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DATA NOTE

3D soil hydraulic database of Europe at 250 m resolution

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Abstract

Soil hydraulic properties are required in various modelling schemes. We propose a consistent spatial soil hydraulic database at 7 soil depths up to 2 m calculated for Europe based on SoilGrids250m and 1 km datasets and pedotransfer functions trained on the European Hydropedological Data Inventory. Saturated water content, water content at field capacity and wilting point, saturated hydraulic conductivity and Mualem-van Genuchten parameters for the description of the moisture retention, and unsaturated hydraulic conductivity curves have been predicted. The derived 3D soil hydraulic layers (EU-SoilHydroGrids ver1.0) can be used for environmental modelling purposes at catchment or continental scale in Europe. Currently, only EU-SoilHydroGrids provides information on the most frequently required soil hydraulic properties with full European coverage up to 2 m depth at 250 m resolution.

KEYWORDS

3D European soil hydraulic maps, EU-SoilHydroGrids, Mualem-van Genuchten parameters, multilayered gridded information, soil hydraulic conductivity, soil water retention

1 | DATA

The multilayered European Soil Hydraulic Database (EU-SoilHydroGrids ver1.0) was derived with European pedotransfer functions (EU-PTFs; Tóth et al., 2015) based on the soil information of SoilGrids250m and aggregated 1 km (Hengl et al., 2017) datasets.

The EU-PTFs (Tóth et al., 2015) were trained on the European Hydropedological Dataset (EU-HYDI; Weynants et al., 2013). EU-HYDI is a collection of data from 29 institutions in 18 European countries and contains data on taxonomical, chemical, and physical soil properties of more than 18,000 soil samples. Pedotransfer functions were calibrated using soil information of 134 to 6,074 soil samples and validated on 57 to 2,357 samples, depending on the type of soil hydraulic property (Tóth et al., 2015).

SoilGrids provides the most detailed information on soil properties with full continental coverage in Europe. It incorporates soil taxonomical, physical, and chemical data of seven soil depths at 250 m resolution (Hengl et al., 2017). We used the following soil properties to calculate the soil hydraulic properties: clay, silt, and sand content (mass %); organic carbon content (g kg^{-1}); bulk density (kg m^{-3}); pH in water and depth to bedrock (cm) at 0, 5, 15, 30, 60, 100, and 200 cm depth. The first four depths, which are less than or equal to 30 cm depth, are considered as topsoil and the remaining handled as subsoil in accordance with the EU-PTFs used for calculations (Tóth et al., 2015).

In case bedrock appears within 200 cm, hydraulic properties were calculated up to the first layer underlying the top of the bedrock providing the possibility to interpolate the soil hydraulic properties through different soil depths. For modelling purposes, the predicted depth to bedrock is available from www.soilgrids.org; data are described in detail in Shangguan, Hengl, Mendes de Jesus, Yuan, and Dai (2017).

2 | METHODS

Soil properties included in SoilGrids database were transformed into the format needed by the EU-PTFs (Tóth et al., 2015). Sand, silt, and clay content were adjusted to sum to 100%, and USDA texture classes (Soil Survey Staff, 1975) were calculated. We selected the best performing and most reliable PTFs that were calibrated on representative data subsets to exclude too much data specific models. Sixteen soil hydraulic properties were calculated for the seven standard depths of SoilGrids: 0, 5, 15, 30, 60, 100, and 200 cm at both 250 m and 1 km resolutions. Given the nonlinear relations between soil hydraulic properties and the other soil properties used as predictors, the mean of a set of predicted hydraulic properties is not equal to the prediction of the property based on the mean of the predictors. Therefore, calculations were also completed on the aggregated SoilGrids1km rather than aggregate soil hydraulic layers derived on 250 m resolution. The 1 km resolution aggregated version of the SoilGrids250m maps were generated using the "average" resampling method in the GDAL software (Mitchell and GDAL Developers, 2014).

Table 1 lists the calculated soil hydraulic properties and the EU-PTFs used to predict them, indicating also the soil properties used as predictors. Saturated water content (THS) refers to the water content at 0 cm matric potential (0 MPa) (pF0). Field capacity (FC) is the water content at −330 cm matric potential (−0.03 MPa), which is the most commonly used value (pF2.5). If terminology of FC is different from the above mentioned—for example, it is assumed as water content at −50, −60, or −100 cm matric potential (−0.005, −0.006, or −0.01 MPa)—it can be calculated from the moisture retention curve (MRC). Wilting point (WP) is calculated as water content at −15,848 cm matric potential (−1.5 MPa; pF4.2). Saturated hydraulic conductivity (KS) is the conductivity at 0 matric potential (0 MPa).

The van Genuchten model (van Genuchten, 1980) is used for the description of the MRC:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha h)^n\right]^m}, \tag{1}$$

where $\theta(h)$ is the water content of the soil ($cm^3\ cm^{-3}$) at a given matric potential value (cm of water column); θ_r is the residual water content ($cm^3\ cm^{-3}$); θ_s is the saturated water content ($cm^3\ cm^{-3}$); and α (cm^{-1}), n (−), and m (−) are fitting parameters. Parameter m equals to $1-1/n$. Parameters θ_r, θ_s, α, n, and, m of the van Genuchten model were calculated and included in EU-SoilHydroGrids ver1.0.

The hydraulic conductivity curve (HCC) is described with the van Genuchten model coupled with the model of Mualem (1976):

$$K(S_e) = K_0 S_e^L \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2, \tag{2}$$

$$S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}, \tag{3}$$

where K is the soil hydraulic conductivity (cm day^{-1}); K_0 is the hydraulic conductivity acting as a matching point at saturation (cm day^{-1}); S_e is the effective saturation (−); and L is a shape parameter related to pore tortuosity (−). Further to parameters K_0 and L, parameters θ_r, θ_s, α, n, and m of HCC were calculated to provide a fully coupled model that describes the unsaturated hydraulic conductivity in the full matric potential range.

Calculations were executed in R (R Core Team, 2016) with the "euptf" package (Weynants & Tóth, 2014) containing the soil hydraulic prediction methods (EU-PTFs; Tóth et al., 2015). The "rgdal" (Bivand, Keitt, & Rowlingson, 2016) and "raster" (Hijmans, 2016) R packages were used to call in and perform calculations on raster files. Layers of SoilGrids250m were tiled with "GSIF" (Hengl, 2016) being able to execute the predictions. Calculations were run in parallel on SoilGrids250m with the "snowfall" (Knaus, 2015) R package.

TABLE 2 Format of calculated soil hydraulic properties in the EU-SoilHydroGrids ver1.0

Soil hydraulic property	Unit	Name in dataset: 250 m resolution	Name in dataset: 1 km resolution
THS × 100	$cm^3\ cm^{-3}$	THS	THS
FC × 100	$cm^3\ cm^{-3}$	FC	FC
WP × 100	$cm^3\ cm^{-3}$	WP	WP
KS × 100	cm day^{-1}	KS	KS
Parameters of MRC:			
θ_r × 10000	$cm^3\ cm^{-3}$	band1 of MRC	MRC_thr
θ_s × 10000	$cm^3\ cm^{-3}$	band2 of MRC	MRC_ths
α × 10000	cm^{-1}	band3 of MRC	MRC_alp
n × 10000	–	band4 of MRC	MRC_n
m × 10000	–	band5 of MRC	MRC_m
Parameters of MRC + HCC:			
θ_r × 10000	$cm^3\ cm^{-3}$	band1 of HCC	HCC_thr
θ_s × 10000	$cm^3\ cm^{-3}$	band2 of HCC	HCC_ths
α × 10000	cm^{-1}	band3 of HCC	HCC_alp
n × 10000	–	band4 of HCC	HCC_n
m × 10000	–	band5 of HCC	HCC_m
K_0 × 10000	cm day^{-1}	band6 of HCC	HCC_K0
L × 10000	–	band7 of HCC	HCC_L

Note. FC = field capacity; HCC = hydraulic conductivity curve; KS = saturated hydraulic conductivity; MRC = moisture retention curve; THS = saturated water content; WP = wilting point.

Parameters n, m and L are dimensionless.

TABLE 1 The list of soil hydraulic properties calculated in EU-SoilHydroGrids and PTFs used for calculations (Tóth et al., 2015) indicating input information from SoilGrids

Calculated soil hydraulic property	PTF used for calculation	Type of model	Soil information of SoilGrids used as input for calculations
THS	PTF06	LR	Silt, clay, T/S, BD, pH
FC	PTF09	LR	Silt, clay, OC
WP	PTF12	LR	Silt, clay, OC
KS	PTF16	RT	Sand, silt, clay, T/S, OC
MRC	PTF22	θr with RT, θs, α and n with LR	Sand, silt, clay, T/S, OC, BD, pH
MRC + HCC	PTF19	MS	Sand, silt, clay, T/S, OC

Note. BD = bulk density; clay = clay content; FC = water content at field capacity; HCC = hydraulic conductivity curve; KS = saturated hydraulic conductivity; LR = multiple linear regression; MRC = moisture retention curve; MS = mean statistics of pre-determined groups; OC = organic carbon content; pH = pH in water; PTFs = pedotransfer functions; RT = regression tree; sand = sand content; silt = silt content; T/S = topsoil and subsoil distinction; THS = saturated water content; WP = water content at wilting point.

We compared the performance of the EU-SoilHydroGrids to that of the European Soil Data Centre's soil hydraulic properties (ESDAC SHP; Tóth & Weynants, 2016) at 1 km scale. The ESDAC SHP were also derived with the EU-PTFs of Tóth et al. (2015), but based on the information of the European Soil Database (http://esdac.jrc.ec.europa.eu/) and only THS, FC, WP, and KS of the topsoil at 1 km resolution were calculated.

For the comparison of EU-SoilHydroGrids and ESDAC SHP, mean THS, FC, WP, and KS values have been calculated in EU-SoilHydroGrids 1 km based on the first four layers of the dataset. We selected samples with measured THS, FC, WP, and KS values from EU-HYDI dataset based on location, and we calculated the properties of the top 30 cm using spline interpolation *mpspline* from R package GSIF (Hengl, 2016). We compared these values to the predicted values from EU-SoilHydroGrids and ESDAC SHP. Performance of EU-SoilHydroGrids and European Soil Database was tested by calculating mean absolute error (MAE) (Equation 4) and root mean square error (RMSE; Equation 5) of the calculated soil hydraulic values and variance of the residuals.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i) \tag{4}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y_i - \hat{y}_i)^2} = \sqrt{MSE} \tag{5}$$

3 | RESULTS

Table 2 lists soil hydraulic parameters calculated for the seven soil depths of SoilGrids dataset at 250 m and 1 km resolution. Figure 1 shows a map of THS, FC, WP, and KS at 15 cm. In those cases where PTF is a regression tree (e.g., Figure 1 KS), there is less variability in the predicted values than in multiple linear regression models. The number after "sl" 1, 2, 3, 4, 5, 6, and 7 indicates depth of the layer 0, 5, 15, 30, 60, 100, and 200 cm, respectively.

Reliability of the calculated soil hydraulic maps depends both on the reliability of soil properties estimated in the SoilGrids database and reliability of the PTFs. Accuracy of SoilGrids 250 m is between 0.54 and 0.83 in terms of R^2 (Hengl et al., 2017). Reliability of the PTFs used to calculate soil hydraulic layers of the EU-SoilHydroGrids ver1.0 was calculated using the test sets of the EU-HYDI dataset (Tóth et al., 2015) and shown in Table 3.

3.1 | Comparison of EU-SoilHydroGrids and soil hydraulic properties available from ESDAC

We evaluated the performance of EU-SoilHydroGrids ver1.0 and ESDAC SHP to reproduce the measured soil hydraulic properties of EU-HYDI on more than 1500 samples (Table 4.). In the EU-SoilHydroGrids dataset all four soil hydraulic properties had smaller MAE and RMSE

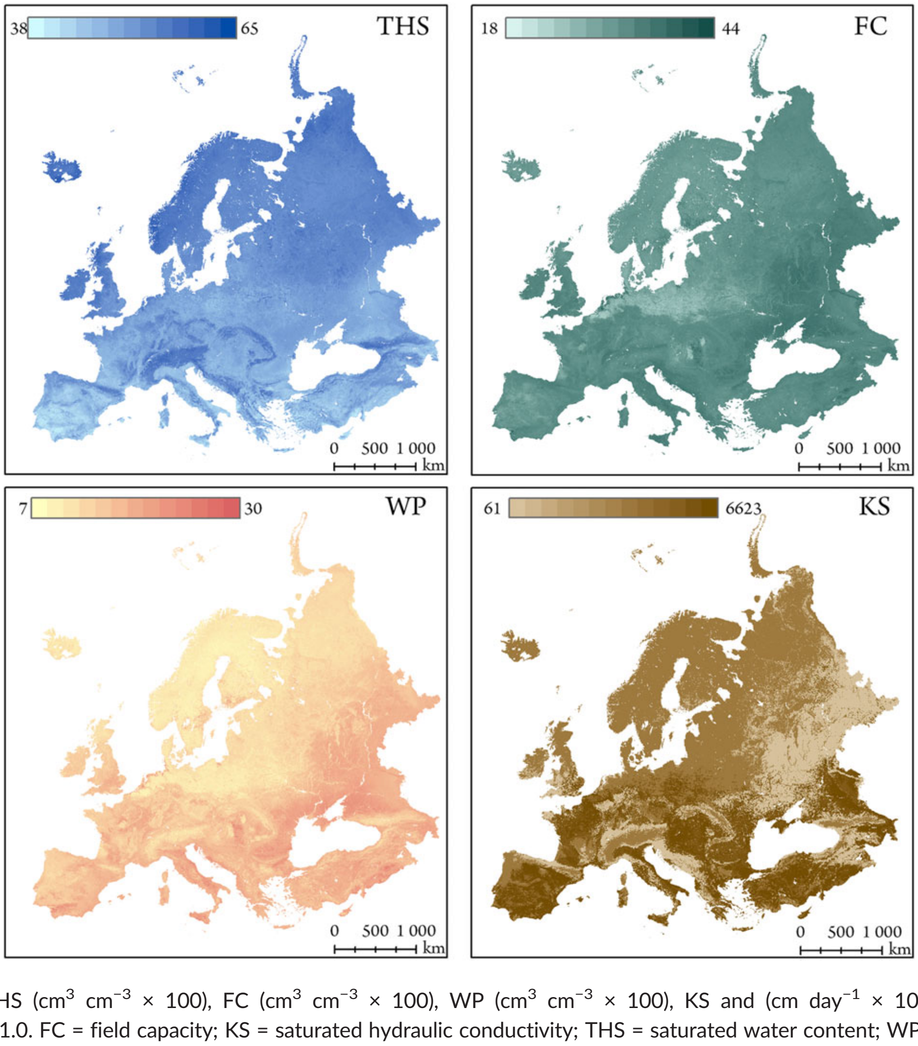

FIGURE 1 Map of THS (cm^3 cm^{-3} × 100), FC (cm^3 cm^{-3} × 100), WP (cm^3 cm^{-3} × 100), KS and (cm day^{-1} × 100) at 15 cm depth in EU-SoilHydroGrids ver1.0. FC = field capacity; KS = saturated hydraulic conductivity; THS = saturated water content; WP = wilting point

TABLE 3 Performance of PTFs tested on EU-HYDI test sets (adapted from Tóth et al., 2015).

Predicted soil hydraulic property	Number of samples used to derive PTF	Number of samples in test set	RMSE on test set
THS ($cm^3\ cm^{-3}$)	1142	156	0.020
FC ($cm^3\ cm^{-3}$)	2356	1005	0.055
WP ($cm^3\ cm^{-3}$)	5530	2357	0.048
log_{10}KS (log_{10}[cm day^{-1}])	2628	1121	1.06
MRC (θ; $cm^3\ cm^{-3}$)	1713	288	0.046
HCC (log_{10}K; log_{10}[cm day^{-1}])	860	176	0.77

Note. EU-HYDI = European Hydropedological Data Inventory; FC = field capacity; HCC = hydraulic conductivity curve; KS = saturated hydraulic conductivity; MRC = moisture retention curve; PTFs = pedotransfer functions; RMSE = root mean square error; WP = wilting point.

TABLE 4 Performance of EU-SoilHydroGrids ver1.0 and ESDAC SHP analysed on measured soil hydraulic values of EU-HYDI samples that have information on location.

Predicted soil hydraulic property	Name of soil hydraulic map	PTF used for calculation[a]	Number of samples	MAE	RMSE
THS of top 30 cm	EU-SoilHydroGrids ver1.0	PTF06	1607	0.076	0.095
($cm^3\ cm^{-3}$)	ESDAC SHP	PTF02	1607	0.081	0.109
FC of top 30 cm	EU-SoilHydroGrids ver1.0	PTF09	1548	0.074	0.096
($cm^3\ cm^{-3}$)	ESDAC SHP	PTF07	1548	0.085	0.110
WP of top 30 cm	EU-SoilHydroGrids ver1.0	PTF12	2652	0.066	0.084
($cm^3\ cm^{-3}$)	ESDAC SHP	PTF10	2652	0.085	0.106
KS of top 30 cm	EU-SoilHydroGrids ver1.0	PTF16	1743	1.10	1.40
(log_{10}[cm day^{-1}])	ESDAC SHP	PTF14	1743	1.23	1.59

Note. ESDAC SHP = European Soil Data Centre's soil hydraulic properties; EU-HYDI = European Hydropedological Data Inventory; FC = field capacity; KS = saturated hydraulic conductivity; MAE = mean absolute error; RMSE = root mean square error; PTFs = pedotransfer functions; WP = wilting point.

[a]Description of PTFs used for the calculations can be found in Tóth et al. (2015).

values (Table 4.) and the variance of the residuals was significantly less than in ESDAC SHP. Performance of soil hydraulic predictions improved up to 21% based on RMSE and MAE values compared to ESDAC SHP.

The improvement of EU-SoilHydroGrids ver 1.0 compared to ESDAC SHP arises from the fact that with SoilGrids we could apply more accurate PTFs because the range of soil properties available for the predictions is wider and more detailed. For example, instead of soil texture, particle size distribution could be used. Also, SoilGrids has a determined resolution, whereas ESDAC is based on polygons of varying size and complexity of soil typology that are simplified to their dominant soil in ESDAC SHP. Further advantages of the EU-SoilHydroGrids are that it provides soil hydraulic properties at seven soil depths up to 2 m, that parameters of MRC and HCC are included as well and that it provides information both at 1 km and 250 m resolution.

Among the soil hydraulic properties, THS had the smallest relative estimation error. After THS, WP and FC had the second and third smallest prediction error. Prediction of KS was the most uncertain. The performance of the predictions depends also on the uncertainty of soil properties in SoilGrids dataset. That analysis is beyond the scope of this paper.

4 | OUTLINE OF THE RANGE OF APPLICATIONS THAT THE DATA MAY HAVE IN HYDROLOGY

EU-SoilHydroGrids ver1.0 provides soil hydrological data with full continental coverage, which enables hydrological, ecological, atmospherical, agricultural or other environmental modelling at continental and regional scales. Both water content at typical matric potentials and parameters describing the whole soil water retention curve are available from the EU-SoilHydroGrids ver1.0 dataset. Further to information on soil water retention, soil hydraulic conductivity in saturated and unsaturated conditions is also provided. If an updated version of SoilGrids becomes available or more efficient PTFs are derived in the future, EU-SoilHydroGrids ver1.0 can be updated as well.

When soil hydraulic layers of EU-SoilHydroGrids ver1.0 are utilized for further applications the followings are worth considering:

- if only and exactly THS and/or FC and/or WP and/or KS is needed from the EU-SoilHydroGrids dataset it is recommended to use THS, FC, WP, KS layers, because they were derived directly with point estimations having lower uncertainty than calculating those from MRC or HCC (Tóth et al., 2015);
- in EU-SoilHydroGrids soil hydraulic data of layers deeper than the bottom of the soil are included as well, which provides the possibility to interpolate soil hydraulic properties through different soil depths; therefore depth to bedrock has to be considered from other sources e.g. www.soilgrids.org;
- soil hydraulic properties are calculated for the fine earth fraction (< 2 mm) and volume of coarse fragments is not considered in the calculations;
- if local soil hydraulic data or local soil hydraulic PTFs and/or local soil information are available their use is recommended because spatial accuracy of EU-SoilHydroGrids is limited, especially

  - above 1000 m sea level and
  - in pedoclimatic regions which were not covered in the EU-HYDI dataset;
- prediction of soil hydraulic conductivity has higher uncertainty than other soil hydraulic properties, conceivably due to the fact that KS is highly influenced by the geometry of the pore space, which is information that is absent in continental scale datasets.

5 | FORMAT AND AVAILABILITY OF EU-SOILHYDROGRIDS VER1.0

Gridded multilayered EU-SoilHydroGrids ver1.0 is available in TIFF format. Maps for all of Europe or selected regions can be downloaded freely for non-commercial use from the Institute for Soil Sciences and Agricultural Chemistry Centre for Agricultural Research Hungarian Academy of Sciences (http://mta-taki.hu/en/eu_soilhydrogrids_3d) and European Soil Data Centre (http://esdac.jrc.ec.europa.eu/).

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