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# pedon: A Python package for analyzing unsaturated soil hydraulic properties

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## Summary

pedon is a Python package for describing and analyzing unsaturated soil hydraulic properties. It provides a framework for soil hydraulic models, along with tools for retrieving parameters from soil databases, applying pedotransfer functions, and fitting soil hydraulic parameters to measurements.

## Statement of need

Researchers and engineers working with unsaturated soils need estimates of soil parameters for variably saturated groundwater flow models. pedon provides a Python toolkit that brings together soil hydraulic models, parameter databases, pedotransfer functions, and fitting routines, making soil analysis faster, more reproducible, and easier to integrate into existing groundwater modeling workflows.

## Soil hydraulic models

A soil hydraulic model is a parametric description of soil hydraulic functions: the soil water retention curve (SWRC) and the unsaturated hydraulic conductivity function (HCF). These relate soil water content and flow to pressure head and vice versa for use in variably saturated groundwater flow models. At this time, pedon provides the following soil models:

- `pedon.Genuchten`: Mualem-van Genuchten (van Genuchten, 1980)
- `pedon.Brooks`: Brooks-Corey (Brooks & Corey, 1964)
- `pedon.Panday`: Mualem-van Genuchten SWRC and Brooks-Corey HCF (Fuentes et al., 1992; Panday, 2025)
- `pedon.Fredlund`: Fredlund-Xing (Fredlund & Xing, 1994)
- `pedon.Haverkamp`: Haverkamp (Haverkamp et al., 1977)
- `pedon.Gardner`: Gardner(-Kozeny) (Bakker & Nieber, 2009; Brutsaert, 1967; Gardner, 1958; Mathias & Butler, 2006)
- `pedon.Rucker`: Gardner-Rucker (Rucker et al., 2005)
- `pedon.GenuchtenGardner`: Mualem-van Genuchten SWRC and Gardner HCF (Gardner, 1958; van Genuchten, 1980)

### Software design

The soil models are implemented as Python classes with model-specific methods for evaluating the SWRC and HCF. For example, the Mualem–van Genuchten model can be used as follows:

```python
import numpy as np
import pedon as pe

mg = pe.Genuchten(
    k_s=106.1,  # saturated conductivity (cm/d)
    theta_r=0.065,  # residual water content (-)
    theta_s=0.41,  # saturated water content (-)
    alpha=0.075,  # shape parameter (1/cm)
    n=1.89,  # shape parameter (-)
)

h = np.logspace(-2, 6, 9)  # pressure head (cm)
theta = mg.theta(h)  # water content (-) at pressure head values
k = mg.k(h)  # hydraulic conductivity (cm/d) at pressure head values
```

The object-oriented design and duck typing provides a clear and consistent structure in which users can define custom soil model classes. Additionally, pedon only depends on well-maintained packages in the Python scientific ecosystem such as NumPy (Harris et al., 2020), SciPy (Virtanen et al., 2020), Matplotlib (Hunter, 2007), and Pandas (McKinney, 2010; The pandas development team, 2020).

# Soil hydraulic parameters

Soil hydraulic parameters depend on soil type and determine the shape of a soil model's SWRC and HCF. They are rarely measured directly and are usually derived from reference datasets, empirical relationships, or laboratory measurements. pedon links these parameters to soil models and provides a framework to obtain them from existing datasets, easily measured soil properties, and direct measurements of soil water content and hydraulic conductivity.

## Parameter datasets

pedon includes a dataset of Brooks–Corey and Mualem–van Genuchten parameters for a wide range of soils. At present, this dataset is compiled from three established soil hydraulic parameter databases:

- Average parameter values for twelve major soil textural groups defined by Carsel & Parrish (1988), also used in the HYDRUS software for variably saturated flow modeling (Šimůnek et al., 2009);
- A dataset from the VS2D software (Healy, 1990) containing both Brooks–Corey and Mualem–van Genuchten parameters;
- The Staring series from the Netherlands (Heinen et al., 2020, 2022; Wösten et al., 2001), which describes soils using the Mualem–van Genuchten model based on hundreds of processed samples (van Genuchten, 1980; Wösten & van Genuchten, 1988).

The databases can be called via the following code:

```python
hydrus = pe.Soil("Sand").from_name(pe.Genuchten, source="HYDRUS")
vs2d = pe.Soil("Sand").from_name(pe.Brooks, source="VS2D")
staring = pe.Soil("B01").from_name(pe.Genuchten, source="Staring_2018")
```

## Parameter estimation

pedon provides two approaches for obtaining soil hydraulic parameters from soil data. The first uses pedotransfer functions based on easily measured soil properties. The second relies on direct measurements of soil water content and hydraulic conductivity.

### Pedotransfer functions

Pedotransfer functions relate easily measured soil properties (e.g. sand, silt, clay or organic matter content and bulk density) to soil hydraulic parameters (Bouma, 1989). pedon implements functions from the literature, including those of Wösten et al. (1999), Wösten et al. (2001), Cosby et al. (1984), and Cooper et al. (2021). It also provides access to parameter databases such as Rosetta (Schaap et al., 2001) and HYPAGS (Peche et al., 2024), the latter enabling estimation from a single value of saturated hydraulic conductivity or representative grain diameters.

```python
# Estimate parameters using Cosby's pedotransfer function
sand_p = 40.0  # sand (%)
clay_p = 10.0  # clay (%)
cosby: pe.Brooks = pe.SoilSample(sand_p=sand_p, clay_p=clay_p).cosby()

# Estimate parameters from saturated conductivity via HYPAGS
ks = 1e-4  # saturated hydraulic conductivity (m/s)
hypags: pe.Genuchten = pe.SoilSample(k=ks).hypags()
```

### Soil hydraulic measurements

pedon can estimate parameters directly when measurements of soil water retention and/or unsaturated hydraulic conductivity are available. A soil model, together with its SWRC and HCF, is fitted to the data by minimizing the difference between measured and simulated values. This uses nonlinear least-squares algorithm from SciPy (Virtanen et al., 2020) and follows the well-established methodology of the RETC software (van Genuchten et al., 1991).

### Soil model conversion

The same fitting procedure can translate between soil models. The SWRC and HCF generated by one model are sampled over a range of pressure heads and refitted using another formulation. This enables direct model comparison (Figure 1) and facilitates integration with external tools when a different model is required.

```python
# Fitting a Brooks-Corey soil model to existing Mualem-van Genuchten soil model
bc = pe.SoilSample(h=h, theta=theta, k=k).fit(pe.Brooks)
```

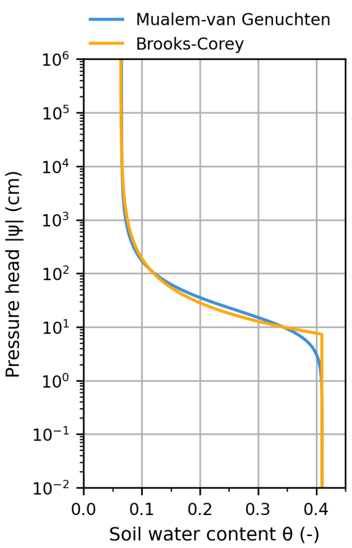


**Figure 1:** Resulting Brooks-Corey SWRC after fitting on the Mualem-van Genuchten soil model

## Research impact statement

Soil hydraulic functions and their parameters are essential for simulating variably saturated groundwater flow. Determining these parameters experimentally is difficult, time-consuming, and uncertain (Brandhorst et al., 2017; van Genuchten et al., 1991). Therefore, parameters are often approximated or estimated from reference databases. pedon bundles soil hydraulic models and parameter sources in a single framework, enabling efficient parameter derivation without extensive literature searches or ad hoc reimplementation. pedon is already used in scientific workflows for variably saturated groundwater flow modeling, including published studies by Vonk et al. (2024) and Collenteur et al. (2025). It is also a dependency of the Python package `dutchsoils`, which is used in a academic context to process Dutch soil datasets (Heinen et al., 2022).

## AI usage disclosure

GitHub Copilot was used during development for reviewing pull requests, writing unit tests, providing code completion, and sanity-checking proposed bug fixes. ChatGPT was used for this manuscript to review references, identify linguistic and grammatical errors, and verify compliance with the Journal of Open Source Software requirements. All AI-generated outputs were reviewed by the authors, who take full responsibility for the accuracy and originality of the works.

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