White paper:

Danish Soil Map for SWAT+

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Background

Hydrological modelling plays a crucial role in understanding the processes within watersheds, where interactions between the water cycle, ecological systems, and human activities affect both the quantity and quality of water resources (Tan et al., 2020). Therefore, hydrological models can support watershed managers and policymakers by offering valuable insights to address environmental challenges (López-Ballesteros et al., 2023). However, the performance of hydrological models is rendered by the characteristics and accuracy of the input data they are based upon, and hydrological models typically requires inputs, such as climate, topography, land use, and soil data. These input data can be obtained from local or global datasets, depending on their availability for an area of interest. Model practitioners typically have to choose between utilizing readily available global datasets, with a relatively coarse resolution or trying to compile locally data with finer resolution and detail. Having local data is by default the better option, but often time or availability limits this choice.

Accurate and representative information on soil texture and soil properties is crucial for proper crop and land management and environmental studies (Adhikari et al., 2013), and it is well recognized that the spatial resolution of this particular data greatly affects the hydrological processes within a watershed. Consequently, using low-resolution soil data can lead to increased uncertainty in hydrological model outputs. For the Soil and Water Assessment Tool (SWAT +), one of the most widely used and comprehensive hydrological models worldwide (Arnold et al. 1998, Gassman et al., 2014), several efforts have been used over time to establish fine resolution global soil maps and databases tailored to provide model specific hydrological properties. Until recently, two main soil products were available at global level: the Digital Soil World Map (DSWM; FAO-UNESCO, 2003) and the Harmonized World Soil Database (HWSD; FAO/IIASA/ISRIC/ISS-CAS/JRC, 2012). However, both soil maps feature relatively coarse spatial resolutions—approximately 5 km (9 km at the equator) for the DSWM and around 1 km for the HWSD. Additionally, the soil profiles in both global databases are simplified into just two horizons: topsoil and subsoil. Each of these horizons represents a largely homogeneous soil layer defined by upper and lower depth boundaries (Hengl and MacMillan, 2019).

In 2019 Hengl et al. created a new and ground-breaking soil map with a resolution of 250m and soil classes and properties for the entire globe (except Antarctica). The soil map was compiled using 3D machine learning algorithms spanning six standard depths (up to 2 m) based on the largest number of soil profile observations worldwide (over 350,000 training points). Furthermore, the soil map – called Open Land Map (OLM), is open access and are available at https://openlandmap.org/. In 2023, López-Ballesteros et al. adopted the OLM dataset and made the necessary translations and parameterizations via an ensemble of pedo-transfer functions based on an approach by Abbaspour et al. (2019), to make it SWAT+ compatible. The resulting soil map and corresponding soil parameter database is called the Digital Soil Open Land Map (DSOLMap) and is open access and available here: https://www.wateritech.com/data. Although this new soil product has harmonized data effectively and increased the resolution significantly, López-Ballesteros et al. (2023) highlighted that local soil data should be selected if available.

Denmark is privileged when it comes to data coverage and availability and is one of the best mapped countries in the world. For soil, the national soil texture database holds more than one observation per km^2 (Adhikari et al., 2013). Throughout the last three decades several studies have processed and created nation-wide soil maps based on the Danish Soil Profile Database Service (which consists of soil texture data and other properties from soil profile horizons collected mainly during the 1980s, Madsen et al., 1992) and complementary soil surveys. Successively, the spatial resolution has increased along with the granularity of the depth dependent soil layer detail. Thus, resolution has improved over time, moving from The Danish Soil Classification at 1:50,000 scale (Madsen et al., 1992), to the soil surface texture maps of Denmark at spatial resolution of 250 m (Greve et al., 2007), and further to the Tekstur2014 soil map at 30.4 m spatial resolution (Adhikari et al., 2013), and latest to the Tekstur2024 with a spatial resolution of 10 m (Møller et al., 2024a,b). This latest soil map of Denmark has been derived also utilizing satellite imagery, resulting in a higher level of detail at local scale as well as information about differences in laboratory analysis-methods across the different soil profile samplings.

WateriTech was involved in the creation of the DSOLMap, by López-Ballesteros et al. (2023) and developed the core python-based framework utilized to download and extract soil information, such as sand, clay, silt and organic carbon content, bulk density, soil water content, and coarse fragment fraction, from the OLM global dataset and furthermore calculation of all other physical soil properties from an ensemble of pedo-transfer functions needed to create a SWAT+ compatible soil map and associated soil property database. WateriTech have since updated the framework to also enable processing of the new high resolution soil map of Denmark and thus the creation of a SWAT+ compatible soil map with an associated soil property database specifically for Denmark and this white paper describes the key concept.

About WateriTech & WaterWebTools

WateriTech is a research and consultancy company founded in 2019 by world leading researchers within water quality modelling and data analytics. The company is based in Denmark but offer its services and solutions globally. WateriTech specializes in the development and application of open source hydrological and ecological models, IoT sensor monitoring and advanced data analytics, and focus on digital solutions for addressing water quality, flooding and drought challenges. WateriTech and partners have developed the highly recognized WaterWebTools platform, which is a user-friendly web-platform for live streaming, quality control and postprocessing of sensor data, as well as operationalization of hydrological and water quality models for forecasting purposes. The WaterWebTools platform, which also allows transmission of data to customers own data platform or 3. party platforms, is widely used in Denmark and across Europe by the municipal and water utility sectors, private companies as well as research institutions.

Introduction

The Soil Water Assessment Tool (SWAT+) is one of the most widely used and comprehensive hydrological models worldwide (Arnold et al. 1998, Gassman et al., 2014). Even though globally available input data exists, which in principle allows model practitioners to apply the model for any watershed in the world, collection of local data can increase model accuracy and representativeness. Denmark is one of the most monitored countries in the world and decades of studies on soil texture mapping have recently resulted in a 10mx10m resolution soil map of Denmark (Møller et al., 2024a, b). However, this Danish soil map is not directly compatible with the SWAT+ model as various soil properties (especially related to hydraulic characteristics) first need to be derived and processed to form the actual soil database format accepted by SWAT+.

A key component in the framework is processing of pedo-transfer functions (Woesten et al., 1999) that utilizes texture information (such as clay, silt and sand content collected during soil surveys) to derive soil hydraulic properties like Available Water Capacity and Soil Hydraulic Conductivity.

Soil data input

The core soil dataset that serves as basis for producing the SWAT+ compatible soil map and associated database consists of raster files with a resolution of 10m x 10m that holds cell information about texture (i.e. clay, sand and silt) and soil organic carbon content as percentage in four depth intervals (1: 0-30 cm; 2: 30-60 cm; 3: 60-100 cm; 4: 100-200 cm). The dataset was prepared by Møller et al. (2024a,b) and compared to the earlier version from 2014 by Adhikari et al. (2013), the new 2024 version has a higher resolution and utilizes satellite imagery. Moreover, information on the underlying soil sample lab-methodology have been incorporated. According to Møller et al. (2024a,b) this has increased the accuracy of the soil map and compared to the earlier version, the latest soil map has higher clay content in given areas (see Møller et al. (2024a,b) for a more detailed comparison). The new soil data version does not include datasets for bulk density which is required by SWAT+, and the dataset from 2014 was therefore used and spatially resampled specifically for bulk density.

Required parameters by SWAT+

An overview of required parameters in the SWAT+ soil database is given in table 1 (see also Neitsch et al., 2009).

Table 1. SWAT+ required parameters in the soil model database along with description and the applied approach used for determining the given parameter.

SWAT+ parameter Name	Description	Approach of determination
OBJECTID	Soil index identifier	See step 4 below
MUID	Map unit identifier	Set globally to default value: "xxx"
SEQN	Sequence number	Set globally to default value: "0"
SNAM	Soil name	The soil profile id from the soil map is used as the soil name with a prefix. Thus set to value "TEXTUR2024_"+ OBJECTID
HYDGRP	Soil hydrologic group (A, B, C, or D)	See step 6 below
SOL_ZMX	Maximum rooting depth of soil profile (mm)	Set to the maximum of the soil map horizon span, i.e.: 2000 mm. Could be qualified based on JB type according to e.g. Styczen et al. (2004)
ANION_EXCL	Fraction of porosity (void space) from which anions are excluded. Optional	Set globally to default value: "0.5"
SOL_CRK	Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume. Only effective on Vertisols (swelling and cracking clay soils). Optional	Set globally to default value: "0.5"
TEXTURE	Texture of soil layer. Optional	Set globally to default value: "xxx". Additional information on texture distributions across the horizons is produced along with the SWAT+ soil database
SOL_Z (by horizon)	Depth from soil surface to bottom of layer (mm)	Is set according to horizon separation of the original soil dataset: 1: 0-30 cm; 2: 30-60 cm; 3: 60-100 cm; 4: 100-200 cm
SOL_BD (by horizon)	Soil bulk density (g cm^{-3})	See step 0 below – is a part of the textur2014 soil map

SOL_AWC (by horizon)	Available water capacity (AWC) of the soil layer (mm H_2O (mm soil)$^{-1}$)	Derived from pedo-transfer functions (see step 5 below) that estimates field capacity (FC) and willting point (WP) from soil textural composition and bulk density. Hereafter available water capacity can be calculated as: AWC = FC – WP
SOL_K (by horizon)	Saturated hydraulic conductivity (mm hr^{-1})	Derived from pedo-transfer functions (see step 5 below) that estimates saturated hydraulic conductivity from soil textural composition and bulk density.
SOL_CBN (by horizon)	Organic carbon content (% soil weight)	Is a part of the textur2024 soil map
CLAY (by horizon)	Clay content (% soil weight)	Is a part of the textur2024 soil map
SILT (by horizon)	Silt content (% soil weight)	Is a part of the textur2024 soil map
SAND (by horizon)	Sand content (% soil weight)	Is a part of the textur2024 soil map
ROCK (by horizon)	Rock fragment content (% total weight)	Set globally to default value: "0"
SOL_ALB (by horizon)	Moist soil albedo (-)	Derived from pedo-transfer functions (see step 5 below) that estimates the field capacity from soil textural composition and bulk density, which is then translates further to moist soil albedo
USLE_K (by horizon)	USLE equation soil erodibility (K) factor (metric ton m^2 hr / (m^3-metric ton cm))	Derived from pedo-transfer functions (see step 5 below) that estimates soil erodibility factor from soil textural composition and organic carbon content
SOL_EC (by horizon)	Electrical conductivity (dS m^{-1}).	Not currently active in SWAT+., but needs to be present. Set globally to default value: "0"

Step by step procedure to derive SWAT+ soil map

Preprocessing of bulk density (step 0)

Soil bulk density is not a part of the new textur2024 dataset by Møller et al. (2024a,b). As an alternative, we therefore used the soil bulk density dataset from the former textur2014 dataset by Adhikari et al. (2013) in 30.4mx30.4m resolution. In Adhikari et al. (2013) bulk density was, in contrast to textures like clay, sand and silt separated into, not four horizons, but six horizons having 0-5cm, 5-15cm and 15-30cm as upper layers. To form a consistent four horizon format for bulk density, an average weighting was applied for the top layer (0-30cm) with weights distributed as: 0-5cm: 0.17, 5-15cm: 0.33 and 15-30cm: 0.5. Moreover, the dataset was resampled to 10mx10m equivalent to the textur2024 dataset.

Clipping data (step 1)

The framework enables extraction/clipping according to a user-defined area of interest (shapefile), which allows soil processing for a subset of the entire dataset coverage, resulting in the faster production of soil maps with variations of, for instance, soil sources or the horizons that define the soil index. Here the original Textur2024 dataset and the pre-processed bulk density data was clipped along a 1000m outward-buffered coastline of Denmark for every horizon (1 to 4) and each soil variable. The use of a buffer was to ensure that later topography delineation in SWAT+ with a potential finer resolution, does not derive scattered no-data cells when overlaying watershed delineation with the soil map.

Land mask creation and interpolation (step 2)

In the textur2024 dataset all cells within in-land waterbodies, constructed and urban areas have been masked out (figure 1), with the main reasons being the lack of reliable soil sample observations within these areas and the fact that constructed areas may not have "true" soil below the surface. However, SWAT+ requires a complete soil coverage and the shapefile defining the area of interest (i.e. Denmark) was converted to a binary raster mask that represents cells where data should be present (i.e. the land mask). Within this land mask the textur2024 dataset cells with "no data" were updated via the nearest neighbor principle.

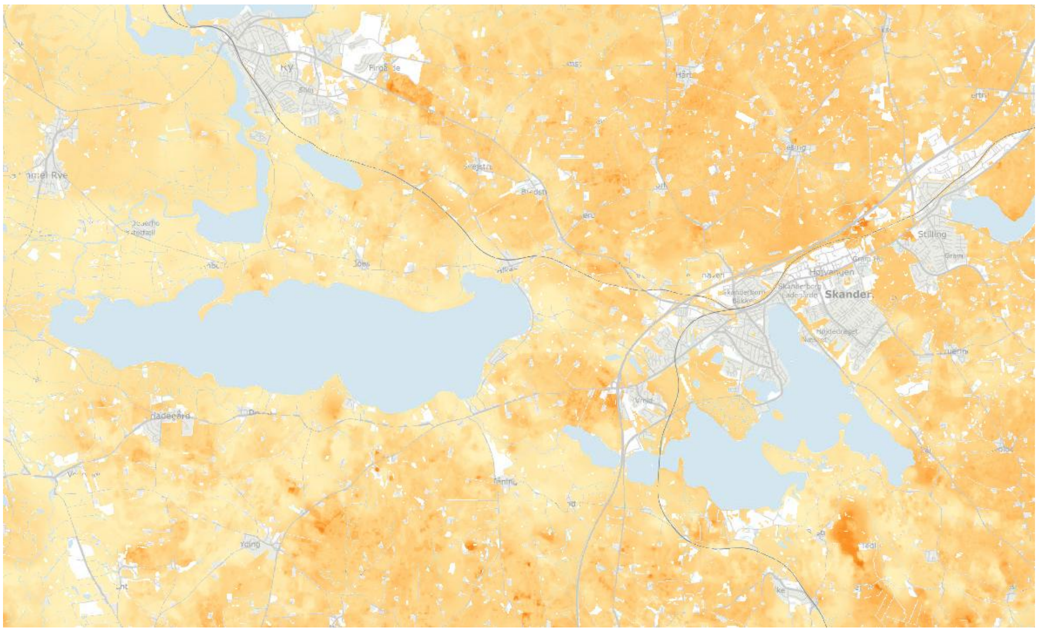


Figure 1. Example of masked out cells in the textur2024 dataset within in-land waterbodies, constructed and urban areas.

Deriving USDA classifications from soil texture properties (step 3)

To calculate the USLE equation soil erodibility (K) factor, the USDA texture classification needs to be derived for the soil map. According to the International Soil Reference and Information Centre (https://www.isric.org/) this can be done with reference to the NRCS Soil Survey Manual (Soil Science Division Staff, 2017) based on the percentage distributions of the texture properties clay, sand and silt (table 2) and is applied for each of the four horizons to create classification rasters.

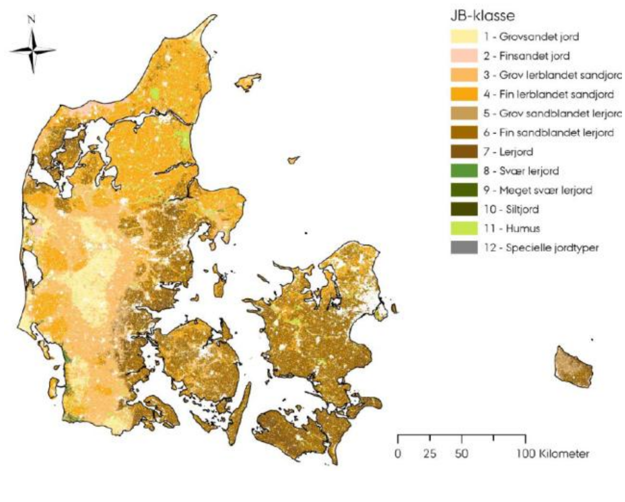
Table 2. Soil texture property criteria for USDA texture classifications after the NRCS Soil Survey Manual (Soil Science Division Staff, 2017).

USDA class description	Criteria
Clay	*where((["clay"] >= 40) & (["sand"] <= 45) & (["silt"] < 40))*
Silty clay	*where((["clay"] >= 40) & (["silt"] >= 40))*
Silty clay loam	*where((["clay"] >= 27, ["clay"] < 40) & (["sand"] <= 20))*
Sandy clay	*where((["clay"] >= 35) & (["clay"] > 45))*
Sandy clay loam	*where((["clay"] >= 20, ["clay"] < 35) & (["silt"] < 28) & (["sand"] > 45))*
Clay loam	*where((["clay"] >= 27, ["clay"] < 40) & (["sand"] > 20, ["sand"] <= 45))*
Silt	*where((["silt"] >= 80) & (["clay"] < 12))*
Silt loam	*where((["silt"] >= 50) & (["clay"] >= 12, ["clay"] < 27) | (["silt"] >= 50, ["silt"] < 80) & (["clay"] < 12))*
Loam	*where((["clay"] >= 7, ["clay"] < 27) & (["silt"] >= 28, ["silt"] < 50) & (["sand"] <= 52))*
Sand	*where([“silt”]+ 1.5*["clay"] < 15)*
Loamy sand	*where((["silt"] + 1.5*["clay"] >= 15) & (["silt"] + 2* ["clay"] < 30))*
Sandy loam	*where((["clay"] >= 7, ["clay"] < 20) & (["sand"] > 52) & (["silt"] + 2*["clay"] >= 30) | (["clay"] < 7) & (["silt"] < 50) & (["silt"] + 2*["clay"] >= 30))*

Definition of the soil map index (step 4)

SWAT+ needs to have a single GIS layer with a soil index map that defines the soil type irrespectively of the number of underlying soil horizons. The soil map index is as such the coupling between the spatial distribution of soil types and the soil database that defines soil type properties. With four horizons, the soil type index is created based on the Danish JB type (table 3), which is a type classification according to soil texture, organic content and lime (Madsen et al., 1992).

Table 3. Danish JB types and distribution in the top soil. Map according to Møller et al. (2024a,b).

Id	JB type description	JB type distribution
1	Grovsandet jord	
2	Finsandet jord	
3	Grov lerblandet sandjord	
4	Fin lerblandet sandjord	
5	Grov sandblandet lerjord	
6	Fin sandblandet lerjord	
7	Lerjord	
8	Svær lerjord	
9	Meget svær lerjord	
10	Siltjord	
11	Humus	
12	Speciel jord	

To create the SWAT+ required soil map index, the unique combinations for the JP types on a grid cell level when overlaid across the four horizons was computed. Output from this step is a raster with the soil map index and a CSV file with supportive information on texture classification (Table 4).

Table 4. Example of the unique combinations at grid level across the four horizons that defines the SWAT+ soil map index based on the soil map by Møller et al. (2024a,b).

Soil ID	Texture ID	Horizon			
		1 (0-30cm)	2 (30-60cm)	3 (60-100cm)	4 (100-200cm)
3878	11,02,02,11,02	Finsandet jord	Finsandet jord	Humus	Finsandet jord
3887	11,02,02,11,11	Finsandet jord	Finsandet jord	Humus	Humus
3901	11,02,03,01,01	Finsandet jord	Grov lerblandet sandjord	Grovsandet jord	Grovsandet jord
3902	11,02,03,01,02	Finsandet jord	Grov lerblandet sandjord	Grovsandet jord	Finsandet jord
3903	11,02,03,01,03	Finsandet jord	Grov lerblandet sandjord	Grovsandet jord	Grov lerblandet sandjord
3913	11,02,03,02,01	Finsandet jord	Grov lerblandet sandjord	Finsandet jord	Grovsandet jord
3925	11,02,03,03,01	Finsandet jord	Grov lerblandet sandjord	Grov lerblandet sandjord	Grovsandet jord
3927	11,02,03,03,03	Finsandet jord	Grov lerblandet sandjord	Grov lerblandet sandjord	Grov lerblandet sandjord

Computation of pedo-transfer functions (step 5)

To derive the soil properties: Available Water Capacity (AWC), Soil Hydraulic Conductivity (SHC), Soil Erodibility Factor (SEF) and Moist Soil Albedo (MSA) the concept of pedo-transfer functions (Woesten et al., 1999) were applied based on texture information (i.e. clay, silt and sand), bulk density and organic carbon content. The framework was designed to derive an ensemble of pedo-transfer functions according to review by Abbaspour et al. (2019) and for instance, the available water capacity was estimated from field capacity (33 kPa) and at wilting point (1500 kPa) based on 15 different pedo-transfer functions. For all pedo-transfer ensembles, the median was utilized as the representative value for its derived property. For the Soil Erodibility Factor the concept of Williams et al., (1995), which was formalized further in Wawer et al., (2005), was applied based on texture compositions (sand, silt and clay) and organic carbon content.

Additional parameter calculations (step 6)

The USDA hydrologic soil group (in SWAT+ terminology: HYDGRP) was classified according to Ross et al. (2018) mapping of USDA texture classifications: 1, 2, 4 to hydrologic soil group "D"; 3, 5, 6, 7, 8, 9 to "C"; 11, 12 to "B" and 10 to "A", respectively. The four classes A, B, C, and D correspond to soils with low, moderately low, moderately high, and high runoff potential.

Derived soil map and soil database for SWAT+

After calculating the parameters listed in table 1, a database file is formatted for compatibility with the SWAT + requirements (see SWAT + documentation for a full overview of the necessary variables and structure). While the soil index map is derived from the unique combination of overlaying the four JB-type classification horizons (which is categorical), the specific property value of e.g. sand content (which is continuous) may vary at horizon level. Consequently, the SWAT+ database variables was averaged per horizon for each unique soil index (i.e. per soil type). For the hydrologic soil group, which should by specified per soil type and not per horizon in the database, the dominant hydrologic soil group across horizons.

The SWAT+ compatible soil map is shown in figure 2. It has a total of 734 different soil types across Denmark, which is a product of the unique combination of the JB-types (1-12) across four horizons (1: 0-30 cm; 2: 30-60 cm; 3: 60-100 cm; 4: 100-200 cm).

Figure 2. SWAT+ compatible soil map based on soil data from Møller et al. (2024a,b) and Adhikari et al. (2013) and various processing described in this white paper.

Table 5 gives examples of derived values for some of the required SWAT+ soil database parameters according to specifications in table 1.

Table 5. Example of derived values according to some of the required SWAT+ soil database parameters.

Variable	Layer	1885	2173	3445	3447	20725	20727
HYDGRP	All	A	A	A	A	A	A
CLAY	1	4.36	4.87	4.46	4.65	4.45	6.03
SAND		21.31	23.40	20.94	23.92	20.72	33.72
SILT		2.77	3.39	2.88	3.21	2.91	4.79
SOL_ALB		0.22	0.22	0.22	0.22	0.22	0.22
SOL_AWC		0.17	0.16	0.15	0.15	0.14	0.15
SOL_BD		1.43	1.45	1.14	1.12	1.16	1.13
SOL_CBN		1.95	1.59	4.55	4.20	8.34	10.09
SOL_K		33.00	32.90	49.66	53.28	64.56	78.10
USLE_K		0.12	0.12	0.11	0.12	0.12	0.12
CLAY	2	4.42	5.01	4.45	4.77	4.45	6.18
SAND		21.78	23.64	21.86	24.70	21.69	33.34
SILT		2.36	2.88	2.38	2.89	2.42	4.34
SOL_ALB		0.22	0.23	0.22	0.22	0.22	0.22
SOL_AWC		0.16	0.15	0.11	0.12	0.11	0.13
SOL_BD		1.48	1.50	0.64	0.59	0.68	0.64
SOL_CBN		1.15	0.88	7.14	7.18	7.21	7.10
SOL_K		31.55	30.66	94.70	98.40	92.30	92.25
USLE_K		0.13	0.14	0.11	0.11	0.11	0.11
CLAY	3	4.57	4.82	4.60	5.93	4.62	7.39
SAND		25.83	25.53	28.39	31.12	27.95	33.40
SILT		2.15	2.53	2.15	2.85	2.17	4.16
SOL_ALB		0.23	0.23	0.22	0.22	0.22	0.22
SOL_AWC		0.15	0.15	0.13	0.14	0.13	0.14
SOL_BD		1.53	1.55	0.82	0.79	0.86	0.84
SOL_CBN		0.67	0.43	6.25	6.27	6.29	6.31
SOL_K		34.28	31.66	91.94	90.60	89.20	80.90
USLE_K		0.14	0.14	0.11	0.11	0.11	0.11
CLAY	4	4.73	4.86	4.81	6.92	4.82	8.12
SAND		25.86	25.05	28.27	30.48	27.83	32.60
SILT		2.55	2.67	2.61	3.55	2.62	4.64
SOL_ALB		0.23	0.23	0.22	0.22	0.22	0.22
SOL_AWC		0.15	0.15	0.15	0.15	0.15	0.15
SOL_BD		1.53	1.55	0.82	0.79	0.86	0.84
SOL_CBN		0.50	0.30	5.82	5.83	5.84	5.82
SOL_K		33.62	30.69	88.60	82.70	86.00	74.30
USLE_K		0.14	0.15	0.11	0.11	0.11	0.11

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