The Journal of Open Source Software

pedon: A Python package for analyzing unsaturated soil hydraulic properties

Martin A. Vonk [1,2] **and Aaron Peche** [3]

1 Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, South Holland, The Netherlands **2** Artesia B.V., Schoonhoven, South Holland, The Netherlands **3** Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Lower Saxony, Germany

DOI: 10.21105/joss.10409

Software

- Review
- Repository
- Archive

Editor: Jayaram Hariharan

Reviewers:

- @tmweigand
- @keurfonluu
- @gmarupilla

Submitted: 12 January 2026
Published: 23 June 2026

Summary

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

Statement of need

Researchers and engineers working with unsaturated soils need estimates of soil hydraulic model parameters for groundwater 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 (or soil model for short) 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 (1976) - van Genuchten (1980)
- `pedon.Brooks`: Brooks & Corey (1964)
- `pedon.Gardner`: Gardner (1958) HCF with a Kozeny (1927) based SWRC (Bakker & Nieber, 2009; Brutsaert, 1967; Mathias & Butler, 2006)
- `pedon.Campbell`: Campbell (1974)
- `pedon.Haverkamp`: Haverkamp et al. (1977)
- `pedon.Kosugi`: Kosugi (1996)
- `pedon.Fredlund`: Fredlund & Xing (1994)
- `pedon.Brunswick`: Weber et al. (2019); Weber et al. (2020)
- `pedon.Kool`: hysteresis model with Mualem-van Genuchten SWRC and HCF (Kool & Parker, 1987)
- `pedon.Gerke`: dual-porosity model with Mualem-van Genuchten SWRC and HCF (Gerke & van Genuchten, 1993)
- `pedon.Rucker`: van Genuchten-like SWRC and Gardner HCF (Rucker et al., 2005)

- pedon.GenuchtenGardner: van Genuchten SWRC and Gardner HCF (Gardner, 1958; van Genuchten, 1980)
- pedon.Panday: van Genuchten SWRC and Brooks-Corey HCF (Fuentes et al., 1992; Panday, 2026)

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 soil model can be used as follows:

```
# Mualem-van Genuchten parameters for Sandy Loam
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(-1, 6, 8)  # 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 (relying on object methods rather than explicit types) provide 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 determine the shape of a soil model's SWRC and HCF, but are rarely measured directly. To address this, pedon links these parameters to soil models by providing a unified framework to derive them from reference datasets, empirical relationships, or direct (laboratory) measurements.

Parameter datasets

pedon includes a large dataset of soil model parameters for a wide range of soils, currently compiled from the following sources:

- HYDRUS (Carsel & Parrish, 1988; Šimůnek et al., 2008) and the Staring series (Heinen et al., 2020, 2022; Wösten et al., 2001) for Mualem–van Genuchten parameters. HYDRUS provides standard averages across twelve major soil textural groups, while the Staring series derives its values from hundreds of processed Dutch soil samples.
- VS2D (Healy, 1990) and Rawls et al. (1982) for Brooks–Corey parameters.
- Clapp & Hornberger (1978) for Campbell parameters.

For example, a parameter set for a sandy soil (classified as "B05" in the Staring series) can easily be obtained from any of the databases via the following code, enabling direct comparison of the resulting SWRCs (Figure 1).

```
hydrus = pe.Soil("Sand").from_name(pe.Genuchten, source="HYDRUS")
staring = pe.Soil("B05").from_name(pe.Genuchten, source="Staring_2018")
rawls = pe.Soil("Sand").from_name(pe.Brooks, source="Rawls")
clapp = pe.Soil("Sand").from_name(pe.Campbell, source="Clapp")
```

The Journal of Open Source Software

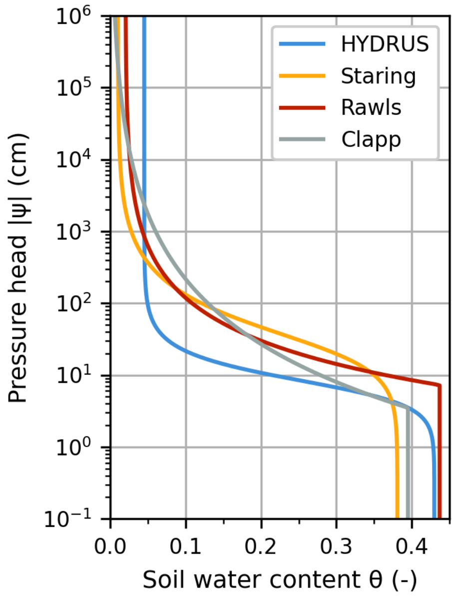

Figure 1: Comparison of SWRCs for a generic sandy soil using parameters retrieved from four different soil databases.

Parameter estimation

pedon provides two approaches for obtaining soil model parameters from soil measurements. 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 model parameters (Bouma, 1989; Van Looy et al., 2017). pedon implements a comprehensive suite of pedotransfer functions from the literature, including those of Cosby et al. (1984), Cooper et al. (2021), Saxton et al. (1986), Saxton & Rawls (2006), Rawls & Brakensiek (1989), Vereecken et al. (1989), Vereecken et al. (1990), Wösten et al. (1999), Rosetta (Schaap et al., 2001; Zhang & Schaap, 2017), Wösten et al. (2001), Hodnett & Tomasella (2002), Weynants et al. (2009), Tóth et al. (2015). The code snippet below shows how to apply three different pedotransfer functions to the same soil sample, resulting in different parameter estimates and thus SWRCs (Figure 2).

```
# Create a soil sample with easily measured properties. Note that
# not all pedotransfer functions require all of these properties,
# but this is a common set that covers most cases.
ss = pe.SoilSample(
    sand_p=60.0,  # sand (%)
    silt_p=30.0,  # silt (%)
    clay_p=10.0,  # clay (%)
    om_p=2.5,  # organic matter (%)
    rho=1.5,  # bulk density (g/cm3)
)

# Estimate van Genuchten parameters using Wösten (HYPRES)
wosten: pe.Genuchten = ss.wosten()
```

```python
# Estimate van Genuchten parameters using Rosetta v3
# Optional dependency requiring installation of `httpx`
rosetta: pe.Genuchten = ss.rosetta(version=3)

# Estimate Brooks-Corey parameters using Saxton
saxton: pe.Brooks = ss.saxton()
```

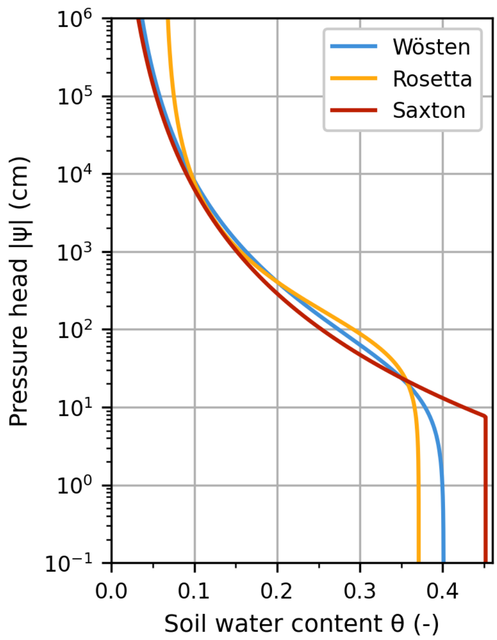

Figure 2: Estimated SWRCs for a single user-defined soil sample using three different pedotransfer functions

Furthermore, pedon provides access to specialized tools such as HYPAGS (Peche et al., 2024; Peche & Houben, 2023) which enables parameter estimation from a single value of saturated hydraulic conductivity or representative grain diameters.

```python
# Estimate parameters using HYPAGS
ks = 1e-3  # saturated hydraulic conductivity (m/s)
hypags: pe.Genuchten = pe.SoilSample(k=ks).hypags()
```

Soil hydraulic measurements

pedon can estimate soil model 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 a 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 3) and facilitates integration with external tools when a different soil model is required (Vonk et al., 2024).

```python
# Fitting a Brooks-Corey soil model to the SWRC and HCF of a
# Mualem-van Genuchten soil model
bcf = pe.SoilSample(h=h, theta=theta, k=k).fit(pe.Brooks)
```

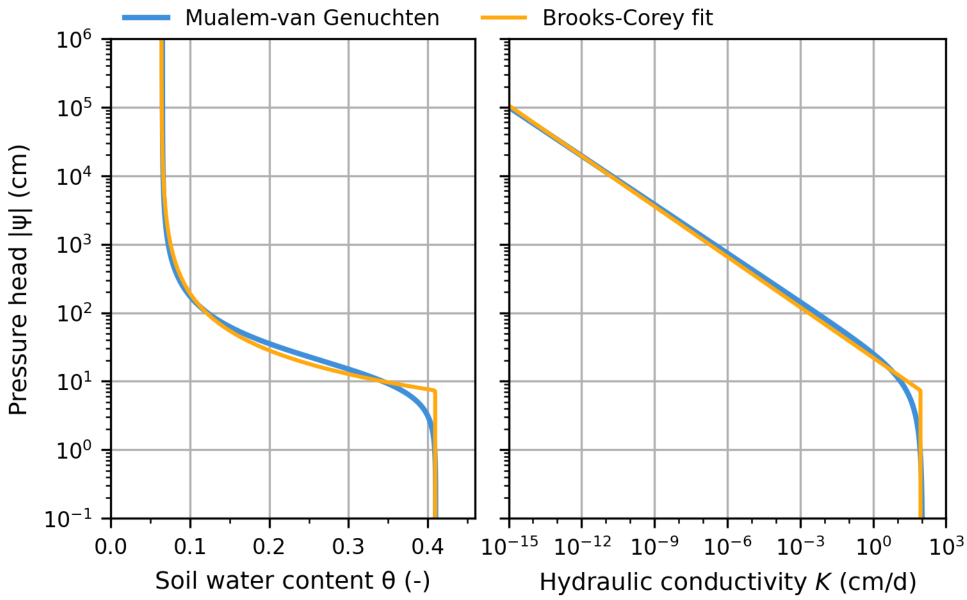

Figure 3: Resulting Brooks-Corey SWRC and HCF after fitting on the Mualem-van Genuchten soil model

State of the field

pedon contributes to the field of groundwater modeling by providing a modular, object-oriented framework that integrates hydraulic soil models, established parameter databases, and pedotransfer functions into a single, reproducible workflow. Existing tools such as unsatfit (Seki et al., 2023), PySWR (Memari & Clement, 2021), and RETC (van Genuchten et al., 1991) are utilities primarily focused on least-squares fitting of predefined soil models. In contrast, pedon enables researchers to define custom soil model formulations and systematically evaluate them against different datasets and pedotransfer functions. This level of interoperability is unique and provides a broader framework for the analysis of unsaturated soil hydraulic properties. At the same time, pedon is developed with a collaborative mindset, exemplified by the integration and extension of the soil model parameter estimation algorithms from HYPAGS (Peche et al., 2024; Peche & Houben, 2023).

Research impact statement

Soil hydraulic models and their parameters are essential for simulating variably saturated groundwater flow (Vereecken et al., 2016). Determining these parameters experimentally is difficult and time-consuming (van Genuchten et al., 1991), and their resulting uncertainty can strongly impact model predictions (Baroni et al., 2010; Brandhorst et al., 2017). Therefore, soil hydraulic model parameters are often approximated or estimated from reference parameter databases. pedon bundles soil models and parameter sources in a single framework, enabling efficient parameter derivation without extensive literature searches or ad hoc reimplementation. pedon (Vonk & Peche, 2026) is already used in scientific workflows for groundwater modeling, including published studies by Vonk et al. (2024) and Collenteur et al. (2025). Here, pedon can easily facilitate coupling to MODFLOW 6 (Langevin et al., 2017) and MODFLOW-USG

Transport (Panday, 2026) via Python (Bakker et al., 2016; Hughes et al., 2024). Additionally, pedon was used by van den Brink et al. (2026) to process Dutch soil datasets (Heinen et al., 2022).

AI usage disclosure

GitHub Copilot was used during software development for reviewing pull requests, writing unit tests and documentation, providing code completion, and sanity-checking proposed bug fixes. ChatGPT and Gemini were 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.

References

Bakker, M., & Nieber, J. L. (2009). Damping of sinusoidal surface flux fluctuations with soil depth. *Vadose Zone Journal*, *8*(1), 119–126. https://doi.org/10.2136/vzj2008.0084

Bakker, M., Post, V., Langevin, C. D., Hughes, J. D., White, J. T., Starn, J. J., & Fienen, M. N. (2016). Scripting MODFLOW model development using Python and FloPy. *Groundwater*, *54*(5), 733–739. https://doi.org/10.1111/gwat.12413

Baroni, G., Facchi, A., Gandolfi, C., Ortuani, B., Horeschi, D., & Dam, J. C. van. (2010). Uncertainty in the determination of soil hydraulic parameters and its influence on the performance of two hydrological models of different complexity. *Hydrology and Earth System Sciences*, *14*(2), 251–270. https://doi.org/10.5194/hess-14-251-2010

Bouma, J. (1989). Using soil survey data for quantitative land evaluation. In B. A. Stewart (Ed.), *Advances in soil science* (Vol. 9, pp. 177–213). Springer. https://doi.org/10.1007/978-1-4612-3532-3_4

Brandhorst, N., Erdal, D., & Neuweiler, I. (2017). Soil moisture prediction with the ensemble Kalman filter: Handling uncertainty of soil hydraulic parameters. *Advances in Water Resources*, *110*, 360–370. https://doi.org/10.1016/j.advwatres.2017.10.022

Brooks, R. H., & Corey, A. T. (1964). Hydraulic properties of porous media. In *Hydrology papers 3*. Colorado State University. https://mountainscholar.org/items/3c7b98df-13e3-486c-9d1e-949a7a869f76

Brutsaert, W. (1967). Some methods of calculating unsaturated permeability. *Transactions of the ASAE*, *10*(3), 400–404. https://doi.org/10.13031/2013.39683

Campbell, G. S. (1974). A simple method for determining unsaturated conductivity from moisture retention data. *Soil Science*, *117*(6), 311–314. https://doi.org/10.1097/00010694-197406000-00001

Carsel, R. F., & Parrish, R. S. (1988). Developing joint probability distributions of soil water retention characteristics. *Water Resources Research*, *24*(5), 755–769. https://doi.org/10.1029/WR024i005p00755

Clapp, R. B., & Hornberger, G. M. (1978). Empirical equations for some soil hydraulic properties. *Water Resources Research*, *14*(4), 601–604. https://doi.org/10.1029/WR014i004p00601

Collenteur, R. A., Vonk, M. A., & Haaf, E. (2025). Quantification and analysis of hydrograph behavior using groundwater signatures. *Groundwater*, *63*(5), 779–789. https://doi.org/10.1111/gwat.13486

Cooper, E., Blyth, E., Cooper, H., Ellis, R., Pinnington, E., & Dadson, S. J. (2021). Using data assimilation to optimize pedotransfer functions using field-scale in situ soil moisture observations. *Hydrology and Earth System Sciences*, *25*, 2445–2461. https://doi.org/10.5194/hess-25-2445-2021

Cosby, B. J., Hornberger, G. M., Clapp, R. B., & Ginn, T. R. (1984). A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils. *Water Resources Research*, *20*(6), 682–690. https://doi.org/10.1029/WR020i006p00682

Fredlund, D. G., & Xing, A. (1994). Equations for the soil-water characteristic curve. *Canadian Geotechnical Journal*, *31*(4), 521–532. https://doi.org/10.1139/t94-061

Fuentes, C., Haverkamp, R., & Parlange, J.-Y. (1992). Parameter constraints on closed-form soil water relationships. *Journal of Hydrology*, *134*(1), 117–142. https://doi.org/10.1016/0022-1694(92)90032-Q

Gardner, W. R. (1958). Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. *Soil Science*, *85*(4), 228–232. https://doi.org/10.1097/00010694-195804000-00006

Gerke, H. H., & van Genuchten, M. Th. (1993). A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. *Water Resources Research*, *29*(2), 305–319. https://doi.org/10.1029/92WR02339

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., Fernández del Río, J., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nature*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Haverkamp, R., Vauclin, M., Touma, J., Wierenga, P. J., & Vachaud, G. (1977). A comparison of numerical simulation models for one-dimensional infiltration. *Soil Science Society of America Journal*, *41*(2), 285–294. https://doi.org/10.2136/sssaj1977.03615995004100020024x

Healy, R. W. (1990). Simulation of solute transport in variably saturated porous media with supplemental information on modifications to the U.S. Geological Survey computer program VS2D. In *Water-resources investigations report*. U.S. Geological Survey. https://doi.org/10.3133/wri904025

Heinen, M., Bakker, G., & Wösten, J. H. M. (2020). *Waterretentie- en doorlatendheidskarakteristieken van boven- en ondergronden in Nederland: De Staringreeks; (update 2018)* (No. 2978). Wageningen Environmental Research. https://doi.org/10.18174/512761

Heinen, M., Mulder, H. M., Bakker, G., Wösten, J. H. M., Brouwer, F., Teuling, K., & Walvoort, D. J. J. (2022). The Dutch soil physical units map: BOFEK. *Geoderma*, *427*, 116123. https://doi.org/10.1016/j.geoderma.2022.116123

Hodnett, M. G., & Tomasella, J. (2002). Marked differences between van Genuchten soil water-retention parameters for temperate and tropical soils: A new water-retention pedo-transfer functions developed for tropical soils. *Geoderma*, *108*(3–4), 155–180. https://doi.org/10.1016/S0016-7061(02)00105-2

Hughes, J. D., Langevin, C. D., Paulinski, S. R., Larsen, J. D., & Brakenhoff, D. (2024). FloPy workflows for creating structured and unstructured MODFLOW models. *Groundwater*, *62*(1), 124–139. https://doi.org/10.1111/gwat.13327

Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science & Engineering*, *9*(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

Kool, J. B., & Parker, J. C. (1987). Development and evaluation of closed-form expressions for hysteretic soil hydraulic properties. *Water Resources Research*, *23*(1), 105–114. https://doi.org/10.1029/WR023i001p00105

Kosugi, K. (1996). Lognormal distribution model for unsaturated soil hydraulic properties. *Water Resources Research*, *32*(9), 2697–2703. https://doi.org/10.1029/96WR01776

Kozeny, J. (1927). Ueber kapillare leitung des wassers im boden. *Sitzungsberichte Der Akademie Der Wissenschaften in Wien, Mathematisch-Naturwissenschaftliche Klasse, Abteilung IIa*, *136*, 271–306.

Langevin, C. D., Hughes, J. D., Banta, E., Niswonger, R., Panday, S., & Provost, A. (2017). Documentation for the MODFLOW 6 groundwater flow model. In *Techniques and methods*. U.S. Geological Survey. https://doi.org/10.3133/tm6A55

Mathias, S. A., & Butler, A. P. (2006). Linearized Richards' equation approach to pumping test analysis in compressible aquifers. *Water Resources Research*, *42*(6), W06408. https://doi.org/10.1029/2005WR004680

McKinney, W. (2010). Data structures for statistical computing in Python. In *Proceedings of the 9th python in science conference* (pp. 56–61). https://doi.org/10.25080/Majora-92bf1922-00a

Memari, S. S., & Clement, T. P. (2021). PySWR - a Python code for fitting soil water retention functions. *Computers & Geosciences*, *156*, 104897. https://doi.org/10.1016/j.cageo.2021.104897

Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, *12*(3), 513–522. https://doi.org/10.1029/WR012i003p00513

Panday, S. (2026). *USG-Transport: Transport and other enhancements to MODFLOW-USG. Version: 2.7.0*. GSI Environmental. https://www.gsienv.com/software/modflow-usg/modflow-usg/

Peche, A., & Houben, G. J. (2023). Estimating characteristic grain sizes and effective porosity from hydraulic conductivity data. *Groundwater*, *61*(4), 574–585. https://doi.org/10.1111/gwat.13266

Peche, A., Houben, G., & Altfelder, S. (2024). Approximation of van Genuchten parameter ranges from hydraulic conductivity data. *Groundwater*, *62*(3), 469–479. https://doi.org/10.1111/gwat.13365

Rawls, W. J., & Brakensiek, D. L. (1989). Estimation of soil water retention and hydraulic properties. In H. J. Morel-Seytoux (Ed.), *Unsaturated flow in hydrologic modeling: Theory and practice* (pp. 275–300). Springer Netherlands. https://doi.org/10.1007/978-94-009-2352-2_10

Rawls, W. J., Brakensiek, D. L., & Saxton, K. E. (1982). Estimation of soil water properties. *Transactions of the ASAE*, *25*(5), 1316–1320. https://doi.org/10.13031/2013.33720

Rucker, D. F., Warrick, A. W., & Ferré, T. P. A. (2005). Parameter equivalence for the Gardner and van Genuchten soil hydraulic conductivity functions for steady vertical flow with inclusions. *Advances in Water Resources*, *28*(7), 689–699. https://doi.org/10.1016/j.advwatres.2005.01.004

Saxton, K. E., & Rawls, W. J. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal*, *70*(5), 1569–1578. https://doi.org/10.2136/sssaj2005.0117

Saxton, K. E., Rawls, W. J., Romberger, J. S., & Papendick, R. I. (1986). Estimating generalized soil-water characteristics from texture. *Soil Science Society of America Journal*, *50*(4), 1031–1036. https://doi.org/10.2136/sssaj1986.03615995005000040039x

Schaap, M. G., Leij, F. J., & van Genuchten, M. Th. (2001). Rosetta: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. *Journal* *of Hydrology*, *251*(3–4), 163–176. https://doi.org/10.1016/S0022-1694(01)00466-8

Seki, K., Toride, N., & van Genuchten, M. Th. (2023). Evaluation of a general model for multimodal unsaturated soil hydraulic properties. *Journal of Hydrology and Hydromechanics*, *71*(1), 22–34. https://doi.org/10.2478/johh-2022-0039

Šimůnek, J., van Genuchten, M. Th., & Šejna, M. (2008). Development and applications of the HYDRUS and STANMOD software packages and related codes. *Vadose Zone Journal*, *7*(2), 587–600. https://doi.org/10.2136/vzj2007.0077

The pandas development team. (2020). *Pandas*. Zenodo. https://doi.org/10.5281/zenodo.3509134

Tóth, B., Weynants, M., Nemes, A., Makó, A., Bilas, G., & Tóth, G. (2015). New generation of hydraulic pedotransfer functions for Europe. *European Journal of Soil Science*, *66*(1), 226–238. https://doi.org/10.1111/ejss.12192

van den Brink, J. M., van Dam, J. C., Mulder, H. M., Ritsema, C. J., & Bartholomeus, R. P. (2026). Effect of increasing conceptual model detail on simulated crop yield-drainage base relations. *Agricultural Water Management*, *329*, 110383. https://doi.org/10.1016/j.agwat.2026.110383

van Genuchten, M. Th. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

van Genuchten, M. Th., Leij, F. J., & Yates, S. R. (1991). *The RETC code for quantifying the hydraulic functions. Version 1.0*. U.S. Salinity Laboratory, USDA, ARS. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=130162

Van Looy, K., Bouma, J., Herbst, M., Koestel, J., Minasny, B., Mishra, U., Montzka, C., Nemes, A., Pachepsky, Y. A., Padarian, J., Schaap, M. G., Tóth, B., Verhoef, A., Vanderborght, J., van der Ploeg, M. J., Weihermüller, L., Zacharias, S., Zhang, Y., & Vereecken, H. (2017). Pedotransfer functions in earth system science: Challenges and perspectives. *Reviews of Geophysics*, *55*(4), 1199–1256. https://doi.org/10.1002/2017RG000581

Vereecken, H., Maes, J., & Feyen, J. (1990). Estimating unsaturated hydraulic conductivity from easily measured soil properties. *Soil Science*, *149*(1), 1–12. https://doi.org/10.1097/00010694-199001000-00001

Vereecken, H., Maes, J., Feyen, J., & Darius, P. (1989). Estimating the soil moisture retention characteristic from texture, bulk density, and carbon content. *Soil Science*, *148*(6), 389–403. https://doi.org/10.1097/00010694-198912000-00001

Vereecken, H., Schnepf, A., Hopmans, J. W., Javaux, M., Or, D., Roose, T., Vanderborght, J., Young, M. H., Amelung, W., Aitkenhead, M., Allison, S. D., Assouline, S., Baveye, P., Berli, M., Brüggemann, N., Finke, P., Flury, M., Gaiser, T., Govers, G., … Huisman, J. A. (2016). Modeling soil processes: Review, key challenges, and new perspectives. *Vadose Zone Journal*, *15*(7), vzj2016.04.0033. https://doi.org/10.2136/vzj2015.09.0131

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy 1.0 Contributors. (2020). SciPy 1.0: Fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2

Vonk, M. A., Collenteur, R. A., Panday, S., Schaars, F., & Bakker, M. (2024). Time series analysis of nonlinear head dynamics using synthetic data generated with a variably saturated model. *Groundwater*, *62*(5), 748–760. https://doi.org/10.1111/gwat.13403

Vonk, M. A., & Peche, A. (2026). *pedon: A Python package for analyzing unsaturated soil hydraulic properties* (Version 0.1.0). Zenodo. https://doi.org/10.5281/zenodo.20590480

Weber, T. K. D., Durner, W., Streck, T., & Diamantopoulos, E. (2019). A modular framework for modeling unsaturated soil hydraulic properties over the full moisture range. *Water Resources Research*, *55*(6), 4994–5011. https://doi.org/10.1029/2018WR024584

Weber, T. K. D., Finkel, M., da Conceição Gonçalves, M., Vereecken, H., & Diamantopoulos, E. (2020). Pedotransfer function for the Brunswick soil hydraulic property model and comparison to the van Genuchten-Mualem model. *Water Resources Research*, *56*(9), e2019WR026820. https://doi.org/10.1029/2019WR026820

Weynants, M., Vereecken, H., & Javaux, M. (2009). Revisiting Vereecken pedotransfer functions: Introducing a closed-form hydraulic model. *Vadose Zone Journal*, *8*(1), 86–95. https://doi.org/10.2136/vzj2008.0062

Wösten, J. H. M., Nemes, A., Lilly, A., & Le Bas, C. (1999). Development and use of a database of hydraulic properties of European soils. *Geoderma*, *90*, 169–185. https://doi.org/10.1016/S0016-7061(98)00132-3

Wösten, J. H. M., Veerman, G. J., de Groot, W. J. M., & Stolte, J. (2001). *Waterretentie- en doorlatendheidskarakteristieken van boven- en ondergronden in Nederland: De Staringreeks* (No. 153). Alterra. https://edepot.wur.nl/43272

Zhang, Y., & Schaap, M. G. (2017). Weighted recalibration of the Rosetta pedotransfer model with improved estimates of hydraulic parameter distributions and summary statistics (Rosetta3). *Journal of Hydrology*, *547*, 39–53. https://doi.org/10.1016/j.jhydrol.2017.01.004