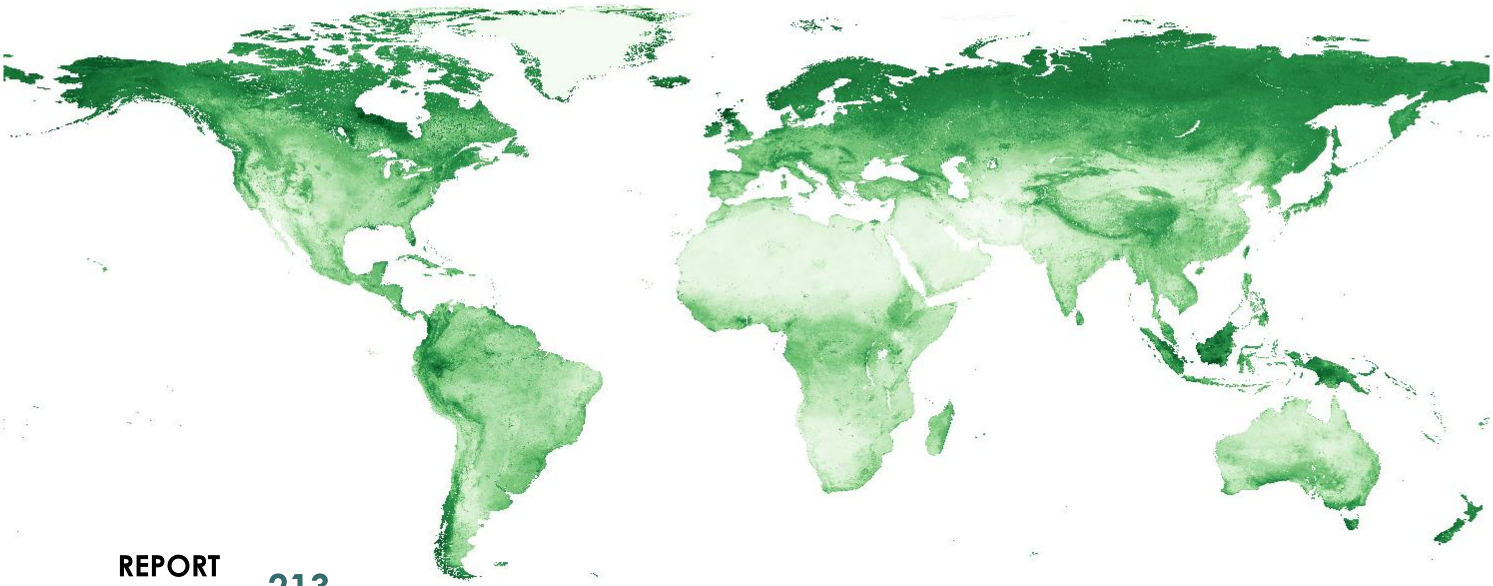
HiHydroSoil v2.0 - High Resolution Soil Maps of Global Hydraulic Properties



REPORT

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Summary

HiHydroSoil v2.0 is a global database of soil hydraulic properties, developed and released by FutureWater. It is intended to serve as a valuable data source for environmental studies and, in particular, geospatial simulation modeling of hydrological processes and ecosystem services. The HiHydroSoil v2.0 database is freely available through the FutureWater website (www.futurewater.eu/hihydrosoil).

This report describes the data and methods used in the development of HiHydroSoil v2.0, as well as its key characteristics and metadata.

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1 Introduction

Soil information is the basis for all environmental studies and an important input to geospatial models. At the same time, reliability and accessibility of these data over the past decades has been limited. Since local soil maps of good quality are often not available, global soil maps with a lower resolution are often used. Furthermore, soil maps do not include information about soil hydraulic properties, which are of importance, e.g. for hydrological modelling, erosion assessment and crop yield modelling.

Since 2011 more soil data has become available and calculation algorithms have been improved, which made it possible to create the global-scale gridded soil dataset SoilGrids1km with a higher resolution and improved accuracy (Hengl et al., 2014). As SoilGrids1km does not include soil hydraulic properties typically needed for hydrological modeling, FutureWater released a global dataset of soil hydraulic properties based on the application of pedotransfer functions: HiHydroSoil v1.2 (de Boer, 2016). This dataset is available in the public domain and has been used by the research, NGO, and consultancy communities worldwide to improve their access to data on soil hydraulics. The release of SoilGrids250m in 2017 (Hengl et al., 2017), its latest update in May 2020[1], and the continuous development of computation and storage capacities, has prompted FutureWater to develop and publish HiHydroSoil v2.0. This database contains a comprehensive inventory of soil hydraulic variables in gridded format. It is available at the global level, with a spatial resolution of 250 meters.

This report presents the data and methods used to derive HiHydroSoil v2.0, lists the key characteristics of the dataset, and demonstrates some typical applications of HiHydroSoil v1.2 so far.

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[1] https://www.isric.org/explore/soilgrids

2 Data and methods

2.1 Input data

In May 2020, ISRIC has released the latest version (v2.0) of its Soilgrids250m product: a high resolution (250 m) dataset with soil properties and classes on a global scale. This dataset is named SoilGrids250m 2.0

Table 1. Input variables for deriving soil hydraulic properties

Name	Variable	Unit
bdod	Bulk density of the fine earth fraction	cg/cm^3
cec	Cation Exchange Capacity of the soil	cmol+/kg
clay	Proportion of clay particles (< 0.002 mm) in the fine earth fraction	‰
soc	Soil organic carbon content in the fine earth fraction	dg/kg
phh20	Soil pH	pH x 10
silt	Proportion of silt particles (≥ 0.002 mm and ≤ 0.05 mm) in the fine earth fraction	‰
sand	Proportion of sand particles (> 0.05 mm) in the fine earth fraction	‰

Every variable is given for six different (standard) depths (sd1-sd6), as indicated in Table 2.

Table 2. Standard soil depths

Name	Standard depth	Thickness of layer
sd1	0-5 cm	5 cm
sd2	5-15 cm	10 cm
sd3	15-30 cm	15 cm
sd4	30-60 cm	30 cm
sd5	60-100 cm	40 cm
sd6	100-200 cm	100 cm

In the creation of HiHydroSoil v2.0, all listed input variables were downloaded for all depths. The SoilGrids portal[1] also contains an uncertainty layer for the different variables. In order to assess regional uncertainties of HiHydroSoil v2.0 data, the user is recommended to explore this data.

For calculation of the Hydrologic Soil Group, the simulated groundwater depth map of de De Graaf et al., (2015) was used as input as well as the Absolute Depth to Bedrock (BDTICM) 250m dataset from the SoilGrids250m dataset from March 2017.

2.2 Pedotransfer functions

In order to convert the soil properties into soil hydraulic functions as described by the Mualem Van Genuchten (MVG) model (Annex 1), so-called pedotransfer functions were used. The pedotransfer functions applied here were described by Tóth et al. (2014), who derived pedotransfer functions for a wide range of European soils. The soil hydraulic parameters that were derived with pedotransfer functions were the parameters of the Soil Moisture Retention curve (θ_r, θ_s, α and N) and K_{sat}.

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[1] https://soilgrids.org/

2.2.1 Residual water content (θ_r)

A simple regression tree was used to determine the residual water content (θ_r in m^3/m^3).

- Rule 1: IF Sand content (%) >= 2.00 $\theta_r = 0.041$
- Rule 2: IF Sand content (%) < 2.00 $\theta_r = 0.179$

2.2.2 Saturated water content (θ_s)

Linear regression was used to determine saturated water content (θ_s in m^3/m^3) with the following equation:

$$\theta_s = 0.83080 - 0.28217 * BD + 0.0002728 * Cl + 0.000187 * Si$$

in which *BD* is bulk density (in g/cm^3), *Cl* is clay content (%) and *Si* is silt content (%).

2.2.3 MVG parameter *α*

For deriving the *α* parameter (1/cm) used in the MVG model, the following equation was used:

$$log_{10}(\alpha) = -0.43348 - 0.41729 * BD - 0.04762 * OC + 0.21810 * T/S - 0.01581 * Cl - 0.01207 * Si$$

in which *OC* is Organic Carbon Content (%), and *T/S* is the topsoil and subsoil distinction. Topsoil was defined as 0-30 cm and subsoil as 30-100 cm (FAO, 2008). When soil depth is within the definition of topsoil, the value for T/S in the equations is 1, otherwise it is 0.

2.2.4 MVG parameter *N*

For deriving the *N* (-) parameter used in the MVG model, the following equation was used:

$$log10(n-1) = 0.22236 - 0.30189 * BD -0.05558 * T/S - 0.005306 * Cl - 0.003084 * Si - 0.01072 * OC$$

2.2.5 Saturated hydraulic conductivity

The saturated hydraulic conductivity (K_{sat} in cm/d) was derived using the following equation:

$$log_{10}K_S = 0.40220 + 0.26122 * pH + 0.44565 * T/S - 0.02329 * Cl - 0.01265 * Si - 0.01038 * CEC$$

in which pH is pH in water and CEC is cation exchange capacity (meq/100g).

It should be noted that in the original SoilGrids data, some variables have different units than in the pedotransfer functions described above. Bulk Density is expressed in kg/m^3, Organic Carbon Content in permilles (‰), pH in pH*10 and CEC in cmolc/kg (which is equal to meq/100g).

2.3 Organic Matter Content

The Organic Matter Content is related to the Organic Carbon Content. Organic Matter Content was calculated by multiplying Organic Carbon Content by the commonly used conversion factor of 1.72[1], which assumes that organic matter has 58% organic carbon.

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[1] See e.g. http://www.soilquality.org.au/factsheets/organic-carbon.

2.4 Soil Texture Class

Soil Texture Classes were calculated according a simplification of the FAO-method[1].

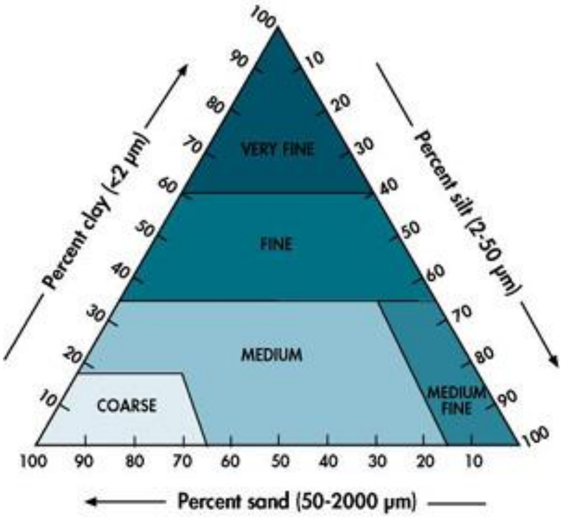

Figure 1. Simplified FAO Soil Texture Classification triangle[2]

Six soil textural classes were distinguished based on the organic matter content, percentage of clay content and percentage of sand content (Table 3).

Table 3. Soil Texture Classes

Code on map	Abbreviation	Description
1	O	Organic
2	VF	Very Fine
3	F	Fine
4	MF	Medium Fine
5	C	Coarse
6	M	Medium

The soil texture classification tree first distinguishes between organic and mineral soils (Figure 2).

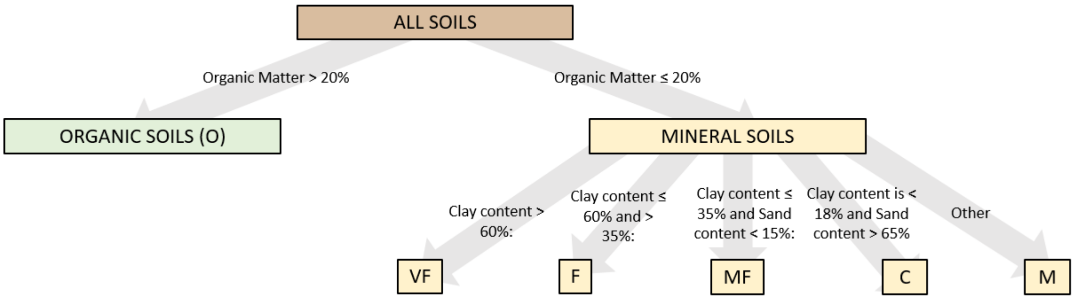

Figure 2. Schematic representation of the soil texture classification tree.

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[1] http://cran.rproject.org/web/packages/soiltexture/vignettes/soiltexture_vignette.pdf

[2] Source: http://www.ess.co.at/MANUALS/WATERWARE/soilclassification.html.

2.5 Hydrologic Soil Group

Along with land use, land management practices and soil hydrologic conditions the Hydrologic Soil Group (HSG) determines the Runoff Curve Number which is often used in hydrological modelling to estimate the direct runoff from rainfall. Four hydrologic soil groups and three dual hydrologic soil groups are described by the USDA (2009) as follows:

- Group A: Soils in this group have low runoff potential when thoroughly wet. Water is transmitted freely through the soil.
- Group B: Soils in this group have moderately low runoff potential when thoroughly wet. Water transmission through the soil is unimpeded.
- Group C: Soils in this group have moderately high runoff potential when thoroughly wet. Water transmission through the soil is somewhat restricted.
- Group D: Soils in this group have high runoff potential when thoroughly wet. Water movement through the soil is restricted or very restricted.
- *Dual hydrologic soil groups*: Soils having a water table within 60 centimeters of the surface are placed in group D, even though the saturated hydraulic conductivity may be favorable for water transmission. If these soils can be adequately drained, then they are assigned to dual hydrologic soil groups (A/D, B/D, and C/D) based on their saturated hydraulic conductivity and the water table depth when drained. The first letter applies to the drained condition and the second to the undrained condition. In this context, adequately drained means that the seasonal high-water table is kept at least 60 centimeters below the surface in a soil, whereas it would be higher in a natural state.

The HSG classification criteria given by the USDA (2009) are given in Table 4.

Table 4. Hydrologic Soil Group classification criteria

Depth to water impermeable layer[1]	Depth to high water table[2]	K_{sat} of least transmissive layer in depth range (cm/d)	K_{sat} depth range (cm)	HSG[3]
< 50 cm	-	-	-	D
≥ 50 cm ≤ 100 cm	< 60 cm	> 345.6	0- 60	A/D
		> 86.4 ≤ 345.6	0- 60	B/D
		> 8.64 ≤ 86.4	0- 60	C/D
		≤ 8.64	0- 60	D
	≥ 60 cm	> 345.6	0- 50[4]	A
		> 86.4 ≤ 345.6	0- 509	B
		> 8.64 ≤ 86.4	0- 509	C
		≤ 8.64	0- 509	D
	< 60 cm	> 86.4	0- 100	A/D
		> 34.56 ≤ 86.4	0- 100	B/D
		> 3.456 ≤ 34.56	0- 100	C/D
		≤ 3.456	0- 100	D
		> 345.6	0- 509	A

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[1] An impermeable layer has a K_{sat} less than 0.0864 cm/d or a component restriction of fragipan; duripan; petrocalcic; orstein; petrogypsic; cemented horizon; dense material; placic; bedrock, paralithic; bedrock, lithic; bedrock, densic; or permafrost.

[2] High water table during any month during the year.

[3] Dual HSG classes are applied only for wet soils (water table less than 60 cm. If these soils can be drained, a less restrictive HSG can be assigned, depending on the Ksat.

[4] Since no distinction between a depth range of 0-60 cm and a depth range of 0-50 cm could be made (*sd1-sd3* = 0-30cm, *sd1-sd4* = 0-60 cm), the minimum K_{sat} was always determined for a depth range of 0-60 cm.

Depth to water impermeable layer[1]	Depth to high water table[2]	K_{sat} of least transmissive layer in depth range (cm/d)	K_{sat} depth range (cm)	HSG[3]
> 100 cm	≥ 60 cm ≤ 100 cm	> 86.4 ≤ 345.6	0- 509	B
		> 8.64 ≤ 86.4	0- 509	C
		≤ 8.64	0- 509	D
	> 100 cm	> 86.4	0- 100	A
		> 34.56 ≤ 86.4	0- 100	B
		> 3.456 ≤ 34.56	0- 100	C
		≤ 3.456	0- 100	D

As can be seen from Table 4 an impermeable layer can consist of bedrock, but it can also be a soil layer with a K_{sat} lower than 0.0864 cm/d. However, the minimum K_{sat} of sd1-sd5 was nowhere lower than 0.154 cm/d. Therefore, only the depth to bedrock was used in the analysis.

2.6 Averaging over different depths

Some modeling applications require only a topsoil and a subsoil compartment, rather than 6 individual depth layers. Such a distinction between top- and subsoil is particularly relevant when vegetation rooting depth needs to be parameterized. To facilitate these applications, an average topsoil and and average subsoil was calculated by taking the weighted average of the variable, e.g.:

$$ORMC\_Topsoil = (D1 * ORMC\_sd1) + (D2 * ORMC\_sd2) + (D3 * ORMC\_sd3) / (D1 + D2 + D3)$$

in which D_1, D_2, D_3 are the depths of layers *sd1*, *sd2* and *sd3* respectively and *ORMC_sd1*, *ORMC_sd2*, *ORMC_sd3* are the Organic Matter Content at *sd1*, *sd2* and *sd3* respectively.
For the soil texture class, residual water content, and MVG model parameters α and N, the average for topsoil and subsoil was calculated by taking the weighted average of the input variables as input to the pedotransfer functions. For example:

$$WCres\_Topsoil = (0.041 * (SNDPPT\_Topsoil \geq 2)) + (0.179 * (SNDPPT\_Topsoil < 2)).$$

For output variable K_{sat}, the average for topsoil and subsoil was calculated as follows:

$$K_{sat}Topsoil = (D_1 + D_2 + D_3) / ((D_1/K_{sat}\_sd1) + (D_2/K_{sat}\_sd2) + (D_3/K_{sat}\_sd2)).$$

2.7 Filling data gaps

The SoilGrids250m 2.0 product contains data gaps for rivers and other water bodies, as well as a large patch of missing data in Central America for several data layers. To facilitate the easy setup of functional spatial models based on the HiHydroSoil v2.0 data, these gaps were filled with HiHydroSoil v1.2 data (see de Boer (2016) for procedures used in this dataset).

3 Results

3.1 Overview of HiHydroSoil v2.0

Table 5 gives an overview of all soil hydraulic properties contained by the HiHydroSoil v2.0 dataset.

Table 5. Soil hydraulic properties included in the HiHydroSoil v2.0 database.

Name	Variable	Unit
ORMC	Organic Matter Content	%
STC	Soil Texture Class	O (Organic), VF (Very Fine), F (Fine), MF (Medium Fine), C (Coarse), M (Medium)
ALPHA	Alpha parameter for Mualem Van Genuchten Equation	1/cm
N	N parameter for Mualem Van Genuchten Equation	-
WCsat	Saturated Water Content	m^3/m^3
WCres	Residual Water Content	m^3/m^3
Ksat	Saturated Hydraulic Conductivity	cm/d
WCpF2	Water content at pF2 (field capacity)	m^3/m^3
WCpF3	Water content at pF3 (wilting point)	m^3/m^3
WCpF4.2	Water content at pF4.2 (permanent wilting point)	m^3/m^3
WCavail	Available water content	m^3/m^3
SAT-FIELD	Water content between saturation point and field capacity (pF2)	m^3/m^3
FIELD-WILT	Water content between field capacity (pF2_ and wilting point (pF3)	m^3/m^3
WILT-PERM	Water content between wilting point (pF3)	m^3/m^3
Hydrologic_Soil_Group	Hydrologic Soil Group	A (low runoff potential), A/D, B (moderately low runoff potential), B/D, C (moderately high runoff potential), C/D, D (high runoff potential)

The variables listed in the above table are provided for all six standard depths, except for the Hydrologic Soil Group which is calculated for the soil layer as a whole. In addition, the soil hydraulic properties were aggregated for the layers that constitute the topsoil (standard depth 1, 2 and 3; 0-30 cm) and for the layers that constitute the subsoil (standard depth 4, 5 and 6; 30-200 cm). The pixel size of all output rasters is 250m x 250m.

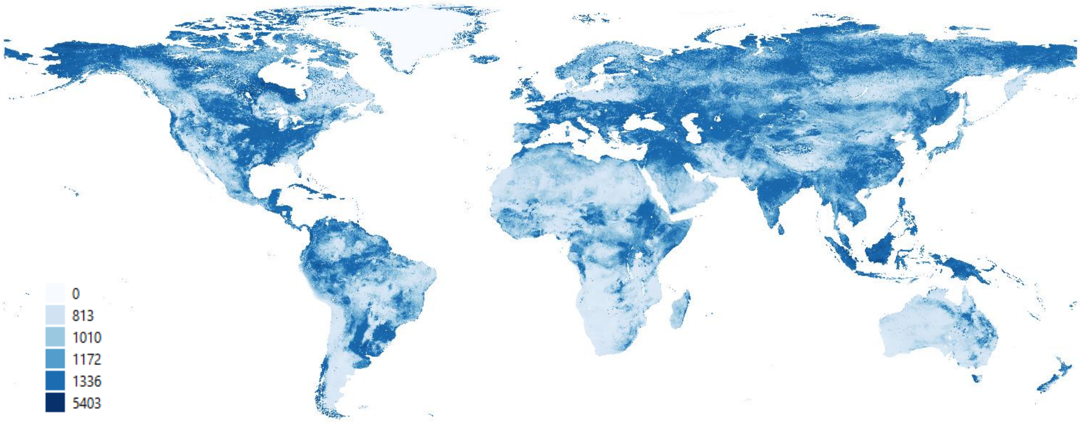

Figure 3. Global map of Water Content at pF4.2 (permanent wilting point) as contained by HiHydroSoil v2.0. Values are in m^3/m^3 multiplied by 10,000 (see section below).

3.2 Accessibility and use

The HiHydroSoil v2.0 database can be accessed through the FutureWater website: www.futurewater.eu/hihydrosoil. After filling the brief request from, a download link to the full dataset will be provided. The HiHydroSoil v2.0 dataset is organized in two folders, one containing the original data for each of the six depths, and one with the aggregated subsoil and topsoil data. All data layers are delivered in geotiff raster format.

To avoid lengthy download times, the data layers originally consisting of float data type were multiplied by a factor of 10,000, and subsequently converted to integer type. It is therefore required to translate the data to the proper units by multiplying with 0.0001. These steps are also described in the readme file delivered with the data.

HiHydroSoil v2.0 can be used freely. It is required to properly cite HiHydroSoil v2.0 in the publication of any research study or report, by referring to this FutureWater report[1].

Further options for disseminating HiHydroSoil v2.0 data through other platforms, e.g. allowing for creation of subset by the user prior to downloading, are currently being explored.

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[1] Simons, G., R. Koster, and P. Droogers, 2020. HiHydroSoil v2.0 - A high resolution soil map of global hydraulic properties. FutureWater report 134, Wageningen, The Netherlands.

4 HiHydroSoil use cases

4.1 Synthesis of HiHydroSoil applications

Due to its gridded nature and relatively high level of detail, HiHydroSoil data have been frequently used over the past 5 years, in technical consultancy studies as well as academic projects. Scientific publications making use of HiHydroSoil include for example Flach et al., (2020), Poortinga et al. (2017), Vereecken et al. (2019). Wijngaard et al., (2018 and 2017), Biemans et al. (2019), Hamel et al. (2017), Mandle et al. (2017), Ofosu et al. (2020), and Faure (2018). In addition, studies based on HiHydroSoil have been presented at various research conferences[1][2][3]. Technical reports using HiHydroSoil include those focusing on assessing ecosystem services, involving work of NGOs like IUCN (Beatty et al., 2018) and WWF (Wolny et al., 2016). In addition, HiHydroSoil was used as the default dataset for soil hydraulic information in Water Accounting reports published by FAO for multiple river basins around the globe[4].

HiHydroSoil applications can be divided in three main categories: stand-alone spatial analyses of hydraulic soil properties in a study area, applications in GIS-based suitability or opportunity mapping by integrating HiHydroSoil with other environmental variables, and using HiHydroSoil as input to grid-based quantitative simulation models such as Spatial Processes in Hydrology (SPHY, Terink et al., 2015) and the Integrated Valuation of Ecosystem Services and Tradeoffs suite (InVEST, Toft et al., 2019). The InVEST documentation recommends HiHydroSoil as the data source for obtaining hydraulic conductivity and Hydrological Soil Group data[5]. As a result, many applications of InVEST in recent years to derive hydrological ecosystem services have been based on HiHydroSoil data.

The sections below provide a few illustrations of recent use of HiHydroSoil data concerning the two latter types of application.

4.2 HiHydroSoil as the default in SPHY model setup

HiHydroSoil was included by FutureWater as the standard input dataset for soil hydraulic properties in the SPHY QGIS pre-processor plugin[6]. Data layers in HiHydroSoil and data requirements of SPHY (K_{sat}, *WCpF2*, *WCpF3*, *WCpF4.2*) are consistent, allowing for the easy creation of grid-based spatial hydrological models.

One example of a SPHY model application based on HiHydroSoil is the analysis and prioritization of landscape restoration options in Madagascar, executed by FutureWater under assignment of the World Bank[7]. Various pilot catchments in Madagascar were evaluated, including the Marovoay catchment in the northeast of the country

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[1] http://olam-soil.org/wp-content/uploads/2017/11/Presentation_soil_structure_SF_fatichi.pdf
[2] http://conference.tr32.de/thursday/1B_Robert_Walko_OLAM-SOIL_Bonn2.pdf
[3] https://www.gh2mf2.org/2019/07/30/a-pilot-hydrological-modelling-in-transboundary-koshi-river-basin-tibetchina-nepal-india/
[4] http://www.fao.org/in-action/remote-sensing-for-water-productivity/resources/publications/wapor-publications/en/
[5] https://storage.googleapis.com/releases.naturalcapitalproject.org/invest-userguide/latest/seasonal_water_yield.html
[6] http://www.sphy.nl/software/
[7] https://www.futurewater.eu/projects/laurel/

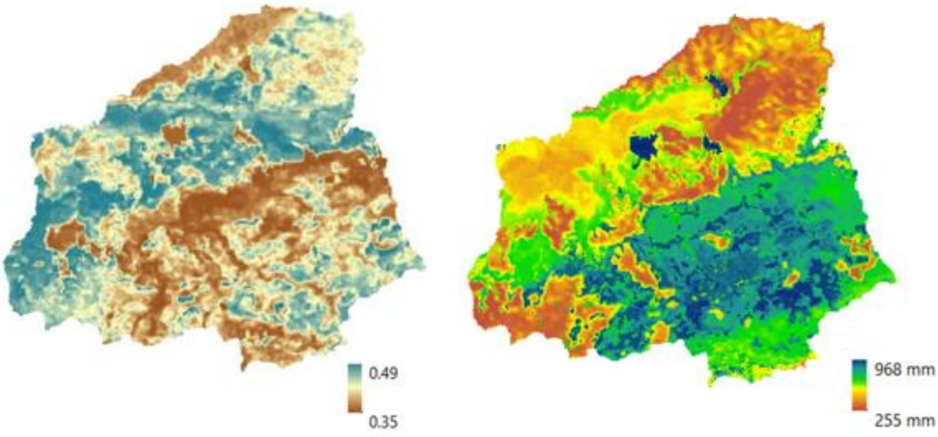

Figure 4. Rootzone saturated water content from HiHydroSoil (left) and average annual evapotranspiration computed by SPHY (right) in Marovoay catchment, Madagascar. Note that the relation between the maps is counterintuitive in certain areas, as other factors such as land use are also incorporated in the model.

4.3 Assessment of hydrological ecosystem services in the Inle Lake catchment, Myanmar

Under assignment of UNDP Myanmar, FutureWater is working on the mapping of ecosystem services in the catchment of Inle Lake[1]. Here, the sediment delivery ratio and seasonal water yield modules of the InVEST suite are applied to map various ecosystem services, such as the reduction of sediment inflow into the lake, the reduction of fast runoff, and contribution to baseflow (dry season water availability, Figure 5). Soil hydraulic properties such as saturated hydraulic conductivity and available water content play an important role in determining the spatial variability of these ecosystem services.

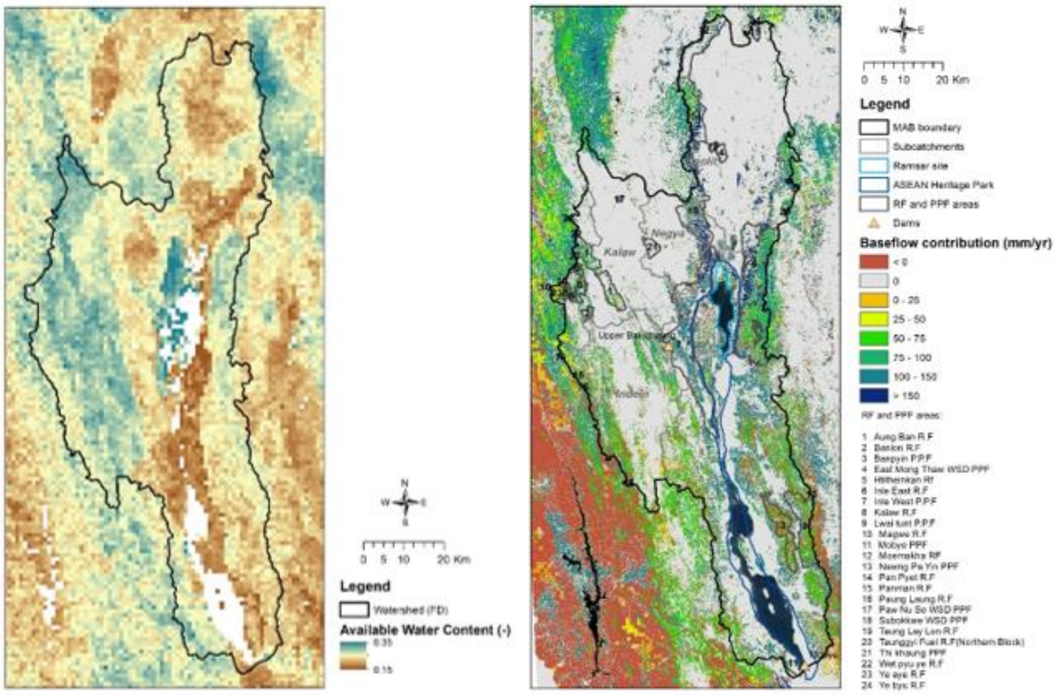

Figure 5. Available water content for the InleLake drainage basin (left) and one of the derived ecosystem services: contribution to baseflow (right).

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[1] https://www.futurewater.eu/projects/boundary-demarcation-and-ecosystem-services-mapping-of-inle-lake-region-myanmar/

4.4 Using HiHydroSoil for agricultural land suitability mapping in Angola

Next to applications in dynamic modelling, HiHydroSoil is also valuable in characterizing a study area in terms of opportunities for certain land management practices, land use changes, or infrastructural measures. An example is the study of agricultural land suitability conducted by FutureWater in Huambo Province, Angola[1]. By integrating the soil hydraulic properties with other parameters such as terrain slope, climate conditions, and soil nutrients, suitability maps were created for three main crops in different growing seasons. This information supports decisions on spatial planning, crop selection and choice of planting dates.

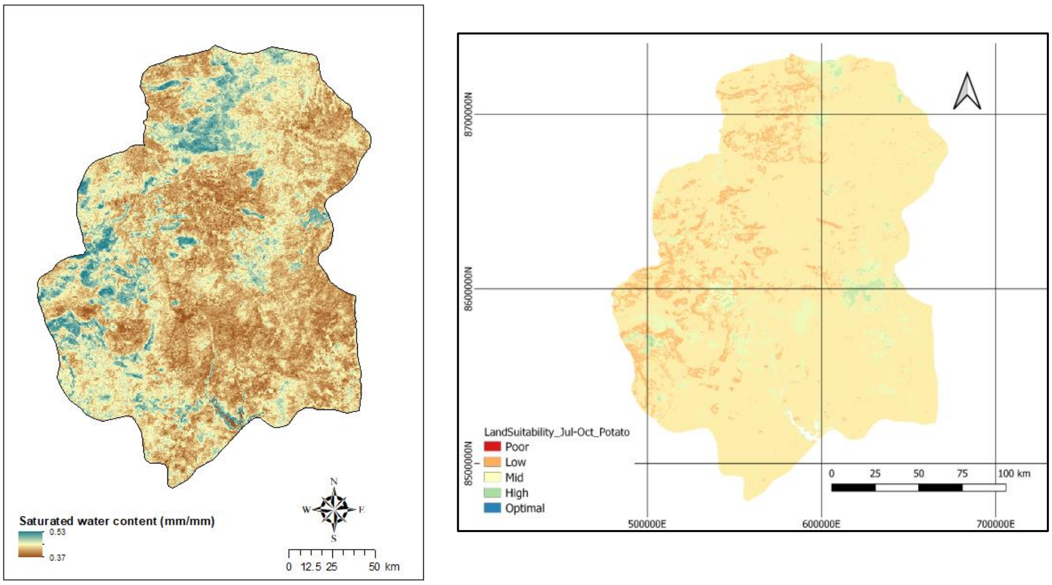

Figure 6. Saturated water content of the topsoil in Huambo Province, Angola, according to HiHydroSoil v1.2 (left), and suitability map for potato cultivation in the July-October growing season (right).

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[1] https://www.futurewater.eu/projects/land-suitability-assessment-angola/

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Annex 1: Mualem Van Genuchten Model

Soil Moisture Retention curve

To calculate water content at a certain pressure head the moisture retention curve derived by Van Genuchten was used (Khaleel et al., 1995)[1]:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|\psi|)^n]^{1-1/n}}$$

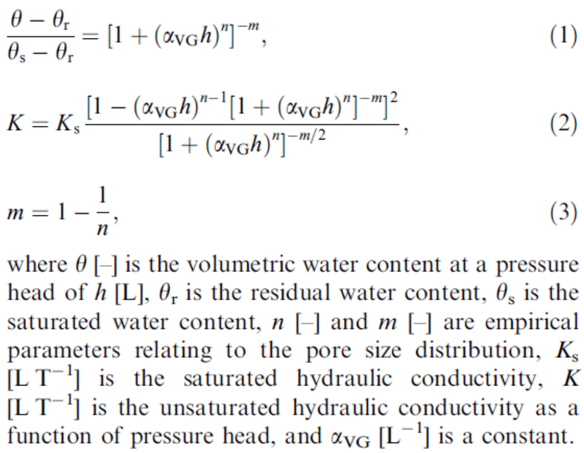
where
θ is volumetric moisture content ($m^3\ m^{-3}$);
θ_s is saturated moisture content ($m^3\ m^{-3}$);
θ_r is residual moisture content ($m^3\ m^{-3}$);
α is a van Genuchten curve-fitting parameter (1/cm);
ψ is matric potential or pressure head (-cm);
n is a van Genuchten curve-fitting parameter (-);
m is 1 - 1/n.

Critical Water Content Values

For calculation of the water content at pF2 with the van Genuchten equation as pressure head of -100 cm was used, for pF3 a pressure head of -1000 cm was taken and for pF 4.2 a pressure head of -16,000 cm was assumed.

Hydraulic conductivity curve

For calculating unsaturated hydraulic conductivity for a certain pressure head the original van Genuchten equation with Mualem substitution (Equation 1 in Figure 7) was used, the value of L was assumed to be 0.5 and K_0 was equal to the K_{sat} that was derived with a pedotransfer function (see Chapter 3). This results in Equation 2 in Figure 7 (Rucker et al., 2005):



$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = [1 + (\alpha_{VG} h)^n]^{-m}, \qquad (1)$$

$$K = K_s \frac{[1 - (\alpha_{VG} h)^{n-1}[1 + (\alpha_{VG} h)^n]^{-m}]^2}{[1 + (\alpha_{VG} h)^n]^{-m/2}}, \qquad (2)$$

$$m = 1 - \frac{1}{n}, \qquad (3)$$

where θ [–] is the volumetric water content at a pressure head of h [L], θ_r is the residual water content, θ_s is the saturated water content, n [–] and m [–] are empirical parameters relating to the pore size distribution, K_s [L T^{-1}] is the saturated hydraulic conductivity, K [L T^{-1}] is the unsaturated hydraulic conductivity as a function of pressure head, and α_{VG} [L^{-1}] is a constant.

Figure 7. Van Genuchten model equations (Rucker et al., 2005)[2].

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