water available for plants to transpire in all 12 soil texture categories (Fig. 5b). For example, if we assume that the soil is 200 cm deep (no shallow bedrock or root limiting horizon), water available to plants will decrease from 50 to 36 cm for medium texture.

In summary, of the proposed changes in the soil parameter values, 84 out of 88 parameter values (95%) from the investigated default soil parameters of the Noah LSM were found to be significantly different for Texas. These changes could significantly affect water and energy flux outputs simulated by the Noah model (e.g. Rosero et al., 2010; Breuer et al., 2012a; Zhang et al., 2014). Consequently, this would then affect the weather forecast and air quality modeling outputs that depend on the Noah LSM providing the lower boundary conditions. For example, Breuer et al. (2012a) showed up to 25% deviations in PBL as a result of differences in soil hydraulic parameter values in the Pannonian Plain. These authors also observed the sensitivity of PBL height to soil water content at field capacity and wilting point. Likewise, predictions of air temperature, wind, and pollutant concentration may be sensitive to variations in initial soil moisture contents by only 4% (Jacobson, 1999). Note that in our study, the differences in field capacity and permanent wilting point between the two parameter tables could reach up to $0.24 \text{ m}^3 \text{ m}^{-3}$ and $0.15 \text{ m}^3 \text{ m}^{-3}$, respectively. This will also have a greater effect on the soil moisture

initialization. Hence, we anticipate the impact of improvement in soil parameter values on weather forecasting and air quality modeling outputs through their effects on the estimating surface water content and energy flux partitioning.

3.2. Evaluation of the revised default soil parameters

For evaluating modeled soil water contents at field capacity and permanent wilting point, we used the revised BB, MAXSMC, and SATPSI parameter values to estimate the soil-water retention curve. The results indicated good agreement between estimated soil water contents and mean measured values at field capacity and permanent wilting point in 11 texture classes (Fig. 6), except in sandy clay. For these 11 soil textural classes, the estimated soil water contents were within the ranges of standard deviations around the means in 95% of the cases. For sandy clay there were only 69 soil samples in Texas, and the data sets of estimated BB and SATPSI parameters were strongly skewed. Increasing sample size in this category may improve the estimation of BB and SATPSI parameters, and consequently the estimation of soil water content. This indicates the strong agreement among soil hydraulic properties and processes when using the revised parameter values compared to the default table.

Moreover, the WLTSMC, REFSMC, and MAXSMC parameters revised for Texas were comparable with the values reported by Rawls et al. (1982), which were created by using measured data from 32 states in the US. Depending on the soil textural class, the difference between WLTSMC values in the revised soil parameter table and the Rawls et al. (1982) ranged from 0 to $0.02 \text{ m}^3 \text{ m}^{-3}$; whereas, the difference ranged from 0.02 to $0.26 \text{ m}^3 \text{ m}^{-3}$ when the Rawls et al. (1982) table was compared with the default soil parameter table. The REFSMC was within

0.03 m³ m⁻³ of the Rawls et al. (1982) values for the revised table compared to up to 0.18 m³ m⁻³ for the default table. Similarly, the MAXSMC was within 0.04 m³ m⁻³ of the Rawls et al. (1982) values for the revised case compared to up to 0.10 m³ m⁻³ for the default case. This comparison with Rawls et al. (1982) indicates that these revised soil parameters are better predictors of soil properties for the conterminous US than the default soil parameter values. This finding is important because these parameters are used in estimation of the total available and potential plant available water content.

3.3. Regional spatial variability of selected default soil parameters

Regional and temporal variation of the model responses is expected based on the outcomes of sensitivity analyses (Bastidas et al., 2006; Hogue et al., 2006; Rosero et al., 2010). For this study, spatial variability of default soil parameters was demonstrated for BB and SATPSI parameters. General trends of variability of these parameters were shown across MLRAs. Table 7 summarizes the number of georeferenced data points available according to MLRAs. Spatial variability between Major Land Resource Areas ranged up to 30% for parameter BB (Fig. 7), and up to 65% for parameter SATPSI for sandy loam, loam and clay textures (Fig. 8). The spatial variability of default parameters implies that parameters could substantially vary across MLRAs, even if they have the same textural classes. For example, the SATPSI varies greatly in the clay texture class (Fig. 8b).

For a more spatially continuous demonstration, we used the gridded CONUS-SOIL data (Miller and White, 1998; White and Miller, 1998) to illustrate BB and SATPSI. Figure 9 shows the variability of BB within the same soil textural class. For example, for the class, clay, percent

clay varies from a 40 to 85. This large difference in percent clay results in a significant difference in BB (Fig. 9). Similarly, SATPSI varies spatially for the same soil textural classes (Fig. 10).

In addition to this horizontal variability, vertical variability is also likely to occur because of vertical changes in organic matter, mineralogy, texture, and structure due to soil horization. It is anticipated that taking into account horizontal and vertical spatial variability of soil parameters in Noah land surface modeling will improve the simulation of soil water and consequently the simulation of water flow, soil temperature, and energy exchange. We recommend evaluation of the model responses of the WRF model coupled with the Noah LSM while using the current and the revised default tables. Differences in the default soil parameters may yield significantly different simulations of the planetary boundary layer (Breuer et al., 2012b) and precipitation (Ács et al., 2010, 2015), thus significant impacts on model results of air quality and land-atmosphere interactions are possible in association with the revised parameter values.

Considering the sensitivity of Noah LSM to BB and SATPSI (Rosero et al., 2010), the uncertainty associated with parameters values in the lookup table could be significant. Currently there is more detailed soil information than what is being used by the Noah LSM. Close collaboration of modelers with soil scientists, as indicated by Wood et al. (2011), may yield a better representation of the soil system in the LSMs for an improved simulation of water and energy fluxes. Moreover, computational advances achieved recently in hyper-resolution modeling may provide the necessary framework and processing efficiency (Kollet et al., 2010; Singh et al., 2015).

Further studies are warranted to explore possibilities of changing Noah codes. The desirable change in codes is three-fold. First, vertical variability of soil profiles should be accommodated

instead of treating soils as homogenous by using the texture of the top horizon applied throughout the whole soil profile (Mirus, 2015). Second, important soil parameters should be estimated considering spatial variability of percent soil textural fractions in hyper-resolution (Singh et al., 2015; Wood et al., 2011), rather than using one value for a given soil texture category over an extended region. Current updates to the CONUS-SOIL, such as POLARIS, should address the need for spatially variable soil parameters (Chaney et al., 2016). Finally, the uncertainty associated with soil complexity in the LSM needs to be addressed.

4. Conclusions

In this study, we have reviewed the development and the use of default soil parameters of the Noah LSM. These parameters have been evaluated against soil data characteristic for Texas. In addition, spatial variability of soil parameters BB and SATPSI was demonstrated in selected texture categories (sandy loam, loam, clay) based on surface soil data points across MLRAs and gridded data of CONUS-SOIL. The findings indicated the following:

- The default soil parameters were significantly different from real soil conditions represented by soil samples in Texas in 84 of 98 examined cases (95%). Revised default parameters were suggested to obtain more accurate and representative Noah model outcomes.
- The revised BB, MAXSMC, and SATPSI values yielded improvement in modeling of retention curves as indicated by better agreement with estimated soil water and measured values of soil water contents at field capacity and permanent wilting point.
- Revised parameters REFSMC, WLTSMC, and DRYSMC that were estimated based on measured soil data were suggested to replace current default values. The revised REFSMC,

WLTSMC, and MAXSMC values provide a closer fit to parameters developed based on the nation-wide data set by Rawls et al. (1982) than the default Noah soil parameters. Changing REFSMC and WLTSMC may yield smaller amounts of the total available soil water and water potentially available for plants.

- Spatial variability across MLRAs of the soil parameters BB and SATPSI was demonstrated in the sandy loam, loam and clay texture classes. The spatial variability ranged up to 30% for parameter BB and up to 65% for parameter SATPSI in the representative texture categories.
- Similarly, we observed a large variation in BB and SATPSI within the same surface soil textural classes in CONUS-SOIL grids.
- Further modifications to the NOAH codes were suggested to accommodate representation of vertical and horizontal variability of soils, to estimate important soil parameters on a cell-by-cell basis, to update the CONUS-SOIL database, and to include uncertainty estimates related to spatial variability of soil hydraulic parameters.

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Table 1. Default soil parameter table of the Noah LSM.

Category Type	BB	DRYSMC	F11	MAXSMC	REFSMC	SATPSI	SATDK	SATDW	WLTSMC	QTZ
		$\text{m}^3 \text{m}^{-3}$	$\text{m}^2 \text{s}^{-1}$	$\text{m}^3 \text{m}^{-3}$	$\text{m}^3 \text{m}^{-3}$	m	m s^{-1}	$\text{m}^2 \text{s}^{-1}$	$\text{m}^3 \text{m}^{-3}$	g g^{-1}
Sand	2.79	0.010	-0.472	0.339	0.236	0.069	1.07E-06	6.08E-07	0.010	0.92
Loamy sand	4.26	0.028	-1.044	0.421	0.383	0.036	1.41E-05	5.14E-06	0.028	0.82
Sandy loam	4.74	0.047	-0.569	0.434	0.383	0.141	5.23E-06	8.05E-06	0.047	0.60
Silt loam	5.33	0.084	0.162	0.476	0.360	0.759	2.81E-06	2.39E-05	0.084	0.25
Silt	5.33	0.084	0.162	0.476	0.383	0.759	2.81E-06	2.39E-05	0.084	0.10
Loam	5.25	0.066	-0.327	0.439	0.329	0.355	3.38E-06	1.43E-05	0.066	0.40
Sandy clay loam	6.66	0.067	-1.491	0.404	0.314	0.135	4.45E-06	9.90E-06	0.067	0.60
Silty clay loam	8.72	0.120	-1.118	0.464	0.387	0.617	2.04E-06	2.37E-05	0.120	0.10
Clay loam	8.17	0.103	-1.297	0.465	0.382	0.263	2.45E-06	1.13E-05	0.103	0.35
Sandy clay	10.73	0.100	-3.209	0.406	0.338	0.098	7.22E-06	1.87E-05	0.100	0.52
Silty clay	10.39	0.126	-1.916	0.468	0.404	0.324	1.34E-06	9.64E-06	0.126	0.10
Clay	11.55	0.138	-2.138	0.468	0.412	0.468	9.74E-07	1.12E-05	0.138	0.25
Organic material	5.25	0.066	-0.327	0.439	0.329	0.355	3.38E-06	1.43E-05	0.066	0.05
Water	0	0	0	1	0	0	0	0	0	0.60
Bedrock	2.79	0.006	-1.111	0.200	0.17	0.069	1.41E-04	1.36E-04	0.006	0.07
Other (land-ice)	4.26	0.028	-1.044	0.421	0.283	0.036	1.41E-05	5.14E-06	0.028	0.25
Playa	11.55	0.030	-10.472	0.468	0.454	0.468	9.74E-07	1.12E-05	0.030	0.60
Lava	2.79	0.006	-0.472	0.200	0.17	0.069	1.41E-04	1.36E-04	0.006	0.52
White sand	2.79	0.010	-0.472	0.339	0.236	0.069	1.07E-06	6.08E-07	0.010	0.92

Table 2. Definitions, units, and source of parameter values listed in the default table.

Parameter	Definition	Unit	Source†
BB	Parameter “b” in hydraulic functions relating water potential and volumetric water content	dimensionless	1, 4, 5, 6, 7
DRYSMC	Soil water content threshold for ceasing evaporation from top soil layer	volume volume ⁻¹	7
F11	Unclear definition and unit, but indicated as soil thermal diffusivity or conductivity coefficient	m ² s ⁻¹	7, 8, 9
MAXSMC	Soil water content at saturation or soil porosity	volume volume ⁻¹	1, 4, 5, 7
REFSMC	Soil water content at field capacity	volume volume ⁻¹	4, 5
SATPSI	Saturation matric potential or air entry water potential	m	1, 4, 7
SATDK	Saturated hydraulic conductivity	m s ⁻¹	1, 4, 5, 7
SATDW	Saturated hydraulic diffusivity	m ² s ⁻¹	4, 5
WLTSMC	Soil water content at wilting point	volume volume ⁻¹	4, 5, 7
QTZ	Quartz content	weight weight ⁻¹	2, 6, 7
Category Type	Soil texture and other land surface classes	none	3, 4, 6, 7

†Numbers indicating the source:

1	<i>Cosby et al.</i> , 1984	4	<i>Chen and Dudhia</i> , 2001	7	<i>Niu</i> , 2011
2	<i>Peters-Lidard et al.</i> , 1998	5	<i>Duan et al.</i> , 2001	8	<i>NCEP</i> , 2003
3	<i>Miller and White</i> , 1998	6	<i>Kumar et al.</i> , 2010	9	<i>Ingwersen et al.</i> , 2011

Table 3. Major land resource areas in Texas and adjacent territories.

Code	Major Land Resource Areas in Texas	Area (km²)
42	Southern Desertic Basins, Plains, and Mountains	147,355
70	Canadian River Plains & Valleys, Upper Pecos River Valley, Central New Mexico Highlands	92,483
77	Southern High Plains	142,033
78	Rolling Limestone Prairie, Central Rolling Red Plains	112,497
80	Central Rolling Red Prairies, Texas North-Central Prairies	67,660
81	Edwards Plateau	102,644
82	Texas Central Basin, Wichita Mountains	7,815
83	Northern, Western, Central, and Lower Rio Grande Plain	82,038
84	Cross Timbers	39,488
85	Grand Prairie	26,675
86	Texas Blackland Prairie	45,817
87	Texas Claypan Area	39,902
133	Western Coastal Plain	117,380
150	Gulf Coast Prairies, Gulf Saline Coast Prairies	51,390
151	Gulf Coast Marsh	7,216
152	Western Gulf Coast Flatwoods	14,160

Table 4. Summary statistics of original soil properties reported for 6,749 soil samples used for overall parameter testing.

Statistics	Clay	Silt	Sand	Soil Water at -1500 kPa	Soil Water at -33 kPa	Air Dry/ Oven Dry Soil Water	Bulk Density
	-----%			-----		dimensionless	Mg m ⁻³
Min	0	0.3	0	0.3	1.4	1	0.79
Max	88.3	84.1	99.3	38.8	58.1	1.244	2.29
Mean	29.6	30.3	40.1	12.5	21.8	1.027	1.47
Median	28.2	30.1	38.4	11.6	21.1	1.022	1.47
SD	17.1	15.4	25.5	7.0	9.2	0.026	0.17
Skew	0.5	0.2	0.3	0.6	0.5	3.6	-0.1
Kurtosis	-0.2	-0.5	-0.9	0.0	0.2	21.2	0.2

Table 5. Models used for estimating values for the revised soil parameters.

Parameter	Unit	Model	Reference
BB	-	$2.91 + 0.159 * \text{Clay}$	<i>Cosby et al., 1984</i>
DRYSMC	$\text{m}^3 \text{m}^{-3}$	$\text{AD} * \text{BD} * 100^{-1}$	
MAXSMC	$\text{m}^3 \text{m}^{-3}$	$(1 - \text{BD}) * 2.65^{-1}$	<i>Cosby et al., 1984</i>
REFSMC	$\text{m}^3 \text{m}^{-3}$	$\text{W}_{\text{FC}} * \text{BD} * 100^{-1}$	<i>Cosby et al., 1984</i>
SATPSI	m	$10^{\text{Log}(1.88 - 0.13 * \text{Sand})} / 100$	<i>Cosby et al., 1984</i>
SATDK	m s^{-1}	$10^{(0.884 + 0.0153 * \text{Sand})} * 0.0254 /$ 3600	<i>Cosby et al., 1984</i>
SATDW	$\text{m}^2 \text{s}^{-1}$	$\text{SATDK} * \text{SATPSI} * \text{BB} * \text{MAXMSC}^{-1}$	<i>Chen and Dudhia, 2001</i>
WLTSMC	$\text{m}^3 \text{m}^{-3}$	$\text{W}_{\text{WP}} * \text{BD} * 100^{-1}$	<i>Cosby et al., 1984</i>

AD is air dry soil water content, % wt; BD is bulk density at -33 kPa, $\text{Mg} / \text{m}^{-3}$; W_{FC} is field capacity soil water content, -33 kPa, % wt; Sand is sand, % wt; Clay is clay, % wt; W_{WP} is wilting point soil water content, -1500 kPa, % wt.

Table 6. The parameter values and standard deviations in parentheses derived based on soil data specific for Texas; Asterisk marks significant difference from the default parameter ($\alpha=0.05$). For silt, testing was not performed due to small sample number (N=3).

Category Type	BB	DRYSMC	MAXSMC	REFSMC	SATPSI	SATDK	SATDW	WLTSMC
		$\text{m}^3 \text{m}^{-3}$	$\text{m}^3 \text{m}^{-3}$	$\text{m}^3 \text{m}^{-3}$	m	m s^{-1}	$\text{m}^2 \text{s}^{-1}$	$\text{m}^3 \text{m}^{-3}$
Sand	3.36* (0.3)	0.004* (0.005)	0.402* (0.043)	0.086* (0.052)	0.047* (0.004)	2.40E-05* (2.7E-06)	9.36E-06* (1.5E-06)	0.024* (0.017)
Loamy sand	4.06* (0.46)	0.010* (0.010)	0.396* (0.046)	0.142* (0.064)	0.063* (0.007)	1.72E-05* (2.0E-06)	1.11E-05* (1.9E-06)	0.057* (0.022)
Sandy loam	4.85* (0.76)	0.016* (0.022)	0.413* (0.056)	0.213* (0.063)	0.105* (0.027)	1.01E-05* (2.9E-06)	1.18E-05* (2.6E-06)	0.081* (0.045)
Silt loam	5.72* (1.1)	0.023* (0.032)	0.456* (0.066)	0.303* (0.057)	0.399* (0.124)	2.20E-06* (1.6E-06)	9.99E-06* (2.1E-06)	0.123* (0.043)
Silt	4.18 (0.47)	0.010 (0.007)	0.438 (0.023)	0.346 (0.031)	0.568 (0.049)	1.30E-06 (1.3E-07)	7.78E-06 (1.3E-06)	0.064 (0.022)
Loam	6.01* (0.8)	0.022* (0.017)	0.440 (0.060)	0.274* (0.052)	0.219* (0.046)	4.12E-06* (8.8E-07)	1.20E-05* (2.3E-06)	0.128* (0.036)
Sandy clay loam	7.03* (0.62)	0.029* (0.016)	0.416* (0.054)	0.288* (0.052)	0.139* (0.028)	7.08E-06* (1.9E-06)	1.58E-05* (2.7E-06)	0.168* (0.042)
Silty clay loam	8.49* (0.55)	0.039* (0.016)	0.457* (0.054)	0.350* (0.041)	0.517* (0.074)	1.48E-06* (2.3E-07)	1.41E-05* (2.0E-06)	0.212* (0.035)
Clay loam	8.20 (0.58)	0.036* (0.018)	0.449* (0.053)	0.335* (0.048)	0.288* (0.062)	3.02E-06* (7.5E-07)	1.52E-05* (2.3E-06)	0.196* (0.038)
Sandy clay	8.98* (0.49)	0.037* (0.023)	0.425* (0.045)	0.355* (0.049)	0.171* (0.020)	5.13E-06* (9.3E-07)	1.93E-05* (2.2E-06)	0.239* (0.031)
Silty clay	10.24* (0.72)	0.052* (0.022)	0.467 (0.50)	0.392* (0.046)	0.588* (0.081)	1.27E-06* (2.1E-07)	1.61E-05* (1.9E-06)	0.264* (0.041)
Clay	11.56 (1.62)	0.058* (0.027)	0.506* (0.052)	0.428* (0.054)	0.483* (0.149)	1.66E-06* (757E-07)	1.74E-05* (1.8E-06)	0.285* (0.047)

Table 7. Numbers of georeferenced top soil samples grouped by MLRAs and texture categories.

Texture Category	Texture Code	MLRA																N
		42	70	77	78	80	81	82	83	84	85	86	87	133	150	151	152	Total
S	1	4	0	14	10	0	0	1	7	0	0	0	1	2	3	0	2	44
LS	2	5	0	14	3	1	0	3	8	4	0	0	2	11	4	0	1	56
SL	3	11	0	35	14	10	0	7	20	6	1	2	7	47	21	0	2	183
SiL	4	6	0	7	18	13	1	0	1	0	1	0	0	16	5	0	1	149
Si	5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
L	6	8	0	23	19	9	1	1	2	4	10	1	2	10	8	0	0	83
SCL	7	3	0	9	1	0	0	0	12	1	0	1	0	3	12	0	0	42
SiCL	8	5	0	11	8	6	3	0	3	2	2	1	1	2	4	0	0	48
CL	9	5	0	15	5	3	3	0	6	0	6	1	2	3	5	0	0	54
SC	10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SiC	11	1	0	1	3	4	2	0	0	0	3	2	1	2	5	0	0	24
C	12	2	0	20	3	2	0	1	14	0	1	6	2	6	17	0	0	74
Total		50	0	149	84	48	10	13	73	17	24	14	18	103	84	0	6	693

Figure captions

Fig. 1. Study area covering Texas and adjacent areas where MLRAs extend across the border.

Fig. 2. Parameters a) BB and b) SATPSI including the default and revised values, and values determined based on Saxton et al. (1986). Bars on the revised symbols represent the stand deviation. The letters indicate texture classes as it follows: sand (S); loamy sand (LS); sandy loam (SL); silt loam (SiL); silt (Si); loam (L); sandy clay loam (SCL); silty clay loam (SiCL); clay loam (CL); sandy clay (SC); silty clay (SiC); clay (C).

Fig. 3. Parameters SATDK and SATDW including the default and revised values, and values determined based on Saxton et al. (1986) labeled SA1986. Bars on the revised symbols represent the stand deviation. The letters indicate texture classes as described in the figure caption of Fig. 2.

Fig. 4. Parameters REFSMC and WLTSMC including the default and revised values. Bars on the revised symbols represent the stand deviation. The letters indicate texture classes as it is described in the figure caption of Fig. 2.

Fig. 5. Difference in a) total available water; b) potential plant available water calculated based on the default and revised soil parameters.

Fig. 6. Water retention curves developed by using default and proposed soil parameters BB, MAXSMC and SATPSI. In addition, default and measured values of parameters REFSMC and WLTS MC are displayed. Error bars represent standard deviations. In the cases when data are skewed, means and standard deviations were back-transformed.

Fig. 7. Spatial variation of parameter BB in selected texture categories across Major Land Resource Areas (MLRAs) in Texas based on data of top soil samples recorded with coordinates; a) means of BB values with standard deviations as error bars and default values indicated by dashed lines; b) differences between the means of BB from the default values in texture categories for MLRAs.

Fig. 8. Spatial variation of parameter SATPSI in selected texture categories across Major Land Resource Areas (MLRAs) in Texas based on data of top soil samples recorded with coordinates; a) means of SATPSI values with standard deviations as error bars and default values indicated by dashed lines; b) difference of means of SATPSI in a texture class and MLRA from the default values.

Fig. 9. Maps of parameter BB of top soils in selected USDA soil texture categories computed from percent clay in CONUS-SOIL raster database. It is presented in NAD 1983 Texas Centric Mapping System Albers coordinate system. The four classes in the legend (from smallest to largest) are: minimum to mean-1SD, mean-1SD to mean, mean + 1SD, and mean +1SD to maximum.

Fig. 10. Maps of parameter SATPSI of top soils in selected USDA soil texture categories computed from percent Sand stored in CONUS-SOIL raster database. It is presented in NAD 1983 Texas Centric Mapping System Albers coordinate system. The four classes in the legend (from smallest to largest) are: minimum to mean-1SD, mean-1SD to mean, mean + 1SD, and mean +1SD to maximum.

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