One Ecosystem 7: e76410
doi: 10.3897/oneeco.7.e76410

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Research Article

Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling

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Academic editor: Ignacio Palomo

Received: 11 Oct 2021 | Accepted: 28 Mar 2022 | Published: 19 Apr 2022

Citation: Dang NA, Jackson BM, Tomscha SA, Lilburne L, Burkhard K, Tran DD, Phi LH, Benavidez R (2022) Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling. One Ecosystem 7: e76410. https://doi.org/10.3897/oneeco.7.e76410

Abstract

Information on soil hydraulic properties (e.g. soil moisture pressure relationships and hydraulic conductivity) is valuable for a wide range of disciplines including hydrology, ecology, environmental management and agriculture. However, this information is often not readily available as direct measurements are costly and time-consuming. Furthermore, as more complex representations of soils are being built into environmental models, users and developers often require sound hydraulic property information, while having limited access to specialist knowledge. Although indirect methods have been developed to obtain soil hydraulic properties from easily measurable or readily available soil properties via pedo-transfer functions (PTFs), few articles provide guidance for obtaining soil hydraulic properties over a wide range of geoclimatic and regional data availability contexts. The aim of this study is, therefore, to develop guidelines and an associated spatially referenced toolbox, NB_PTFs, to speed the process of acquiring sensible soil hydraulic properties for different geoclimatic and data-rich/sparse regions. The guide compiles available information about soil hydraulic properties, as well as a large number (151) of PTFs, not collated in any other guidance to date. NB_PTFs is an open-source ArcGIS toolbox which allows users to quickly get values, graphs and spatial distributions of soil hydraulic properties. The soil hydraulic properties, obtained using the guide and the toolbox, can be used as inputs for various models amongst other purposes. To demonstrate the use of the guidelines and the toolbox in different geoclimatic and data-availability contexts, the paper presents two case studies: the Vietnamese Mekong Delta and New Zealand Hurunui catchment. The Vietnamese Mekong Delta shows the use of these guidelines in a tropical, flat location with limited information on soil physical, chemical and hydraulic properties. The Hurunui catchment represents a case study for a semi-arid and hilly area in an area with detailed soil information.

Keywords

Pedo-transfer functions, soil moisture content, soil water content, soil hydraulic conductivity, data sparse, hydrology

Introduction

Soil is a multicomponent system, consisting of solid particles, liquids, gases and living organisms, that operates at the interface of the lithosphere, hydrosphere, atmosphere and biosphere (Mohamed and Antia 1998). Being situated at this crucial nexus means soil plays a fundamental role in the Earth's ecosystems (Vereecken et al. 2015, Adhikari and Hartemink 2016, Van Looy et al. 2017). In particular, soil's ability to store and filter water governs a wide variety of the Earth's ecosystem functions. Through these hydraulic functions, soil delivers a variety of ecosystem services to humanity, including water retention, water supply, water regulation, flood risk mitigation, sediment retention, water purification, nutrient cycling etc. (Daily et al. (1997), Adhikari and Hartemink (2016), Baveye et al. (2016)). For example, the infiltration of rainwater or irrigation water into soil recharges groundwater, regulating drinking water supplies and the availability of water to crop roots. The integration of infiltration with the storage capacity of soil slows and reduces surface runoff (Baveye et al. 2016). Information on soil hydraulic properties is, therefore, fundamental for describing and predicting water processes, including evapotranspiration, infiltration and runoff, as well as their links to ecosystem processes and services (Montzka et al. 2017).

Soil hydraulic properties are required inputs for many climate, hydrology and crop models (Wösten and Tamari 1999, Nemes et al. 2003, Timlin et al. 2004, Vereecken et al. 2015), but each type of model requires different soil hydraulic properties (Table 1). For example, lumped conceptual catchment models require soil moisture thresholds in both surface and root-zone storage. The semi-distributed model SWAT needs information on soil hydraulic groups, plant available water and saturated hydraulic conductivity (SWAT 2012). Many physics-based, spatially-distributed models and land-surface models require the soil moisture retention curve (SMRC) and hydraulic conductivity curve (HCC) to solve the Richards equation (1930)*[1] (Vereecken et al. 2019). Similarly, crop models also need hydraulic conductivity and SMRC to simulate soil water balance for crop growth predictions (Ma et al. 2009). Soil hydraulic properties are important for irrigation scheduling models and agro-environmental models as well (Castellini and Iovino 2019). Regional and global climate and weather prediction models also require adequate parameterisation of soil hydraulic properties (Montzka et al. 2017).

Table 1.

Examples of models requiring soil hydraulic property inputs.

Model type	**Examples**	**Soil hydraulic property inputs**
Lumped conceptual catchment models	MIKE NAM rainfall – runoff model of DHI Water & Environment (Nielsen and Hansen 1973, DHI 2017b)	- Surface and root-zone soil moisture storage - Infiltration rate at field capacity
	PDM (Probability Distributed Moisture model) (Moore 2007)	- Surface soil moisture storage
	VMH rainfall–runoff model (Willems 2014)	- Surface and root-zone soil moisture storage
Semi-distributed hydrology model	SWAT (SWAT 2012)	- Soil hydraulic groups - Plant available water - Saturated hydraulic conductivity (K_{sat})
Physically based, spatially distributed models	MIKE-SHE (DHI 2017a)	Two-Layer UZ method: - Soil moisture content at saturation, field capacity, wilting point - Saturated hydraulic conductivity - Soil suction at wilting point Richards equation method: - SMRC and HCC
	HYDRUS (Sejna et al. 2012)	- SMRC and HCC to solve Richards equation
	HEC-HMS (Scharffenberg 2016)	Parameters to solve Green and Ampt Loss equation (a simplification of comprehensive Richards equation for unsteady water flow in soil): - Saturated moisture content - Wetting front suction - Saturated hydraulic conductivity
Land-surface models	JULES (Joint UK Land Environment Simulator) (Best et al. 2011)	- SMRC and K_{sat} to solve Richards equation
	NCAR LSM (Bonan 1996)	- SMRC and HCC to solve Richards equation

Model type	Examples	Soil hydraulic property inputs
	Noah-MP (Niu et al. 2011)	Parameter to identify soil moisture factor controlling stomatal resistance: - Soil moisture at wilting point - Soil moisture at field capacity - Saturated matric potential - Wilting matric potential
Crop models	CERES (Crop Environment Resource Synthesis) (Basso et al. 2016)	- Soil moisture content at different depths
	WOFOST (World Food Studies Simulation Model) (Boogaard et al. 2014)	- Moisture storage capacity - Initial available moisture content
	WAVE (Water and Agrochemicals in the soil, crop and Vadose Environment) (Vanclooster et al. 1996)	- SMRC and HCC to solve Richards equation
	SWAP (Soil-Water-Atmosphere-Plant) (Kroes et al. 2008)	- SMRC and HCC to solve Richards equation
	RZWQM2 (Root Zone Water Quality Model) (Ma et al. 2009)	- SMRC - Saturated hydraulic conductivity (K_{sat})
	APSIM (Agricultural Production Systems sIMulator) (Holzworth et al. 2014)	- Air dry moisture content - Initial soil moisture content - Soil moisture content at saturation - Soil moisture content at field capacity - Soil moisture content at permanent wilting point - Plant available water - Saturated hydraulic conductivity (K_{sat})
Irrigation scheduling models	ISAREG (Pereira et al. 2003)	- Soil moisture at wilting point - Soil moisture at field capacity - Plant available water
	ISM (Irrigation Scheduling Model) (George et al. 2000)	- Soil moisture at wilting point - Soil moisture at field capacity - Plant available water
	CROPWAT (Clarke et al. 2000)	- Plant available water - Plant readily available water - Moisture deficit
Agro-environmental models	DSSAT (Decision Support System for Agrotechnology Transfer) (Porter et al. 2019)	- Soil moisture at saturation - Soil moisture at wilting point - Soil moisture at field capacity
Regional and global climate and weather prediction models	Ocean-Land-Atmosphere Model (Fatichi et al. 2020)	- Saturated hydraulic conductivity (K_{sat})
Ecosystem services models	InVEST (Sharp et al. 2021)	- Plant available water
	ARIES (Bagstad et al. 2011)	- Soil infiltration
	Nature Braid (Jackson et al. 2013)	- Permeability class - Drainable water - Plant available water - Saturated hydraulic conductivity

More generic tools that model hydrological ecosystem services often take soil hydraulic properties into account in a less direct way. The Annual Water Yield tool of InVEST model requires a plant available water content*[2] grid to estimate the actual evapotranspiration (Sharp et al. 2021). Average annual soil infiltration is used in ARIES floodwater sink module to find areas with different infiltration capacities (Bagstad et al. 2011). The Nature Braid model (next generation of the Land Utilisation and Capability Indicator model - LUCI) takes information on the storage and permeability capacity of elements within the landscape from soil and land-use data to identify floodwater sinks (Jackson et al. 2013). For these ecosystem service models, quality soil hydraulic data at optimum spatial resolution are important to implement realistic and sustainable land and water management practices (Mishra et al. 1999, Hengl et al. 2015).

Information on soil hydraulic properties is often not available because direct measurements are both labour intensive and expensive (Wösten and Tamari 1999, Nemes et al. 2003, Pachepsky and Rawls 2004). Additionally, it is impossible in practice to measure soil hydraulic properties for large scale hydrological applications (Twarakavi et al. 2009, Ket et al. 2018), such as catchment or regional hydrological models (Pechlivanidis et al. 2011). Furthermore, information on soil hydraulic properties, including soil moisture content, soil moisture retention curve (SMRC), saturated hydraulic conductivity and hydraulic conductivity curve (HCC), is normally unavailable or insufficient in the soil databases of many countries (Jarvis et al. 2002, Patil and Singh 2016). Fine spatial resolution data, hence, rarely exists (Pechlivanidis et al. 2011). The lack of soil hydraulic information remains a major limitation to successful hydrological modelling (Nemes et al. 2003, Smettem et al. 2004, Patil and Singh 2016, Abbaspour et al. 2019). For example, current land-surface models mostly (95%) use default regionally-sourced soil parameters; for example, soil moisture pressure relationships and hydraulic conductivity, which generally do not represent the spatial variability of study areas and cause significant uncertainty in models' output (Van Looy et al. 2017).

Many attempts have been made to statistically correlate soil hydraulic properties with more easily measured soil variables or readily available soil properties via Pedo-transfer functions (PTFs). The development of PTFs has established an important dialogue between soil scientists and hydrologists (Smettem et al. 2004). PTFs are easy to apply, inexpensive, conceptually robust and relatively accurate (Wösten et al. 2001, Jarvis et al. 2002). PTFs are useful for estimating soil hydraulic parameters needed for hydrological modelling and other purposes at different scales (Wösten et al. 2001, Jarvis et al. 2002, Smettem et al. 2004, Guber et al. 2006, Cichota et al. 2013). In this context, PTFs have been implemented in various models, as well as in public domain software frameworks, to simulate the behaviour of complex hydrological models (Flanagan 2004), land-surface models (Van Looy et al. 2017), agricultural systems (Castellini and Iovino 2019) and ecosystem services of soils (Vereecken et al. 2016). How far the potential of PTFs can be taken to support Earth system science applications still needs to be further explored (Van Looy et al. 2017), especially in data-sparse regions (da Silva et al. 2017, Bayabil et al. 2019).

In the last few years, a number of research projects have explored the use of PTFs and available soil maps, such as Soil Grids 1-km, to upscale and map soil hydraulic properties over different scales (Table 2) (Dai et al. 2013, Baveye et al. 2016, Froukje 2016, Montzka et al. 2017, Zhang et al. 2018). Some examples of regions with soil hydraulic property maps include Germany (Behrens and Scholten 2006), tropical South America (Marthews et al. 2014) and Europe (ESDAC 2016). While global and regional data of soil hydraulic properties and PTFs are useful for large-scale studies, they may not be suitable for specific regions or local studies, which require site-specific or finer resolution data. Global datasets often use PTFs developed for specific regions and extrapolate their use to estimate global soil properties, for example, HihydroSoil used the PTFs of Tóth et al. (2015) which were developed for Europe. As such, soil hydraulic property values and maps, which are specific to local soils, are needed. There have been several freely available PTFs software/tools developed to make the process of soil hydraulic properties parameterisation easier and faster. Those tools including CalcPTF (USDA 2010), ROSETTA (Schaap et al. 2001, Zhang and Schaap 2017), SOILPAR (Acutis and Donatelli 2003) etc. which either use PTFs developed by the respective authors or a compilation of published PTFs. However, these tools mostly focus on estimating soil hydraulic properties in temperate climates. In addition, these tools do not regularly update to include recently-developed PTFs.

Table 2.

Several key examples of global maps of soil hydraulic properties, their approach and their input data.

Soil map name/source	**Input data to distribute the value of global soil hydraulic properties**	**PTF and approach**	**Soil hydraulic parameters**
Global Maps of Soil Hydraulic Properties HiHydroSoil 1km (Froukje 2016) and HiHydroSoil 250m (Simons et al. 2020)	SoilGrids 1-km	Tóth et al. (2015) based on regression analysis	Mualem-van Genuchten (MvG) model parameters for SMRC and HCC, soil water at key pressures and saturated hydraulic conductivity
Global soil hydraulic properties map (Montzka et al. 2017)	SoilGrids 1-km	ROSETTA (Schaap et al. 2001, Zhang and Schaap 2017)	Mualem-van Genuchten parameters for SMRC and HCC and saturated hydraulic conductivity
The global maps of soil hydraulic properties (Zhang et al. 2018)	SoilGrids 1-km	Artificial neural networks (ANNs)	Kosugi model's parameters for SMRC and HCC

The determination of soil hydraulic properties for models remains a difficult task due to both the inherent variability of soils and the lack of parameterisation guidance (Beven 1993, Malone et al. 2015). Although an exponential increase in literature devoted to the use and development of hydrological models has been observed over the years, few articles provide general parameterisation guidelines to assist in hydrologic model applications (Malone et al. 2015). Model user manuals often provide very broad value ranges for many parameters, but give severely inadequate guidance on how to assign appropriate values in specific applications (Malone et al. 2015). Sensible parameter selection is critical to model predictive performance and, in most hydrological models, soil hydraulic property parameters are the most sensitive ones (Christiaens and Feyen 2002, Baroni et al. 2010, Yuan et al. 2015, Wesseling et al. 2020), having a very large influence on model results (Malone et al. 2015, Wesseling et al. 2020). It is recognised that developing better soil hydraulic parameterisation guidelines for hydrologic models is likely to help in generating appropriate parameter sets (Ahuja and Ma 2011, Malone et al. 2015). Guidance for using secondary data (through literature and available databases) to optimise parameters is also lacking (Malone et al. 2015). Models are data-intensive and preparing model inputs, including model parameters, consumes a large part of the research time-frame (Abbaspour et al. 2019). Increasing interest in accurate soil water modelling for various purposes is further strengthening the need for detailed guidance for soil hydraulic properties parameterisation, especially for inexperienced modellers.

In response to the current gaps, the first objective of this study is to develop guidelines that assist in parameterisation of soil hydraulic properties for a wide range of climatic and data availability contexts. The guide contains up-to-date information on available soil databases and over 150 PTFs developed for temperate, tropical and arid climates. The guide focuses on the most common soil hydraulic parameters, including soil moisture content at pressures (for example, -0kPa, -1kPa, -10kPa, -20kPa, -33kPa, -100kPa, -200kPa, -500kPa, -1500kPa), soil moisture retention curve (SMRC), saturated hydraulic conductivity (K_{sat}), hydraulic conductivity curve (HCC) and key soil moisture content thresholds for plant growth (saturation point (SAT), field capacity point (FC), stomata closure point (WSC), permanent wilting point (PWP)), as well as availability of soil water to plants (drainable water (DW), plant available water (PAW), readily plant available water (RAW) etc.). In the guide, we also discuss the relationship between infiltration capacity and hydraulic conductivity, which is one of the challenges for moving parameters between physically based and conceptual models. Infiltration capacity is generally a required input for soil water movement conceptual models; however, measuring infiltration capacity through indirect methods is extremely problematic, as it is difficult to relate measured values to the parameters of available infiltration models*[3]. Methods for estimating hydraulic conductivity are more available, although still costly. A better understanding of how infiltration capacity parameters can be estimated from hydraulic conductivity may make infiltration capacity estimates more robust. This is beyond the scope of our current work, but further details on the relationship between the two and methods to use to measure or approximate them are contained in the Suppl. material 1.

The second objective is to develop an ArcGIS toolbox which assists in calculating and mapping soil hydraulic properties from shapefile inputs containing commonly measured soil properties. The tool initially consists of published PTFs for estimating soil moisture content and hydraulic conductivity in temperate, tropical and arid climates. This first implementation of the tool includes:

1. point PTFs for obtaining soil moisture content at particular pressure heads;
2. parametric PTFs for establishing soil moisture content - pressure head relationships;

3. parametric PTFs for soil hydraulic conductivity – pressure head relationships and
4. saturated hydraulic conductivity (K_{sat}) PTFs.

The toolbox was developed as an offshoot of the Nature Braid (NB) model framework . It is both embedded within Nature Braid and available as a stand-alone tool. The tool is still in development for supporting a wider range of PTFs in the future versions. The tool provides:

1. values of soil moisture content at key pressure heads;
2. a graph of SMRC;
3. a graph of HCC;
4. a predicted value of saturated hydraulic conductivity;
5. values of key soil moisture characteristics useful for conceptual models, such as drainable water (DW), plant available water (PAW) and readily plant available water (RAW), as well as
6. shapefile outputs of soil hydraulic properties.

The third objective is to demonstrate the use of the guidelines and toolbox for obtaining soil hydraulic properties required by the Nature Braid model in different geoclimatic conditions and under different levels of data availability with two case studies, Vietnam Mekong Delta (VMD) and Hurunui catchment in the Canterbury region of New Zealand. The VMD provides a case study for a tropical, flat area with extremely limited information regarding soil properties. The three sets of soil maps and soil properties used for the VMD case study are: FAO global soil map and soil properties 2007 (FAO 2007); Mekong River Commission's soil map (MRC 2002) and WISE global soil properties (Batjes 2009); and Vietnamese soil map and WISE global soil properties (Batjes 2009). The Hurunui catchment provides a case study for a semi-arid and hilly area with more detailed information available for soil physical and chemical properties, as well as soil hydraulic properties. The three sets of soil maps and soil properties used for the Hurunui case study are: FAO global soil map and soil properties 2007 (FAO 2007); FSL soil map (Manaaki Whenua - Landcare Research 2010) and WISE global soil properties (Batjes 2009); and S-map and soil properties (Manaaki Whenua - Landcare Research 2020). S-map also provides soil hydraulic properties information which were used to compare with the output of NB_PTFs toolbox. The guidelines and the toolbox are designed to be useful for scientists, researchers, practitioners and planners in parameterising soil hydraulic parameters for their models, especially in data-sparse regions.

Materials and Methods

The guidelines were developed, based on an in-depth review of available resources (databases, tools, publications etc.) to guide the selection of soil hydraulic properties. The guidelines are structured in what we hope is a user-friendly and rapid way to gain information on soil hydraulic properties and give recommendations on how the available resources should be used properly. The associated toolbox, NB_PTFs, provides a convenient way to obtain values, graphs and maps of the spatial distribution of soil hydraulic properties in different data availability and geoclimatic contexts.

Guidelines for parameterising soil hydraulic properties version 1.0

These guidelines were developed to support the process of parameterising soil hydraulic properties required by various models by gathering fragmented data and information on soil hydraulic properties. Fig. 1 presents an overall flow chart for the guidelines. In the current version, the guidelines contain instructions on how to obtain information on soil moisture and hydraulic conductivity. Soil moisture information includes soil moisture at key pressure heads and/or a continuous soil moisture retention curve (SMRC) relating soil moisture to pressure from wilting point or below to saturation. Similarly, soil hydraulic conductivity information includes saturated hydraulic conductivity (K_{sat}), and information on conductivity as pressure drops below saturation and/or the soil hydraulic conductivity curve (HHC).

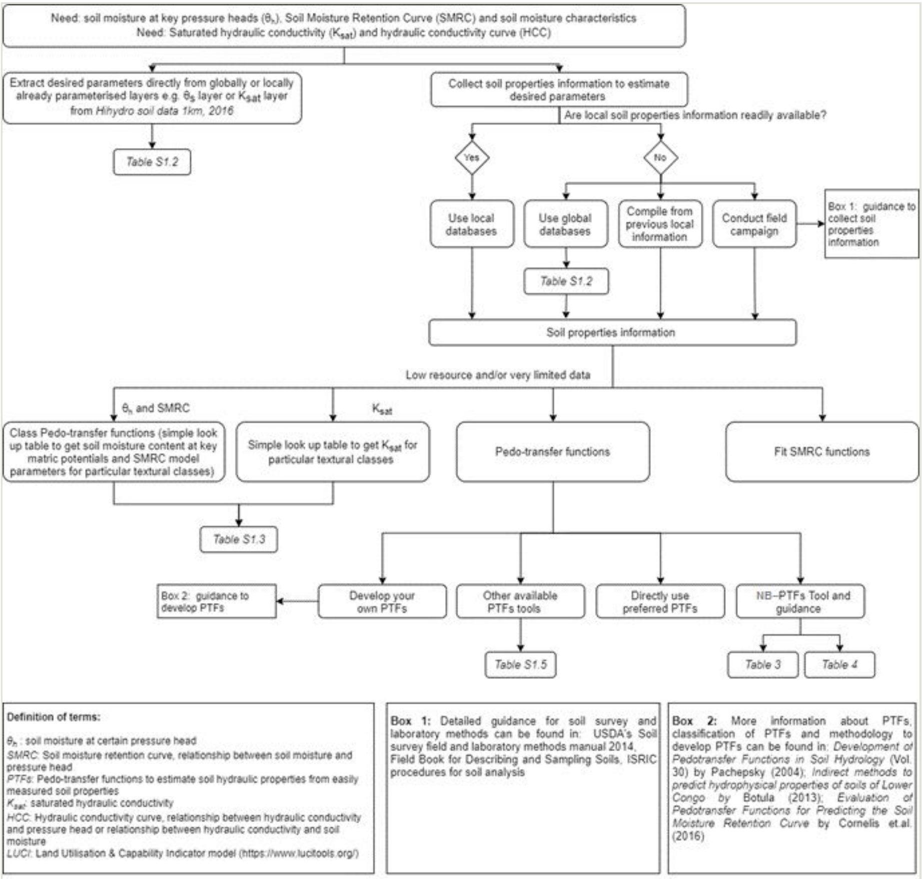

Figure 1.

Overall flowchart of the guidelines for parameterising soil hydraulic properties.

Soil hydraulic information can be obtained directly from global or local databases (Table S1.2, Suppl. material 1). The latest summary of *Soil Physical and Hydraulic Properties databases* is by Nemes (2011). Table S1.2 (Suppl. material 1) gathers soil databases information summarised by Nemes (2011) and other soil databases available to date. The range of properties that the soil databases cover varies; some of the databases are rich in information and some contain less information. Data mostly exist in two main forms: tabular information and gridded maps. For example, SoilGrids^{TM}, which was established using over 230,000 soil profile observations from the WoSIS (World Soil Information Service) database, is the global digital soil mapping system with the highest resolution to date, at 250m and 1 km (Hengl et al. 2015). SoilGrids spatial prediction layers include maps of volumetric moisture content at field capacity and wilting point. While information on soil moisture content can be found in a number of spatial databases, information on hydraulic conductivity is only available in few databases, for example, the Hihydro soil database (Froukje 2016), the SoilKsatDB database (Gupta et al. 2020) and the Global soil hydraulic properties map (Montzka et al. 2017). Measuring K_{sat} remains challenging. K_{sat} depends on the shape, distribution and size of soil pores, as well as the volume of water in these pores (Iwanek 2008). Soil pores are not only influenced by soil texture and structure, but also by biological factors, such as earthworms and vegetation roots (Marapara 2016). These factors make K_{sat} extremely variable, both spatially and temporally (Oosterbaan and Nijland 1994).

An example of tabular data is NRCS-NSSC, which is the largest original data collection that contains soil hydraulic data. Those are, however, typically limited to two or three moisture retention points (-10; -33; and -1500 kPa) and no hydraulic conductivity data are available (Nemes 2011). By contrast, the UNSODA and HYPRES databases contain, for most soils, moisture retention measured at least at 4–8 pressures. More than half the samples in HYPRES and UNSODA also have information on saturated hydraulic conductivity and fewer on unsaturated hydraulic conductivity (Nemes 2011). Another example of tabular data is WISE - Global Soil Profile Data which holds data for 10,250 soil profiles with 47,800 horizons from 149 countries. The WISE database contains information on soil moisture content at -10kPa (pF*[4] 2.0), -33kPa (pF 2.5) and -1500 kPa (pF 4.5). The WISE and IGBP-DIS databases are also the only global datasets containing data for tropical and subtropical countries. If data for moisture retention and unsaturated hydraulic conductivity are available, those data can be fitted to SMRC functions using various data-fitting techniques, for example, utilising mathematical optimisation methods, like the numerical simplex or amoeba algorithms (Pan et al. 2019).

If it is not possible to obtain soil hydraulic information through pre-existing databases, information on soil physical and chemical properties can be collected or compiled for estimating soil hydraulic parameters through PTFs. Depending on the availability of data, time and budget, information on soil physical and chemical properties (soil texture, bulk density, organic matter etc.) can be obtained either from local or global databases (Table S1.2, Suppl. material 1), compiled from local information or sampled through a field campaign. Guidance for field collection and laboratory analysis of soil properties is widely available, for example, the "*USDA's soil survey field and laboratory manual*" (Staff Soil

Survey 2014), the "*Procedures for soil analysis*" (Reeuwijk 2009) or specific guidance for soil survey of each country is also available (Box 1, flowchart, Fig. 1).

The soil data, once collected, can be used to develop PTFs or used as inputs in published PTFs to obtain the required parameters. In these guidelines, we do not provide much detail on the different techniques for developing PTFs, which are well summarised in Wösten et al. (1999) for regression techniques; Pachepsky et al. (1996) and Schaap et al. (1998) for Artificial neural networks (ANNs) techniques; Vapnik (1995) and Lamorski et al. (2008) for Support Vector Machines (SVM) and in Nemes et al. (2006) for k-Nearest Neighbour methods (see Box 2, flowchart, Fig. 1). Since developing new PTFs is a very arduous task which requires a large soil database of good quality, utilising existing PTFs is, for most people, the only practical option (Nguyen et al. 2015). Information on soil hydraulic parameters can be extracted from look-up tables, also called "class PTFs", which provide textural class-average hydraulic parameters (Van Looy et al. 2017). Examples of look-up tables are presented in table S1.3, Suppl. material 1. Two other types of PTFs in the guidelines are point and parametric PTFs which can be used to estimate soil hydraulic parameters from collected/compiled soil physical and chemical properties. Table 3 and Table 4 give detailed guidance as to where the information on PTFs can be found in Suppl. material 1. Point PTFs, a PTF for a single point on the SMRC, for different moisture ranges can be compiled from different studies to best represent soil hydraulic properties of a specific study area. For example, Cichota et al. (2013) found that the PTFs from Saxton and Rawls (2006) performed best at high pressure heads (-1500 kPa to -100 kPa) for New Zealand soils, while the PTFs by Weynants et al. (2009) performed best in the mid-range of pressure heads (-20 kPa to -10 kPa). In addition, depending on the specific characteristics of soil samples and soil properties used to develop PTFs, some PTFs may represent some soil types well, while being inappropriate for others. We, therefore, recommend comparing actual soil data (when available) with different PTFs to choose the one or more PTFs that will provide the most reliable soil hydraulic properties of a specific study.

Table 3.

Guidance for finding information on soil moisture PTFs, depending on data availability and climate context (Sa: Sand; Si: Silt; Cl: Clay; BD: Bulk Density; OM: Organic Matter; OC: Organic Carbon).

No.	Data available	Temperate climate		Tropical climate		Arid climate	
		θ_h	SMRC	θ_h	SMRC	θ_h	SMRC
1	Soil texture (Sa, Si, Cl); BD; OM/OC; and other soil properties	*Table S1.6, section Point PTFs (1)*	*Table S1.6, section SMRC (1)*	*Table S1.7, section Point PTFs (1)*	*Table S1.7, section SMRC (1)*	*Table S1.8, section Point PTFs (1)*	
2	Soil texture (Sa, Si, Cl); BD; OM/OC	*Table S1.6, section Point PTFs (2)*	*Table S1.6, section SMRC (2)*	*Table S1.7, section Point PTFs (2)*	*Table S1.7, section SMRC (2)*	*Table S1.8, section Point PTFs (2)*	
3	Soil texture (Sa, Si, Cl); OM/OC	*Table S1.6, section Point PTFs (3)*		*Table S1.7, section Point PTFs (3)*		*Table S1.8, section Point PTFs (3)*	

No.	Data available	Temperate climate		Tropical climate		Arid climate	
		θ_h	SMRC	θ_h	SMRC	θ_h	SMRC
4	Soil texture (Sa, Si, Cl); BD	*Table S1.6, section Point PTFs (4)*	*Table S1.6, section SMRC (4)*	*Table S1.7, section Point PTFs (4)*		*Table S1.8, section Point PTFs (4)*	*Table S1.8, section SMRC (4)*
5	Soil texture (Sa, Si, Cl)	*Table S1.6, section Point PTFs (5)*	*Table S1.6, section SMRC (5)*	*Table S1.7 , section Point PTFs (5)*		*Table S1.8, section Point PTFs (5)*	

Table 4.

Guidance for finding information on soil hydraulic conductivity PTFs, depending on data availability and climate context.

No.	Data available	Temperate climate		Tropical climate		Arid climate	
		Ksat	HCC	Ksat	HCC	Ksat	HCC
1	Particle size distribution information	*Table S1.9, section K_{sat} (1)*					
2	Particle size distribution information and SMRC models parameters	*Table S1.9, section K_{sat} (2)*					
3	SWRC models parameters	*Table S1.9, section K_{sat} (3)*					
4	Effective porosity	*Table S1.9, section K_{sat} (4)*		*Table S1.10, section K_{sat} (4)*			
5	Soil texture (Sa, Si, Cl) and porosity	*Table S1.9, section K_{sat} (5)*	*Table S1.9, section HCC (5)*	*Table S1.10, section K_{sat} (5)*		*Table S1.11, section K_{sat} (5)*	
6	Soil texture (Sa, Si, Cl); BD; OM/OC	*Table S1.9, section K_{sat} (6)*	*Table S1.9, section HCC (6)*			*Table S1.11, section HCC (6)*	
7	Soil texture (Sa, Si, Cl); OM/ OC	*Table S1.9, section K_{sat} (7)*					
8	Soil texture (Sa, Si, Cl); BD	*Table S1.9, section K_{sat} (8)*		*Table S1.10, section K_{sat} (8)*			
9	Soil texture (Sa, Si, Cl)	*Table S1.9, section K_{sat} (9)*		*Table S1.10, section K_{sat} (9)*			

There have been a large number of PTFs developed to date. The required inputs vary as do the units and pressure heads of the PTF estimates. This can be confusing to users. Our review found various studies using PTFs incorrectly, for example, using PTFs originally designed for gravimetric moisture content to estimate volumetric moisture content. The many issues where originally published PTFs have been referenced, but incorrectly applied - with erroneous mathematical formulations or input units - were highlighted in van Den Berg et al. (1997). Therefore, our guidelines only present for consideration PTFs from original or what we consider to be trustworthy sources for PTFs.

Tools (with embedded PTFs) can be used to get soil hydraulic parameters, for example, Soil PAR, SPAW, CalcPTF or ROSETTA etc. (Table S1.5, Suppl. material 1). The NB_PTFs tool was developed for the same purpose. The tool contains various PTFs to estimate soil moisture and hydraulic conductivity for different climatic regions and provides spatially explicit output. The comparison of the NB_PTFs tool and other PTFs is given in Table S1.5. More details of the NB_PTFs tool are described in the next section.

Tables S1.6, S1.7 and S1.8 (Suppl. material 1) contain 95 soil moisture PTFs and supplementary information for the datasets used to develop them for temperate, tropical and arid climates, respectively. Our guidance, currently version 1.0, compiles PTFs for the van Genuchten model and Brooks & Corey model. In future versions of this guidance, we will include more point PTFs and PTFs to estimate other SMRC functions (table S1.4). The collected PTFs were classified in the five groups depending on their required input parameters (Table 3). Users can select their preferred PTF to estimate required hydraulic parameters, based on the availability of data.

Although K_{sat} is an important input for hydrological models, information on K_{sat} PTFs is disjointed across literature and there are not many available PTFs or tools that estimate K_{sat}. Tables S1.9, S1.10 and S1.11 (Suppl. material 1) contain about 56 PTFs for estimating saturated hydraulic conductivity and hydraulic conductivity characteristics (the *Mualem van Genuchten* model) for temperate, tropical and arid climates, respectively. The PTFs were divided into nine groups representing the differences in required inputs (Table 4).

PTF evaluation is recommended to find the most suitable PTFs for a user's study area. Methods to select PTFs can be found in Nemes et al. (2003), Donatelli et al. (2004) and Givi et al. (2004). The selected PTFs should be from regions having similar climatological and pedological conditions to the user's data. Only a limited number of studies have evaluated datasets of soils from humid and sub-humid tropics (Tomasella and Hodnett 2004, Reichert et al. 2009, Botula et al. 2012). Hodnett and Tomasella (2002) caution the practice of applying PTFs developed using temperate soil databases to soils of the tropics. They observed marked differences between parameters which describe types of soil moisture retention behaviour of soils in temperate vs. tropical climates. Such differences have been attributed to discrepancies in chemical, physical and microbial community properties between soils. Indeed, although the soil-forming factors may be similar in both temperate and tropical climates, the extent of these factors is different. Cornelis et al. (2001) and McBratney et al. (2002), amongst others, warned that the extrapolation of PTFs beyond the statistical limits of the calibration dataset and the geographical locations of soils from which they were developed should be avoided or, at least, carefully evaluated for their predictive quality. Nguyen et al. (2015), amongst others, note that, for a PTF to be considered robust, calibration datasets should be large and representative to account for variability of soil properties in the region of interest. In practice, however, information is significantly sparser than ideal. Another problem is that different countries use different thresholds to classify between silt and sand, hence “silt” may mean something different amongst countries. For example, New Zealand (NZ) defines silt at particle size between 0.002 – 0.06 mm (John et al. 2002) while the United States (US) uses the range 0.002 – 0.05 mm (USDA 1987) and FAO use the range 0.002 – 0.0063 mm to define silt (FAO 2006). Consequently, that leads to the difference in thresholds to define sand amongst classification systems. The silt/clay threshold is more commonly agreed amongst countries with clay defined at less than 0.002 mm. However, accurately differentiating between clay and fine silt is difficult due to limitations in measurement techniques (Genrich 1972, Coates and Hulse 1985). In addition, textural triangles are different amongst countries regarding number of classes, definition of classes (ranges of particle size to define classes) and class names. For example, the US’ textural triangle has silty clay loam which is not included in the NZ one and silt loam in US has 10-20% clay, 60-70% silt and 20% sand, while silt loam in NZ has the texture of 18-35% clay, 40-82% silt and 30% sand. These measurement and classification differences mean PTFs developed in different countries are not necessarily directly comparable even if they appear to have the same texture and classification and/or use similar input data. Where local data are not available, searching for PTFs trained on soils of similar geographic conditions is recommended.

NB_PTFs toolbox version 1.0

NB_PTFs, written in Python (ArcPy), is an open source ArcGIS toolbox that can be used to calculate values, create graphs and a shapefile of soil hydraulic properties, including soil moisture content and hydraulic conductivity. The toolbox has been first developed and is included as part of the Nature Braid framework, but can also be accessed as a stand-alone toolbox. The GitHub link to download NB_PTFs can be found at https://github.com/thenaturebraid/NB_PTFs. The toolbox can be used to guide parameterisation of required soil hydraulic parameters, not only for Nature Braid, but also other models and applications. The uniqueness of this toolbox is that it is specifically developed to support a wide range of different data availability and climate contexts. The tool also seeks to be as user friendly as possible, providing a range of different and complementary output formats including values, graphs and spatial distribution information on soil hydraulic properties.

The toolbox includes PTFs from a wide range of climates including temperate, tropical and arid climates. PTFs included in the toolbox were selected, based on the number of citations from Google Scholar within each climate group, with the PTFs with the highest citations being selected. In our current version 1.0, NB_PTFs contains options for using relatively easily obtained information, such as sand, silt, clay, bulk density etc. to estimate soil moisture content. Currently, it contains twenty-one point-PTFs and seven PTFs estimating parameters for the van Genuchten moisture retention function and six PTFs estimating parameters for the Brooks and Corey function (Suppl. material 2). As for hydraulic conductivity, the toolbox has nine PTF options for K_{sat} estimation and two PTF options for parameterising the Mualem hydraulic conductivity pressure function. Users can select the most suitable PTFs from the drop-down list. Details of the PTFs and the datasets used to develop the PTFs can be found in Suppl. material 1. We recommend that users select

PTFs that were developed in the same climate as their study areas. In addition, users should compare their soil dataset and the dataset used to develop potential PTFs to find the most suitable PTF. NB_PTFs version 1.1 will include additional point PTFs, as well as PTFs for other SMRC models; for example, Campbell and Kosugi. Additional PTFs for K_{sat} and HCC will also be added in future versions. We additionally anticipate these versions may include the option to use Artificial Neural Networks (ANNs) and Supervised Vector Machine (SVM) learning to generate PTFs and map soil hydraulic properties from generated PTFs.

The required input for NB_PTFs is a shapefile containing the information on soil types and properties (sand, silt, clay, organic carbon, bulk density etc.). Users should select suitable PTFs first, then prepare input data, based on the soil properties required for the chosen PTFs. An example of input data can be found in Suppl. material 2. If local soil maps and soil properties are not available, guidance from the previous section can be used to obtain the required input. The input can be point or polygon shapefiles. If polygons are used as an input, the output map can be directly converted to a raster/gridded layer for subsequent spatially-explicit modelling. If points are used as an input, a map of catchment/region soil properties can be produced by either interpolating soil properties then applying PTFs or applying PTFs then interpolating the result to get catchment map of soil hydraulic properties (Picciafuoco et al. 2019).

In the current version, NB_PTFs does not contain an interpolation function. Users need to ensure that the unit of input data is converted to the unit used in the NB_PTFs toolbox (Table 5). If the selected PTFs require organic matter (OM) but the input data only has organic carbon (OC) or inversely, the user can define the conversion factor or use the default factor in the NB_PTFs toolbox. The current default value is 1.724 to convert OC to OM and 0.58 to convert OM to OC (Sleutel et al. 2007). Soil hydraulic properties are different in different soil layers. In our guidelines and tool, some equations that differentiate amongst soil layers (topsoil and subsoil) were included.

Table 5.

Parameters and units for NB_PTFs tool.

Input	Unit
Volumetric moisture content	cm^3 cm^{-3}
Hydraulic conductivity	mm hr^{-1}
Sand content	%
Silt content	%
Clay content	%
Organic matter content	%
Organic carbon content	%
Bulk density	g cm^{-3}
Cation exchange capacity - CEC	cmol kg^{-1}

The toolbox provides a graph of SMRC when the van Genuchten or the Brooks and Corey function is selected and HCC when the Mualem van Genuchten is selected. If users only need values or value ranges of soil hydraulic properties, this information can be extracted from the attribute table of the output shapefile or the csv files within the output folder (Suppl. material 2).

For modelling purposes, there are generally four key soil moisture thresholds (saturation, field capacity, the pressure at which stoma closure due to water stress and permanent wilting point) and water held between these different thresholds (drainable water, plant available water, readily plant available water, not readily plant available water and hydroscopic water) interact quite differently with the environment, as discussed below and in Table 6. Those key soil moisture thresholds and soil moisture characteristics for plants are generally identified using SMRC (Fig. 2). Guidance on how to identify those parameters can be found in Table 6. In general, moisture content at saturation and permanent wilting point can be defined using a single pressure. In theory, the pressure head/pressure potential used to identify the point of saturation (SAT) is 0kPa (0 cm). However, it should be noted that, in practice, some void spaces will still contain air even when the soil is "saturated". Permanent wilting point (PWP) can also generally be defined as a single pressure for a given plant and is similar between most plants, commonly at -1500 kPa (15,000 cm). However, there is not a universal appropriate single pressure corresponding to field capacity (FC) which is very important to define drainable water (water held between saturation and field capacity) and plant available water (water held between field capacity and permanent wilting point). It is because the pressure determining field capacity changes depending on where the water table is, as well as on soil texture and soil depth (Hillel 2004). For measurement purposes, moisture content at a single pressure is still assumed to be representative for field capacity. The pressure used to define FC may differ, but there is general agreement that FC for most soils commonly corresponds to the water held at a representative pressure potential point between -10 to -33 kPa, depending on the soil texture. For example −10 kPa is generally used to define FC of sandy soil; −20 kPa represents FC of medium textured soils and −33 kPa represents FC of heavy textured soils (Dahiya et al. 1988, Gijsman et al. 2007, Leenaars et al. 2018). The stomata closure point (WSC) varies between crops (WADAF 2019). The pressure corresponding to the stomata closure point is normally within -40 kPa and – 100kPa (Narjary et al. 2012); for example, WSC of most fruit crops is at -40 kPa, perennial pastures and crops (maize, soybeans) is at -60 kPa, annual pasture and hardy crops (cotton, sorghum etc.) is at -100 kPa (WADAF 2019). Readily plant available water is the water held between FC and WSC. Water held between WSC and PWP is not readily available for plants (NRAW). Water held below PWP is hydroscopic water (HW). NB_PTFs toolbox has functions to extract soil moisture values at key pressures (for example -0kPa, -1kPa, -10kPa, -20kPa, -33kPa, -100kPa, -200kPa, -500kPa, -1500kPa). From the exported values, key moisture thresholds can be identified. From that, the plant-related soil moisture characteristics can be estimated.

Table 6.

Key soil moisture content thresholds and plant available water thresholds.

Parameter	Definition	Guidance
SAT (Saturated moisture content)	- SAT represents the maximum amount of water can be held in a soil. At SAT, nearly all soil pores are filled with water and soil water can be drained by gravity	In theory, the pressure head/pressure potential used to identify the point of saturation (SAT) is 0kPa (0 cm). However, it should be noted that, in practice, some void spaces will still contain air, even when the soil is "saturated"
FC (Field capacity)	There are various definitions of FC: - Veihmeyer and Hendrickson (1931): "FC is the amount of water held in soil after the excess gravitational water has drained away and after the rate of downward movement of water has materially decreased." (p.181) - Hillel (1998): "FC is the volumetric moisture content distribution in the upper part of a soil profile that, in the course of ponded infiltration (with ponding depth smaller than 10 cm), becomes fully wetted at the end of infiltration and remains exposed to the subsequent process of drainage without evapotranspiration or rain for 48h." (chp.6) - Soil Science Glossary Terms Committee (2008): "FC is the content of water, on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible" (p.23)	There is not a universal appropriate single pressure corresponding to field capacity which is very important to define drainable water and plant available water. It is because the pressure determining field capacity changes, depending on where the water table is, as well as soil texture and soil depth (Hillel 2004). For measurement purposes, moisture content at a single pressure is still assumed to be representative for field capacity. The pressure used to define FC may differ, but there is general agreement that FC for most soils commonly corresponds to the water held at a representative pressure potential point between -10 to -33 kPa, depending on the soil texture. For sandy soils, −10 kPa (100cm or pF2.0) is generally used to define FC; for medium textured soils, −20 kPa (200 cm or pF2.3) and for heavy textured soils, −33 kPa (330 cm or pF2.5) (Dahiya et al. 1988, Gijsman et al. 2007, Leenaars et al. 2018).
WSC (Stomata closure point)	WSC is the point at which plants' stomata close due to water stress. WSC is also called the critical point or refill point in some literature (Froukje 2016)	Stomata closure point (WSC) point varies between crops (WADAF 2019). The pressure corresponding to stomata closure point is normally within -40 kPa and – 100kPa (Narjary et al. 2012); for example, WSC of most fruit crops at -40 kPa, perennial pastures and crops (maize, soybeans) is at -60 kPa, annual pasture and hardy crops (cotton, sorghum etc.) at -100 kPa (WADAF 2019).
PWP (Permanent wilting point)	PWP is the point at which matric forces hold water too tightly for plant extraction so plants can no longer extract water from a soil.	PWP is crop-specific, it is commonly defined as the pressure head of 15,000 cm or pressure potential of -1500 kPa or pF 4.2 (Gijsman et al. 2007)

Parameter	Definition	Guidance
DW (Drainable water)	Drainable water is water held between saturation and field capacity. Drainable water is transitory, subject to free drainage over short time periods; hence, is it is generally considered unavailable to plants.	DW= Water content at saturation (SAT) – Water content at field capacity (FC)
PAW (Plant available water)	Plant available water is water held from field capacity (an upper limit for the permanent wilting point (to a lower limit) (Hillel 2004). Water held between these two states is retained against the force of gravity, but not so tightly that it cannot be extracted by plants	PAW = Field capacity (FC) – PWP (Permanent wilting point)
RAW (Readily plant available water)	Portion of the available water holding capacity easily used by the crop before crop water stress develops	Readily plant available water or management allowable depletion is normally estimated by the equation: RAW= Field capacity (FC) – Stomata closure point (WSC) Or RAW= PAW*fraction The fraction is diverse depending on soil type. In the NB_PTFs toolbox, the fraction default value is 0.5, but users can define the fraction themselves.
NRAW (Not readily available water)	NRAW is water held between stomata closure point and permanent wilting point	NRAW = Stomata closure point (WSC) – Permanent wilting point (PWP)
HG (Hygroscopic water)	HG is water held below permanent wilting point	

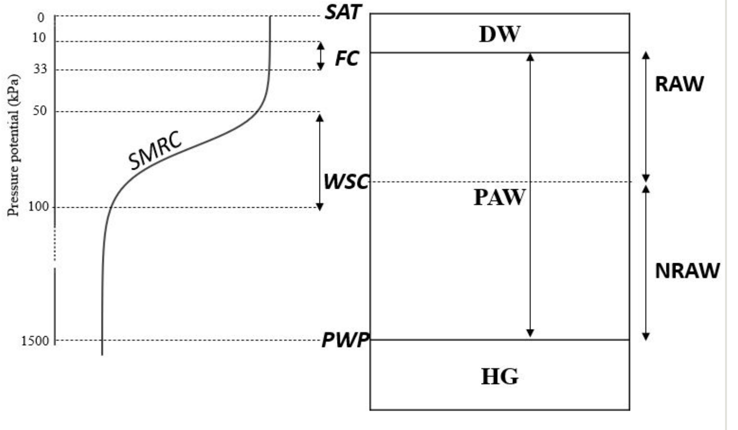

Figure 2.

Key soil moisture thresholds and plant water availability thresholds can be extracted from NB_PTFs, with explanations of parameters being found in Table 6.

Case studies

The following case studies demonstrate the use of our guidelines and NB_PTFs toolbox to obtain information required by Nature Braid; however, we note the outputs from NB_PTFs are not just intended for Nature Braid, but to more broadly provide information for hydraulic property parameterisation for a range of other models. The outputs obtained from NB_PTFs toolbox provide information on required soil hydraulic parameters for the Nature Braid model (permeability class and plant available water). From NB_PTFs, information of field capacity (FC) and permanent wilting point (PWP) can be estimated and then used to calculate plant available water. Based on our guidelines, information on saturated hydraulic conductivity can be used to identify a permeability class for the soil table used in Nature Braid. A higher saturated hydraulic conductivity means higher permeability. Using our guidelines and NB_PTFs toolbox enables the more appropriate application of Nature Braid to a wider range of geoclimatic regions instead of using the default soil table for temperate regions.

Vietnamese Mekong Delta case study

The VMD represents a data-sparse region where information on soil hydraulic properties is very limited. The lack of information on soil hydraulic properties is a great obstacle for accurate modelling predictions in the area. This case study was chosen to support modelling practices in the data-sparse VMD and more broadly other data-sparse regions. Some results from the case study, for example, drainable water, plant available water and saturated hydraulic conductivity were also used for the application of the Nature Braid model to map multiple ecosystem services in the VMD (Dang et al. 2021).

Main characteristic of the Vietnamese Mekong Delta

Vietnamese Mekong Delta (VMD) is the most downstream reach of the Mekong, which is one of the world's largest rivers (Fig. 3) (MRC 2016). The VMD was formed by sediment deposited at the point where the Mekong River meets the Vietnamese East Sea. The Delta covers 39,000 km^2 of flat area with an average elevation of 0.8 m and an elevation range of 0.5-5m above sea level (MDP 2013). Due to its rich water and sediment resources, the VMD is important for agriculture and aquaculture. It helps sustain the livelihoods and food security of its 17 million inhabitants. Nationally, it contributes about 50% of Vietnam's rice production, 60% of aquaculture production and 70% of fruit production annually (GSO 2019). Located in a tropical monsoon climate zone, the VMD has two distinct seasons. The dry season from December to the end of April and the rainy season from May to November (Hung et al. 2012). Floods typically occur during the monsoon, with inundation lasting up to 3 months (Hung et al. 2012). Over recent decades, the VMD has witnessed extensive development of man-made water control infrastructure, especially dyke systems with the main purpose of protecting rice fields from flooding (Hung et al. 2014). Water scarcity in the dry season also poses a problem to VMD farmers. With the VMD's large dependence on water resources, modelling water in the VMD has attracted attention from scientists, practitioners and planners to guide management. However, soil hydraulic parameters for these models are normally set to the range recommended by each model's manual, which may be poorly suited for the VMD's soil conditions. Therefore, obtaining more appropriate soil hydraulic properties is particularly important for optimising soil-water management practices. Improved practices may help farmers cope with growing water scarcity in the VMD (Nguyen et al. 2015).

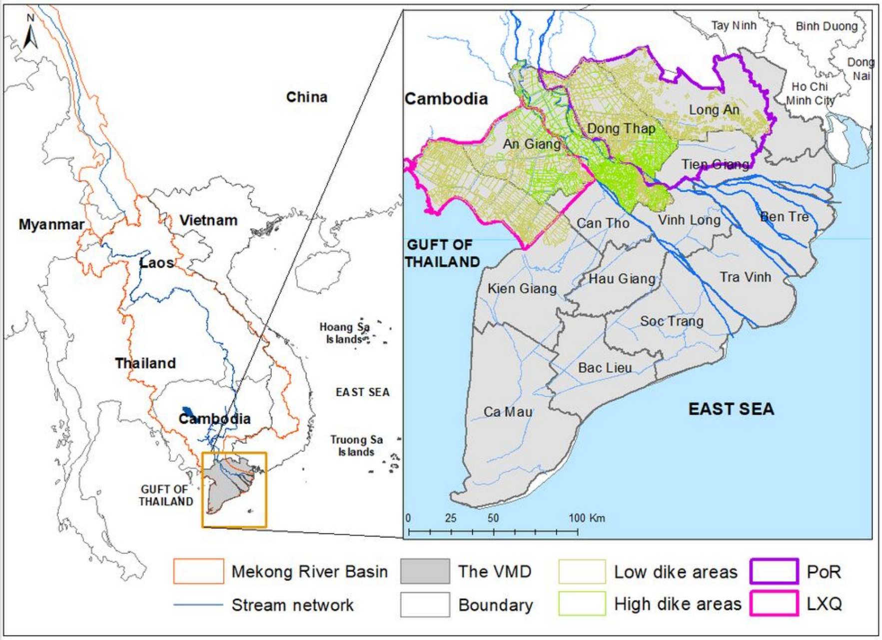

Figure 3.

Location of the Vietnam Mekong Delta (VMD).

Selection of soil data for the Vietnamese Mekong Delta case study

Adequate local sampling of soil properties of the VMD do not exist to date. A local soil map is available; however, the soil map only has information on soil classes (in both the official Vietnamese soil categorisation and also the FAO-UNESCO 1990 soil categorisation) without accompanying information on soil properties. For the VMD, the Vietnamese soil map contains 25 soil classes when mapped into the national soil classification, but the number of classes reduces to 14 according to the FAO classification. The reason for this loss of detail is that the Vietnamese national classification has more detail on saline and acid sulphate levels within soils. Using the FAO classification, nine unique classes according to the Vietnamese classification were all mapped to a single FAO class: Thionic Fluvisols. Two more unique types were mapped to Thionic Histosols, another two to Solonchaks and two others to Salic Fluvisols. Given the importance Vietnamese soil scientists have placed on saline and acid sulphate levels, it is clear this further detail will be important when considering various measures of productivity, ecosystem services and soil health. However, for the purpose of deriving soil hydraulic properties, these influences are secondary and not generally considered in PTFs. Hence, the use of the FAO classification is not likely to lead to much loss of information.

Following the '*Guidelines for parameterising soil hydraulic properties version 1.0*', three sets of soil maps and associated soil properties were selected: a FAO global soil map (Fig. 4a) using FAO-UNSESCO 1974 categorisation and soil properties (FAO 2007); a Mekong River Basin soil map obtained from the Mekong Region Commission (MRC 2002), linked to the FAO-UNESCO 1989 categorisation, referred to as the MRC soil map (Fig. 4b) which we linked to WISE global soil properties (Batjes 2009); and a local soil map obtained from Dong Thap University, linked to the FAO-UNESCO 1990 categorisation, referred to as the VN soil map (Fig. 5) which we also linked to WISE global soil properties (Batjes 2009). The FAO soil map (FAO 2007) has been commonly used for hydrological modelling in the VMD and the Mekong River Basin (Lauri et al. 2012, Hoang et al. 2016, Duc Tran et al. 2017). However, the FAO soil map is coarse in spatial scale and has only high-level soil classifications, so is of limited suitability for applying environmental/hydrological/climate model applications at fine scale (for example, farm scale or rice field scale). The MRC and VN soil maps contain more detailed soil classifications and are mapped at a finer spatial scale (the local VN map being the most spatially resolved).

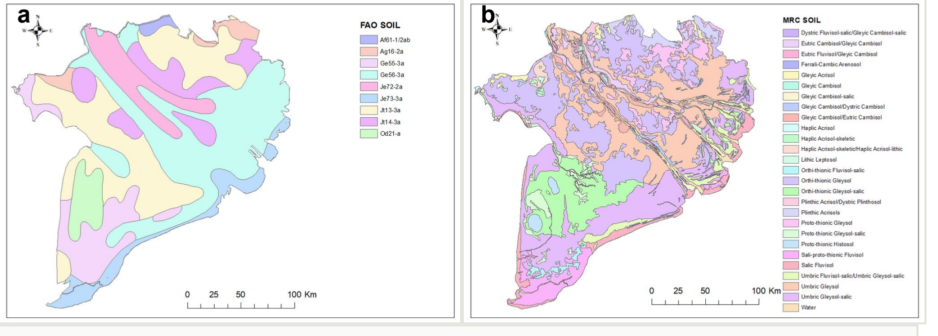

Figure 4.

Soil maps obtained from (a) FAO, (b) MRC.

The use of soil maps at different spatial scales from global to regional and local in this case study allow us to compare the quality of soil hydraulic properties obtained from different data sources. As information on soil properties was not contained in the MRC and VN soil maps and not found in any regional or national databases, soil physical and chemical properties were related to the WISE database Version 3, which contains a large number of soil samples from tropical and sub-tropical regions (Gijsman et al. 2007) and is consistent in its textural classification with those used in our soil maps. From the WISE database, tropical samples, based on FAO-UNESCO 1990, were extracted for soil types of the MRC soil map and soil types of the VN soil map. For each soil type, values of soil properties were averaged to estimate an approximate value for soil properties in the VMD. Soil property information (Sand, Silt, Clay, Bulk Density, Organic Carbon, CEC, $CaCO_3$, Gravel) was joined with the MRC and VN soil maps.

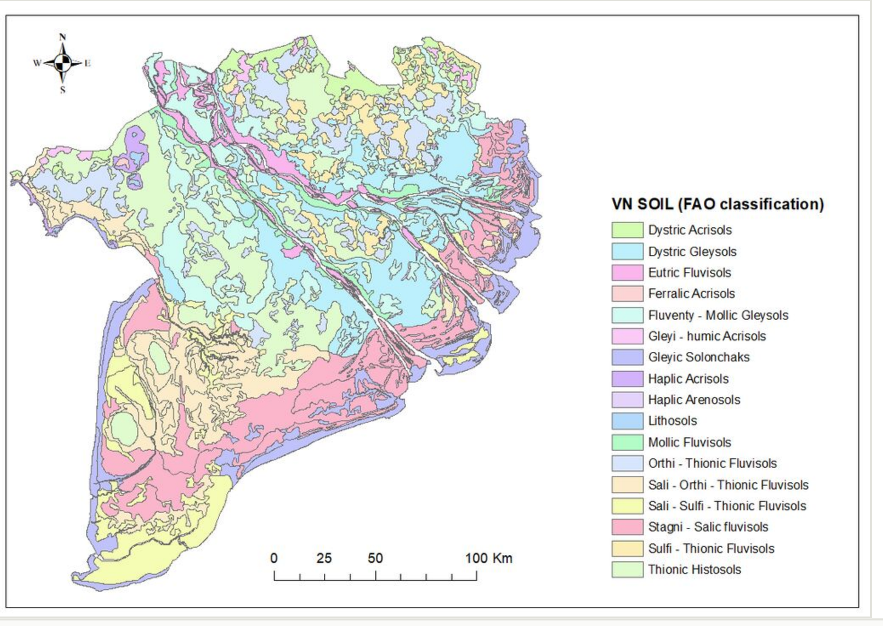

Figure 5.

The soil map for the VMD using the Vietnam soil classification system.

Selection of PTFs for the VMD case study

From the list of PTFs suitable for tropical regions, the moisture retention PTFs by Nguyen et al. (2014) were selected for the VMD case study. These point PTFs were established for agricultural soils in the VMD, especially for paddy-field soils in the Delta. The PTFs were developed using stepwise multiple linear regression with the input data of 160 profiles collected in the VMD and validated with the dataset from Le (2003) (29 samples taken from 10 soil profiles in the VMD). The PTFs from Nguyen et al. (2014) were developed at eight pressure heads: -1kPa, -3kPa, -6 kPa, -10kPa, -20kPa, -33kPa, -100kPa and -1500kPa. In addition, PTFs by Wösten et al. (1999) and Hodnett and Tomasella (2002) were used to obtain van Genuchten soil moisture retention curve for the VMD. The Hodnett and Tomasella (2002) relationship was selected for comparison because the PTFs were developed in another tropical climate (Brazil). Although the PTFs by Wösten et al. (1999) were developed using soil samples from a temperate climate (Europe), the sample size is huge (4030 samples) and previous studies have noted they represent moisture retention characteristics in tropical soils well (Wösten et al. 2013, Zhang et al. 2019). As for K_{sat}, there are fewer K_{sat} PTFs developed for tropical environments. The two published PTFs, selected for this test, were those of Ahuja et al. (1989) and Minasny and McBratney (2000), based on the similarity between VMD soil properties and the datasets used to develop these two models. PTFs by Wösten et al. (1999) and Weynants et al. (2009) were used to establish Mualem van Genuchten HCC because HCC PTFs for a tropical climate have not been found to date.

In order to identify key soil moisture thresholds for plants, it is important to select pressure potentials that appropriately represent field capacity (FC) and permanent wilting point (PWP). For the VMD case study, according to our guidelines, pressure potential at -33kPa was selected to represent field capacity (FC) because the VMD soils are mostly fine textured soil (Dahiya et al. 1988, Gijsman et al. 2007, Leenaars et al. 2018) and -1500kPa was selected to represent the permanent wilting point (PWP) as -1500 kPa is commonly used to define the permanent wilting point (Gijsman et al. 2007). Furthermore, a similar selection of FC and PWT was used in the soil measurement for paddy-fields conducted in the VMD by Nguyen et al. (2015).

Results and discussion - the VMD case study

Using the NB_PTFs toolbox, shapefiles of various soil hydraulic properties can be obtained in less than 1 min. These shapefiles can be subsequently presented as maps. Fig. 6 presents maps of soil moisture content at field capacity using Nguyen et al. (2014) PTFs. Results of soil moisture content at field capacity obtained using the three datasets have quite similar value ranges. However, the information is rather coarse when using FAO soil maps and soil properties. The highest spatial detail in information is obtained when using the local soil map and soil properties from WISE soil database.

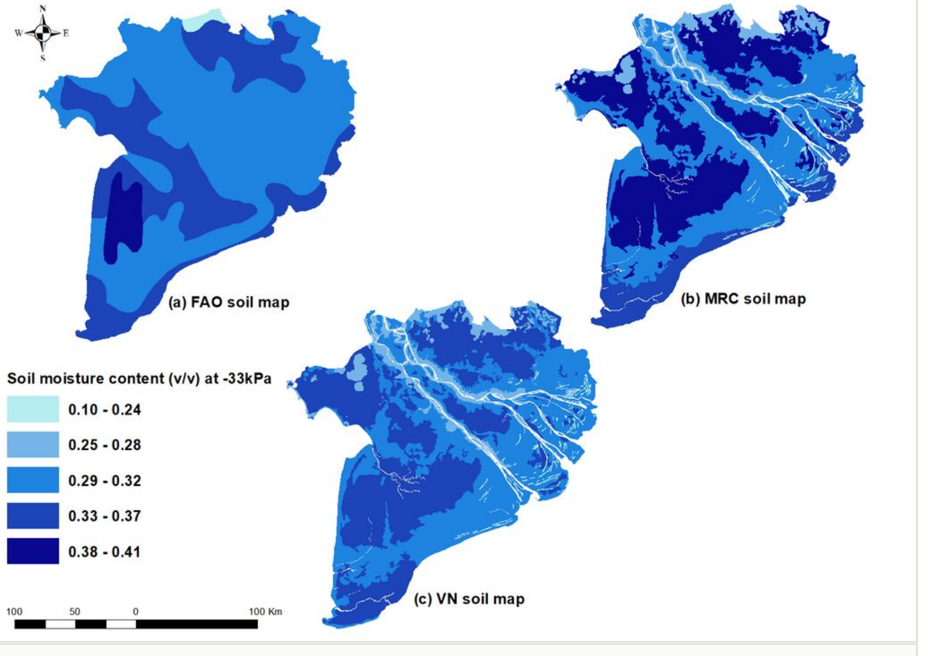

Figure 6.

Maps of soil moisture content at -33kPa (field capacity) for top-soil using Nguyen et al. (2014) PTFs; (a) FAO soil map, (b) MRC soil map, (c) VN soil map.

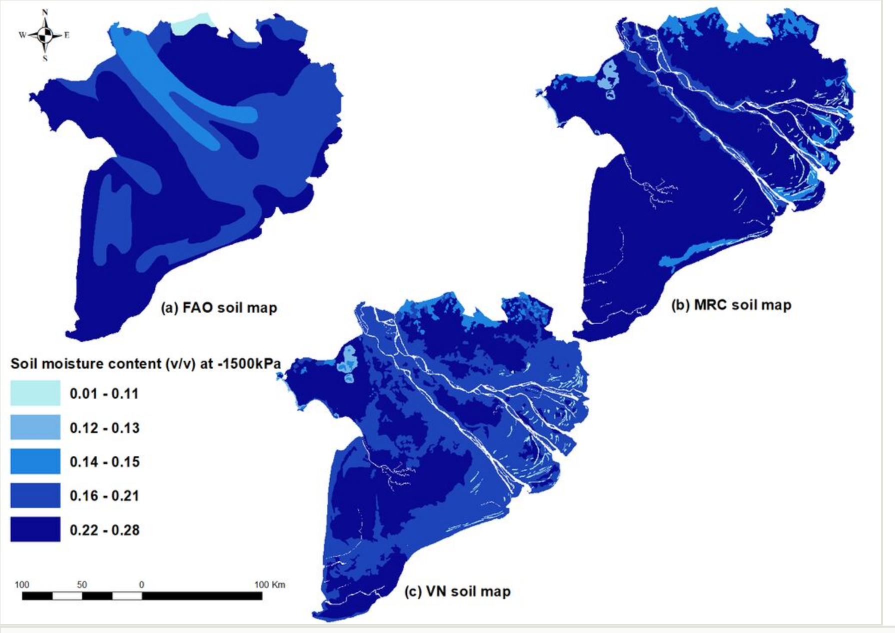

Figure 7.

Maps of soil moisture content produced by NB_PTFs at -1500kPa (permanent wilting point) using Nguyen et al. (2014) PTFs; (a) FAO soil map, (b) MRC soil map, (c) VN soil map.

Similarly, Fig. 7 presents the maps of soil moisture content at wilting point using Nguyen et al. (2014) PTFs. Results of soil moisture content at wilting point obtained using the three datasets also have quite similar value ranges. The information is not detailed when using FAO soil map and soil properties and MRC soil map and WISE soil database. The highest detailed information is only obtained using the local soil map and soil properties from the WISE soil database.

In addition to point PTFs, SMRCs can be obtained via NB_PTFs. SMRCs are the required inputs for many models which solve Richards's equation. Fig. 8 provides examples of van Genuchten SMRCs obtained from the toolbox using PTFs by Wösten et al. (1999) (developed for temperate regions, Fig. 8a) and Hodnett and Tomasella (2002) (developed for a tropical region: Brazil, Fig. 8b). In Fig. 9, soil moisture content at eight pressures (-1kPa, -3kPa, -6kPa, -10kPa, -20kPa, -33kPa, -100kPa and -1500kPa) obtained from the local PTFs by Nguyen et al. (2014) were placed over the SMRCs from Wösten et al. (1999) and Hodnett and Tomasella (2002) PTFs to understand how they compare with each other across soil types.

Examining the results presented in Fig. 9, all but one (Thionic Histosols) of the soil SMRCs obtained from the three PTFs look physically realistic. Unfortunately, we have no site-specific hydraulic property data (a problem, that in part, was the rationale behind this paper). Concerning results can be seen when examining the soil moisture characteristic of Thionic Histosols (Hst) - a peat soil – which is very different when using the three selected

PTFs (Fig. 9l). Both the Wösten et al. (1999) PTFs and the Nguyen et al. (2014) PTFs are clearly not appropriate for this soil type as both show physically unrealistic behaviour. In the case of the Wösten et al. (1999) PTF, the soil remains near saturation under enormous tensions, even at the extreme of permanent wilting point. Issues with low performance in organic soils have already been flagged in previous research, which notes the lack of consideration of peat soils' botanical composition in the PTFs development (Liu and Lennartz 2019). However, the performance shown here is worse than “low”; it appears to be completely unsuitable for this particular soil. Although the Wösten et al. (1999) relationships were trained on a dataset including some soils with high organic carbon from Europe, the combined inputs to the PTF, such as texture, bulk density etc. here are producing unfeasible results. We suggest extreme caution is used if applying the Wösten et al. (1999) or similar relationships to tropical peat soils.

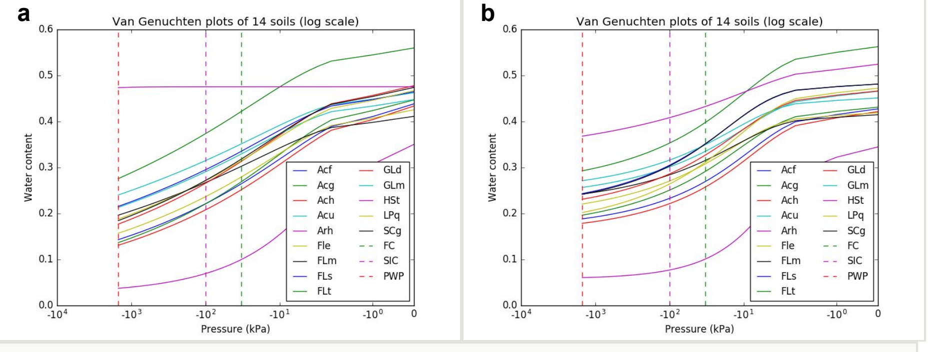

Figure 8.

van Genuchten SMRCs established using VN soil map, (a) Wösten et al. (1999) PTF and (b) Hodnett and Tomasella (2002) PTF.

Similarly, the Nguyen et al. (2014) PTF appears unsuitable for such soils. In the case of the peat soil, as pressure decreased from saturation, the moisture content around -6kPa went up higher than the saturation point, which is physically incorrect. The samples used to develop Nguyen et al. (2014) PTFs did not include peat soil samples. The SMRC of Hst obtained from Hodnett and Tomasella (2002) PTFs look less concerning and, as detailed in the supplementary information, have been trained on soil that included some with > 30% OC. However, we still do not have any data evidence to confirm that the Hodnett and Tomasella (2002) PTFs can provide appropriate SMRC for peat soil of the VMD.

Peat is known to be particularly hard to parameterise in models due to its extreme diversity; hydraulic parameters of peat soils vary over a wide range and, to complicate matters further, peat decomposition significantly modifies all hydraulic parameters (Holden 2005, Liu and Lennartz 2019). Obtaining locally derived PTFs, or at least PTFs derived in similar geoclimatic regions that are trained specifically on soils with high OC, is suggested. For tropical regions, such as Vietnam, an interesting candidate might be, for example, one developed for high carbon soils in Ecuador (Gebauer et al. 2020). More exploration of which PTFs are suitable for differing peats or other high OC soils in different climates and geographic settings is recommended.

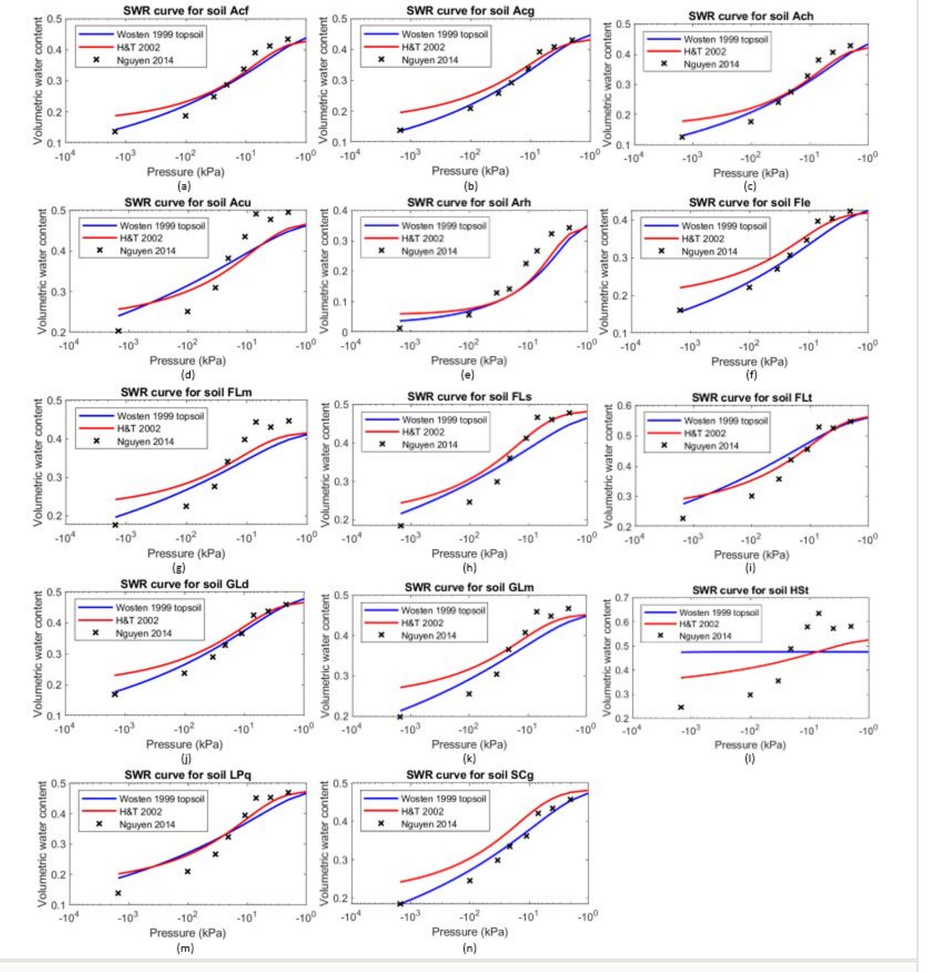

Figure 9.

van Genuchten SMRCs established for 14 FAO-UNESCO 1990 soils (VN soil map) using Wösten et al. (1999) PTFs for top soil (referred to as Wosten 1999) and Hodnett and Tomasella (2002) PTFs (referred to as H&T 2002) and soil moisture content at eight pressures using Nguyen et al. (2014) PTFs (referred to as Nguyen2014).

Saturated hydraulic conductivity (K_{sat}) and Hydraulic conductivity curve (HCC) can also be obtained from the NB_PTFs toolbox. Fig. 10 and Fig. 11 present maps of K_{sat} using PTFs from Ahuja et al. (1989) and Minasny and McBratney (2000), respectively. Comparing output maps obtained from the three input datasets and the two PTFs (Fig. 10a with Fig. 11 a, Fig. 10b with Fig. 11b and Fig. 10c and Fig. 11c), the K_{sat} maps have similar patterns when using the two different PTFs. However, the value ranges are different. The PTF from Minasny and McBratney (2000) leads to a higher K_{sat} value than the PTF from Ahuja et al.

(1989). The FAO map and MRC map datasets have higher K_{sat} values than the local map dataset.

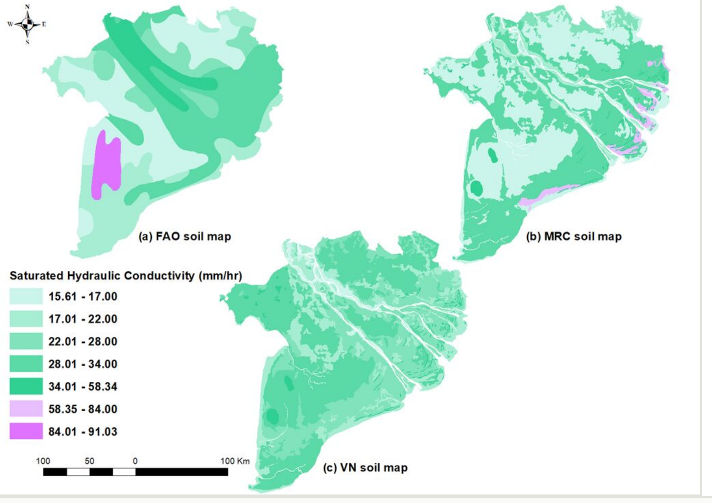

Figure 10.

Maps of saturated hydraulic conductivity using Ahuja et al. (1989) PTF; (a) FAO soil map, (b) MRC soil map, (c) VN soil map.

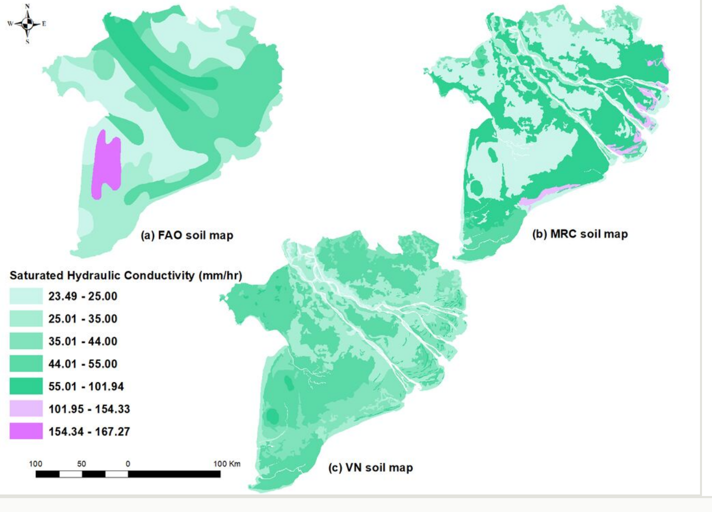

Figure 11.

Maps of saturated hydraulic conductivity using Minasny and McBratney (2000) PTF; (a) FAO soil map, (b) MRC soil map, (c) VN soil map.

If local measurement data are not available, measured data from literature or global databases can help identify a reasonable value range for K_{sat}. Recently, the SoilKsatDB database stores soil-saturated hydraulic conductivity measurements from all over the world

(Gupta et al. 2020). For example, soil samples in the SoilKsatDB database, which have similar soil texture, BD and OC content to *alluvial soils with yellow red mottles* in the VN soil map, have K_{sat} range from 4.8 - 47.9 mm hr^{-1} (11.25 – 114.96 cm day^{-1}). The K_{sat} values of this soil obtained from Ahuja et al. (1989) and Minasny and McBratney (2000) PTF are 22.05 and 32.52 mm hr^{-1}, respectively. The two PTFs, therefore, are expected to be a reasonable estimation of K_{sat} for *alluvial soils with yellow red mottles*. However, the K_{sat} value of *peaty acid sulphate soil* is rather high when using the two PTFs, 58.34 mm hr^{-1} when using Ahuja et al. (1989) PTF and 101.94 mm $hr^{-1}$with Minasny and McBratney (2000) PTF. The K_{sat} value of the samples in the SoilKsatDB database, which have soil properties similar to *peaty acid sulphate soils*, have a value range from 5.1 – 11.16 mm hr^{-1} (12.24 – 26.8 cm day^{-1}). The high value of K_{sat} of *peaty acid sulphate soil* may be due to two main reasons: the point PTFs for estimating soil moisture content by Nguyen et al. (2014) were not established for peaty soil and the K_{sat} PTFs by Ahuja et al. (1989) (Fig. 10) and Minasny and McBratney (2000) (Fig. 11) only use moisture content (*effective porosity** [5]) as input and do not consider OC content which is an important property of peaty soil. With robust processing and a wide range of PTFs included, NB_PTFs can support the comparison of different PTFs and find the most suitable one for different contexts.

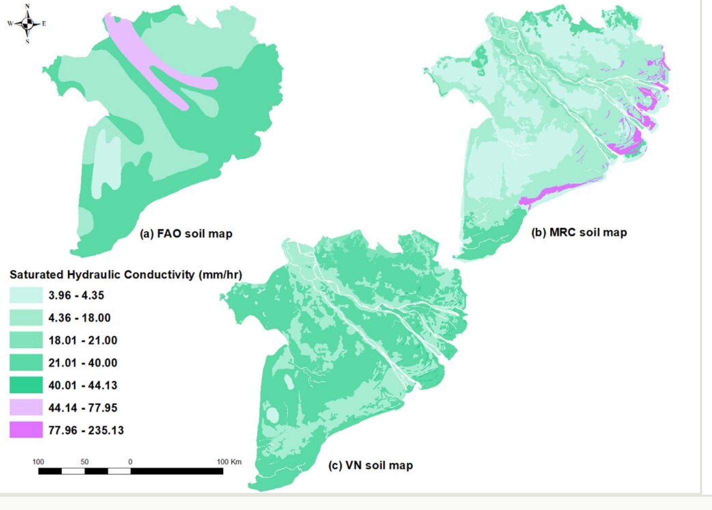

Figure 12.

Maps of saturated hydraulic conductivity using Wösten et al. (1999) PTF; (a) FAO soil map, (b) MRC soil map, (c) VN soil map.

The three datasets were then tested with Mualem van Genuchten PTFs by Wösten et al. (1999) and Weynants et al. (2009). Fig. 12 and Fig. 13 present K_{sat} value obtained from the two PTFs. Wösten et al. (1999) gives a higher value range of K_{sat} compared to Weynants et al. (2009) PTF. Fig. 14 presents Muelm van Genuchten HCCs. From HCCs graphs, hydraulic conductivity of almost all soils types have quite similar characteristics when using the two PTFs. However, soil hydraulic conductivity values obtained from Wösten et al. (1999) PTF hold higher values at higher pressure heads (less negative) compared to HCCs obtained from Weynants et al. (2009), then drop quickly at lower pressure heads (more negative). Soil HCCs obtained from Weynants et al. (2009) decrease gradually when pressure head decreases.

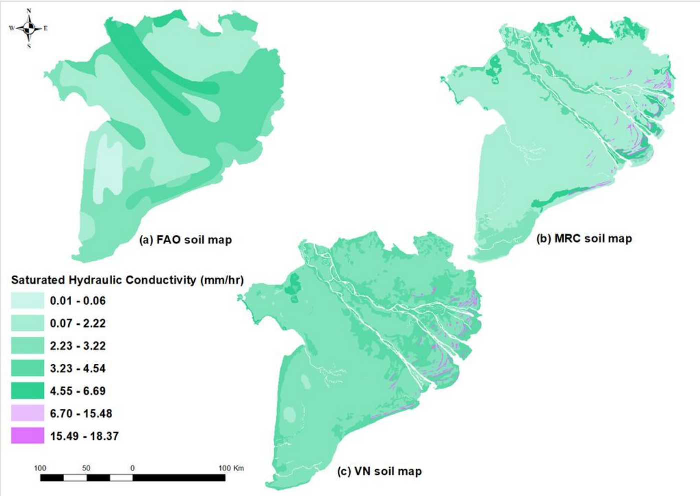

Figure 13.

Maps of saturated hydraulic conductivity using Weynants et al. (2009); (a) FAO map, (b) MRC map, (c) VN soil map.

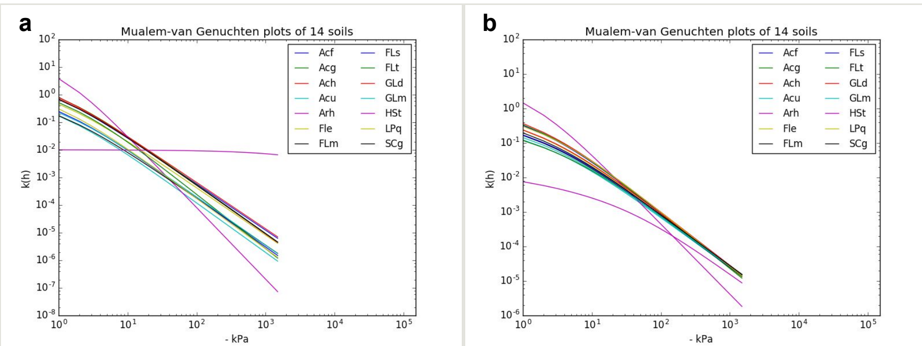

Figure 14.

Mualem van Genuchten HCCs established using VN soil map, (a) Wösten et al. (1999) PTF and (b) Weynants et al. (2009) PTF.

The outputs from the NB_PTFs toolbox were compared with the global database, HiHydroSoil (Table 7 and Table 8). In general, soil moisture content values at saturation point and -100kPa of the NB_PTFs output using VN soil and Nguyen et al. (2014) PTF are rather similar to the corresponding values of the HihydroSoil database. Large differences can be seen at -10kPa and -1500kPa. The differences can be explained by HiHydroSoil using a European soil database as the PTFs were developed for European soils, rather than being developed in the VMD. Field capacity is defined at -10kPa in the HiHydroSoil, while it is defined at -33kPa in the VMD (Nguyen et al. 2015). K_{sat} value of HiHydroSoil is lower compared with the value obtained using VN soil and selected PTFs (Ahuja et al. 1989, Wösten et al. 1999, Minasny and McBratney 2000, Weynants et al. 2009). This may be because K_{sat} was lower in HiHydroSoil compared to the Global Soil Map of Hydraulic Properties, which was commonly used by other sources to determine K_{sat} (Froukje 2016).

Table 7.

Soil moisture content obtained from the NB_PTFs toolbox using VN soil map and Nguyen et al. (2014) PTF compared with HiHydroSoil.

SOIL TYPE	WC sat (v/v) Nguyen et al. (2014)	WC sat (v/v) ***Hihydro Soil***	WC at -10kPa (v/v) Nguyen et al. (2014)	WC at -33kPa (v/v) Nguyen et al. (2014)	WC at -10kPa (v/v) ***Hihydro Soil***	WC at -100kPa (v/v) Nguyen et al. (2014)	WC at -100kPa (v/v) ***HiHydro Soil***	WC at -1500 kPa (v/v) Nguyen et al. (2014)	WC at -1500 kPa (v/v) ***HiHydro Soil***
Dystric Gleysols (Gld)	0.46	*0.45*	0.37	0.29	*0.38*	0.24	*0.24*	0.17	*0.13*
Eutric Fluvisols (Fle)	0.42	*0.42*	0.35	0.27	*0.33*	0.22	*0.19*	0.16	*0.09*
Lithosols (Lpq)	0.47	*0.47*	0.39	0.27	*0.37*	0.21	*0.22*	0.14	*0.12*
Mollic Gleysols (GLm)	0.47	*0.45*	0.41	0.30	*0.38*	0.26	*0.24*	0.20	*0.13*
Haplic Acrisols (Ach)	0.43	*0.47*	0.33	0.24	*0.10*	0.18	*0.22*	0.13	*0.12*
Dystric Acrisols (Acg)	0.43	*0.46*	0.34	0.26	*0.36*	0.21	*0.22*	0.14	*0.12*
Humic Acrisols (Acu)	0.50	*0.45*	0.44	0.31	*0.36*	0.25	*0.22*	0.20	*0.12*
Mollic Fluvisols (FLm)	0.45	*0.46*	0.40	0.28	*0.37*	0.23	*0.23*	0.18	*0.13*
Solonchaks (SCg)	0.46	*0.43*	0.36	0.30	*0.33*	0.25	*0.18*	0.18	*0.08*
Salic fluvisols (FLs)	0.46	*0.44*	0.36	0.30	*0.35*	0.25	*0.21*	0.18	*0.11*
Thionic Histosols (HSt)	0.58	*0.48*	0.58	0.35	*0.40*	0.30	*0.25*	0.25	*0.14*
Thionic Fluvisols (FLt)	0.55	*0.48*	0.46	0.36	*0.40*	0.30	*0.24*	0.23	*0.13*
Haplic Arenosols (Arh)	0.34	*0.44*	0.23	0.13	*0.35*	0.06	*0.21*	0.01	*0.11*
Ferralic Acrisols (Acf)	0.43	*0.45*	0.34	0.25	*0.36*	0.19	*0.22*	0.14	*0.12*

Table 8.

K_{sat} obtained from the NB_PTFs toolbox using VN soil and PTFs by Ahuja et al. (1989), Wösten et al. (1999), Minasny and McBratney (2000) PTF and (b) Weynants et al. (2009) compared with HiHydroSoil.

SOIL TYPE	K_{sat} (mm/hr) Ahuja et al. (1989)	K_{sat} (mm/hr) Minasny and McBratney (2000)	K_{sat} (mm/hr) Wösten et al. (1999)	K_{sat} (mm/hr) Weynants et al. (2009)	K_{sat} (mm/hr) **HiHydro Soil**
Dystric Gleysols (Gld)	22.06	34.53	24.50	3.79	*6.61*

SOIL TYPE	K_{sat} (mm/hr) Ahuja et al. (1989)	K_{sat} (mm/hr) Minasny and McBratney (2000)	K_{sat} (mm/hr) Wösten et al. (1999)	K_{sat} (mm/hr) Weynants et al. (2009)	K_{sat} (mm/hr) **HiHydro Soil**
Eutric Fluvisols (Fle)	16.40	24.82	14.70	3.55	*6.58*
Lithosols (Lpq)	41.54	69.85	14.86	3.69	*7.22*
Mollic Gleysols (GLm)	19.34	29.83	11.14	2.45	*6.35*
Haplic Acrisols (Ach)	30.66	49.81	31.31	6.00	*8.26*
Dystric Acrisols (Acg)	22.67	35.60	20.94	4.54	*5.68*
Humic Acrisols (Acu)	30.21	49.01	11.97	2.43	*5.67*
Mollic Fluvisols (FLm)	22.89	35.98	8.79	2.76	*7.18*
Solonchaks (SCg)	18.13	27.75	24.48	3.57	*6.9*
Salic fluvisols (FLs)	18.13	27.75	24.48	3.57	*6.43*
Thionic Histosols (HSt)	58.34	101.94	0.01	0.06	*5.52*
Thionic Fluvisols (FLt)	31.71	51.72	24.87	2.22	*5.11*
Haplic Arenosols (Arh)	47.52	81.14	44.13	15.48	*7.54*
Ferralic Acrisols (Acf)	29.16	47.11	29.40	5.45	*7.03*

New Zealand Hurunui catchment case study

In the Asian Pacific Region, New Zealand is one of the countries that has detailed information on soil properties. The New Zealand Hurunui catchment case study was conducted to explore the outcomes of the guidelines and NB_PTFs toolbox in a hilly temperate region, where more soil information is available compared to the VMD.

Main characteristics of the Hurunui catchment

The Hurunui catchment is located in the North Canterbury region of New Zealand (Fig. 15). It begins at the Leithfield Beach and extends to the Conway River, south of the Kaikoura Peninsula. It is bordered on the west by the snow-capped peaks of the Southern Alps and on the east by the rich oceanic waters of the Pacific (Hurunui District Council 2021). The main land use in the catchment is sheep farming. Large areas of Hurunui are steep, limiting field access for soil and land resource surveyors in New Zealand (Hurunui District

Council 2021). Therefore, models of soil-landscape relationships are important for mapping soils in the catchment.

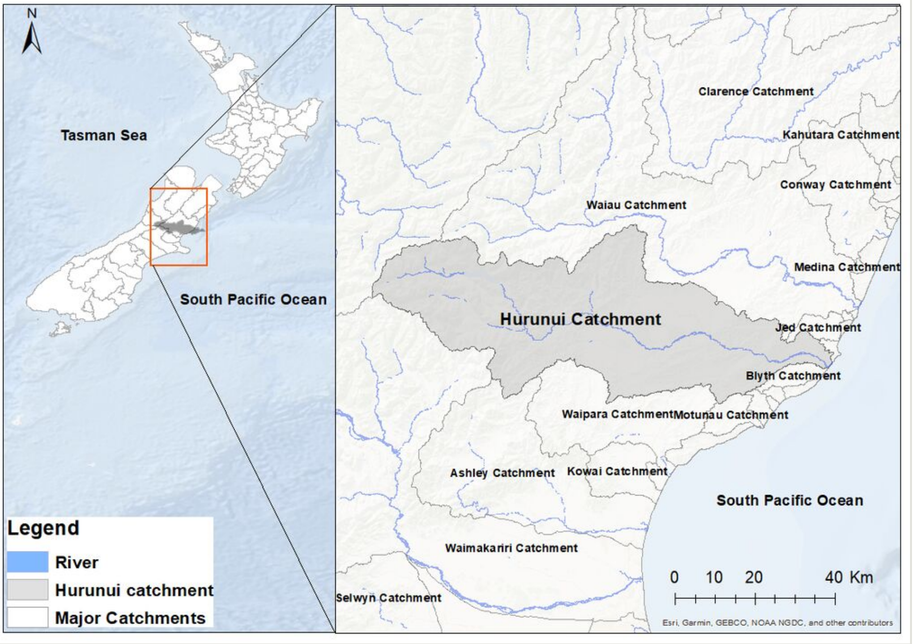

Figure 15.

Hurunui catchment on New Zealand's South Island.

Selection of soil data for the Hurunui case study

For the Hurunui catchment case study, three sets of soil maps and soil properties were also selected to understand how different levels of detail in input information can affect the quality of soil hydraulic property outputs. The three datasets were: FAO global soil map and soil properties 2007 (FAO 2007); the New Zealand Fundamental Soil Layers (FSL) (Manaaki Whenua - Landcare Research 2010) and WISE global soil properties (Batjes 2009); and S-map soil map and soil properties (Manaaki Whenua - Landcare Research 2020). The FAO global soil map contains information on soil physical and chemical properties (sand, silt, clay, bulk density, OC content, CEC etc.) at very rough scales. FSL was generated using regional soil databases. The data contain soil fertility/toxicity, some soil moisture properties (total profile available water and profile readily available water), topography and climate. FSL is freely accessed; however, it does not contain detailed soil physical and chemical properties (for example sand, silt, clay and bulk density), nor does it contain direct information relating to other soil moisture properties critical for hydrological modelling (for example, soil moisture at certain pressure heads, saturated hydraulic conductivity). NZSC soils within FSL data were linked with FAO soil classes of WISE soil database, using the handbook of soil terminology, correlation and classification by Krasilnikov et al. (2009). Linking NZ soil classes with FAO soil classes in WISE soil database reduces the number of soil classes in FSL map from 32 NZSC classes to 10 FAO-WRB soil classes.

S-map is significantly more detailed than FSL in the soil information it provides and its spatial mapping is also generally considered to be more reliable and resolved. Information from S-map includes, amongst many other things, hydraulic properties (soil moisture content at seven pressure heads, including soil moisture at saturation, field capacity and permanent wilting point, profile available water); however, at the time of this study, S-map still does not cover the whole of New Zealand (Lilburne et al. 2020). In general, within New Zealand, there is a strong tendency for S-map to have high and often near-complete coverage in agriculturally productive and/or low-lying areas and low coverage in low production, hilly to mountainous areas. In line with this general observation, S-map does not have full coverage on the Hurunui catchment, with the plains mostly mapped, but negligible mapping in the high country. Despite this lack of full catchment coverage, the highly-detailed soil hydraulic properties from S-map are useful for comparing with lower resolution outputs obtained from the NB_PTFs toolbox using FAO and FSL data. We note also that, in the Canterbury region where the Hurunui is located, the regional government have funded work*[6] linking and updating older soil maps in regions where S-map has not yet been directly mapped, to most of the rest of the region (excluding only conservation estate land). It may, therefore, have been possible to obtain, for most of the unmapped portion of the catchment, the level of soil property detail contained in S-map, but less spatially resolved and accurate. For the purposes of our work, concerned with generating broadly applicable national and international guidelines and tools, we did not attempt this. However, we recommend any readers of our paper interested specifically in modelling the Hurunui or broader Canterbury region, or in how to use partially mapped higher detail soil information to augment fully mapped less detailed information, investigate this data source and the methodologies behind its generation.

PTFs selection

Cichota et al. (2013) tested different PTFs for New Zealand and found that the PTFs from Saxton and Rawls (2006) performed reasonably well at the high suction end, but were poor near saturation. The PTF from Weynants et al. (2009) performed best in the mid-range suction. The paper suggests that choosing different PTFs for different moisture ranges and combining them could render a better fit throughout the entire curve. Good performance of the PTFs from Wösten et al. (1999) was also demonstrated by the low values of the intercept of the linear regression between the values of soil retention derived from measurements and those from the PTFs (Cichota et al. 2013). Therefore, we selected three PTFs from Wösten et al. (1999), Saxton and Rawls (2006) and Weynants et al. (2009) in this case study.

For the Hurunui case study, following recommendations outlined in our above guidelines, pressure potential at -10kPa was selected to represent field capacity (FC), because the Hurunui soils are mostly coarse to medium texture (Dahiya et al. 1988, Gijsman et al. 2007 , Leenaars et al. 2018) and -1500kPa was selected to represent the permanent wilting point (PWP) as -1500 kPa is a commonly used permanent wilting point Gijsman et al. (2007). Other New Zealand-specific guidance on soil moisture content measurement also selected FC at -10kPa and PWP at -1500kPa (Emma and Fiona 2018). For saturated hydraulic conductivity, the PTFs by Rawls and Brakensiek (1989)and Saxton and Rawls (2006) obtained the highest correlation coefficient with the reference data (Cichota et al. 2013). Hence, these two PTFs were tested in NB_PTFs toolbox.

Results and discussion - the Hurunui case study

Similar to the VMD case study, soil hydraulic properties in the Hurunui catchment were obtained from the NB_PTFs toolbox using different soil maps. The results demonstrate how detailed soil hydraulic properties can be derived from the global soil map, general local soil map and detailed local soil map. Fig. 16 presents maps of soil moisture content at -10kPa using Saxton and Rawls (2006) PTF with the three input datasets. The results show that the ranges of soil moisture content at -10 kPa for FSL and S-map are quite similar. The result for FAO soil map has a rather different pattern compared to the results of FSL and S-map. The level of detail increases as soil maps increase in detail, with FAO soil map being the least detailed, followed by FSL soil map and S-map having the greatest detail. The same pattern can be seen in the soil moisture content results at -1500kPa (Fig. 17).

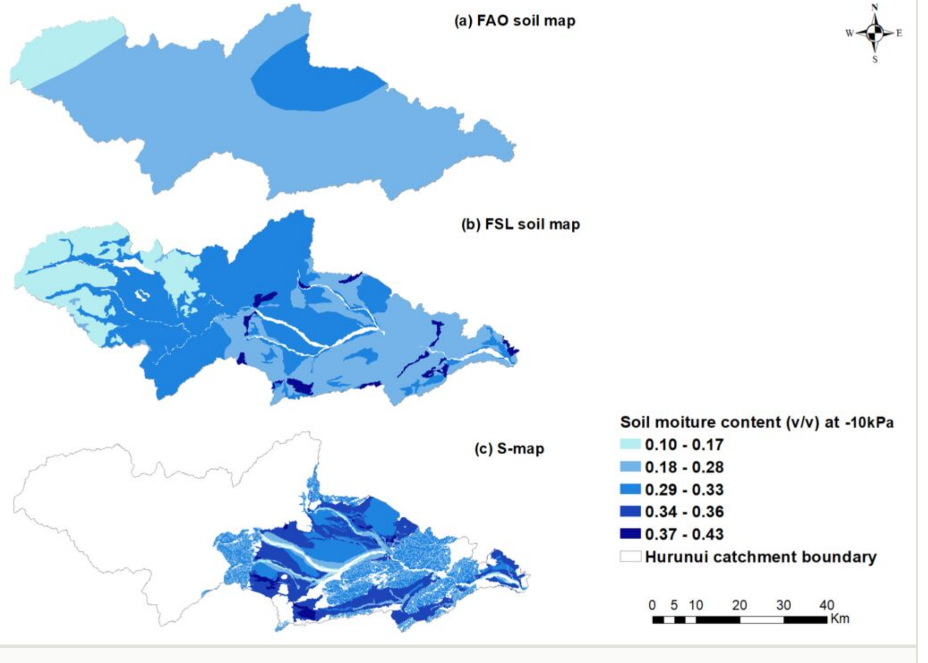

Figure 16.

Soil moisture content at -10kPa using Saxton and Rawls (2006) PTF; (a) FAO soil map, (b) FSL soil map, (c) S-map.

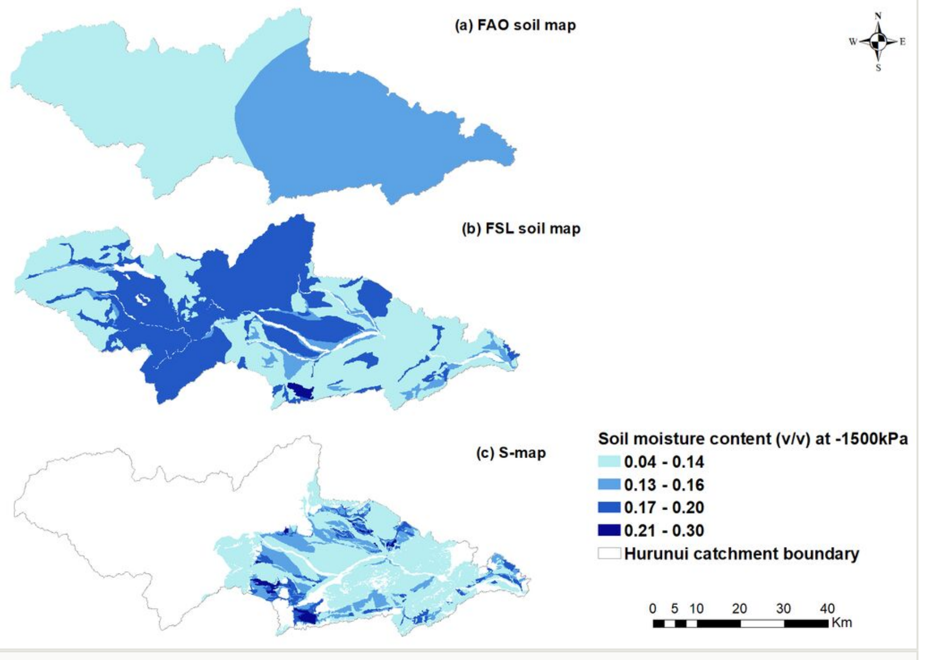

Figure 17.

Soil moisture content at -1500kPa using Saxton and Rawls (2006) PTF; (a) FAO soil map, (b) FSL soil map, (c) S-map.

Fig. 18 presents maps of K_{sat} obtained using the three datasets. The pattern of K_{sat} obtained using FAO data is rather different than using FSL map and S-map. The K_{sat} value obtained using FSL map and WISE soil database is quite close to the value obtained using S-map data. It demonstrates the potential of using FSL maps together with the WISE soil database for identifying K_{sat} for the area where S-map is still not available. Comparing the soil samples with the same texture of soil types of New Zealand in the SoilKsatDB database (Gupta et al. 2020), the range of K_{sat} found is 0.03 – 89.1 mm hr^{-1} (0.076 – 213.84 cm day^{-1}).

The three datasets were also tested with the Mualem van Genuchten PTF by Wösten et al. (1999). The K_{sat} maps are presented in Fig. 19. A similar pattern can be seen between the resulting maps of FSL and S-map data (Fig. 19b and Fig. 19c). The value range of K_{sat} obtained using FAO data is much higher than the range obtained using FSL and S-map. Examples of van Genuchten SMRCs and Mualem van Genuchten HCCs using FSL map together with WISE soil database are in Fig. 20.

The soil moisture content results obtained from NB_PTFs tool were compared with soil moisture content information from the S-map data (Table 9 and Table 10). We see the moisture content results obtained using the PTF from Saxton and Rawls (2006) are closest to the S-map data at -1500kPa. The PTFs from Wösten et al. (1999) and Weynants et al.

(2009) performed well at saturation and in the mid-range suction. The results of our study are similar to what were found by Cichota et al. (2013).

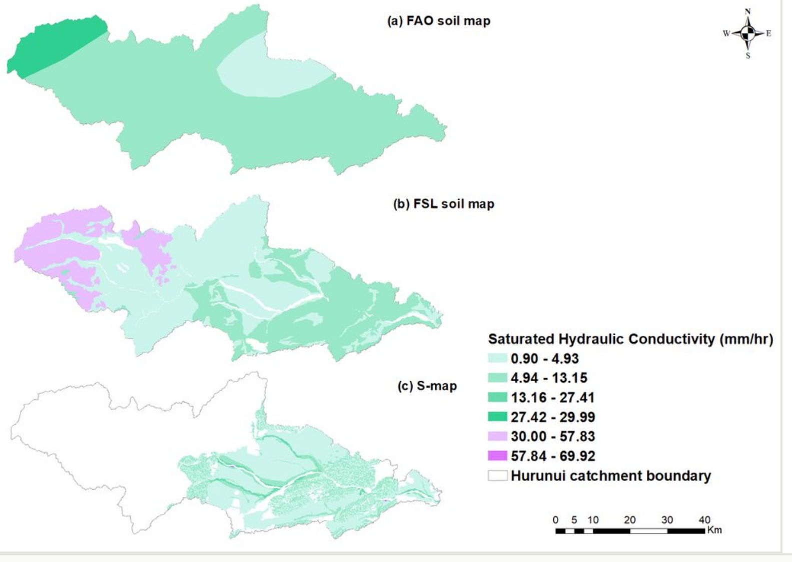

Figure 18.

Maps of saturated hydraulic conductivity using Saxton and Rawls (2006); (a) FAO soil map, (b) FSL soil map, (c) S-map.

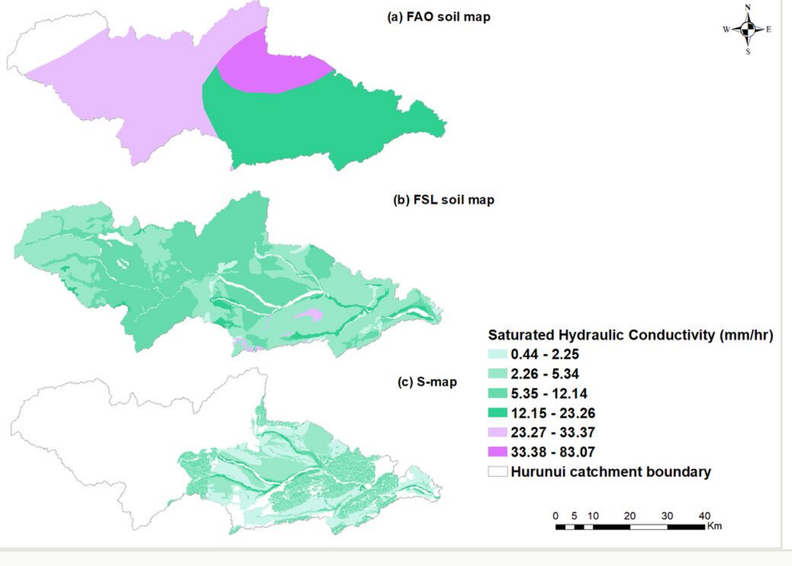

Figure 19.

Maps of saturated hydraulic conductivity using Wösten et al. (1999); (a) FAO soil map, (b) FSL soil map, (c) S-map.

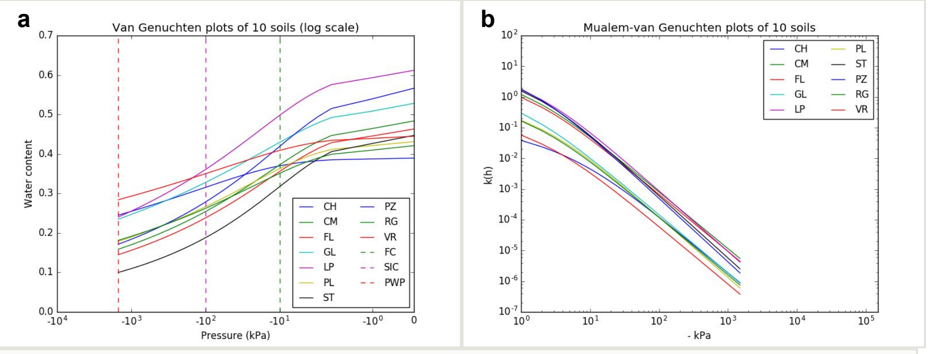

Figure 20.

SMRCs (a) and HCCs (b) using FSL soil map and Wösten et al. (1999) PTF.

Table 9.

Comparison of soil moisture generated via NB_PTFs toolbox using S-map vs. weighted average of individual S-map sibling soil moisture.

NZSC	WCsat (v/v) Saxton and Rawls (2006)	WCsat (v/v) Wösten et al. (1999)	WCsat (v/v) Wey-nants et al. (2009)	WCsat (v/v) ***S-map data***	WC -10kPa (v/v) Saxton and Rawls (2006)	WC -10kPa (v/v) Wösten et al. (1999)	WC -10kPa (v/v) Wey-nants et al. (2009)	WC -10kPa (v/v) ***S-map data***	WC -1500kPa (v/v) Saxton and Rawls (2006	WC -1500kPa (v/v) Wösten et al. (1999)	WC -1500kPa (v/v) Wey-nants et al. (2009)	WC -1500kPa (v/v) ***S-map data***
BFA	0.42	0.51	0.49	*0.47*	0.32	0.38	0.40	*0.34*	0.14	0.25	0.21	*0.15*
BFP	0.41	0.51	0.48	*0.5*	0.31	0.37	0.39	*0.36*	0.13	0.23	0.20	*0.16*
BFT	0.42	0.52	0.49	*0.56*	0.32	0.37	0.40	*0.42*	0.14	0.24	0.21	*0.19*
BOA	0.42	0.51	0.49	*0.44*	0.31	0.37	0.39	*0.32*	0.14	0.24	0.21	*0.14*
BOP	0.42	0.51	0.49	*0.55*	0.33	0.37	0.40	*0.42*	0.14	0.24	0.21	*0.21*
BOT	0.41	0.51	0.48	*0.53*	0.31	0.37	0.39	*0.40*	0.13	0.23	0.20	*0.17*
EOJ	0.43	0.47	0.47	*0.50*	0.33	0.36	0.39	*0.36*	0.15	0.24	0.21	*0.17*
EOJC	0.43	0.47	0.47	*0.51*	0.34	0.36	0.39	*0.36*	0.16	0.23	0.21	*0.17*
EOM	0.47	0.51	0.51	*0.47*	0.39	0.40	0.46	*0.37*	0.22	0.30	0.30	*0.24*
EOMJ	0.44	0.47	0.47	*0.51*	0.35	0.38	0.40	*0.39*	0.15	0.25	0.21	*0.18*
EVMC	0.48	0.55	0.53	*0.48*	0.39	0.42	0.48	*0.39*	0.23	0.32	0.32	*0.29*
GOJ	0.48	0.57	0.54	*0.54*	0.39	0.41	0.48	*0.44*	0.23	0.29	0.31	*0.25*
GOO	0.45	0.85	0.63	*0.86*	0.36	0.83	0.61	*0.64*	0.17	0.82	0.40	*0.19*
GOT	0.43	0.56	0.51	*0.53*	0.34	0.40	0.44	*0.41*	0.16	0.28	0.24	*0.19*
GRT	0.40	0.54	0.49	*0.48*	0.24	0.36	0.37	*0.34*	0.09	0.22	0.18	*0.12*
OHM	0.42	0.87	0.61	*0.86*	0.33	0.85	0.58	*0.64*	0.10	0.84	0.32	*0.19*
PIM	0.43	0.49	0.48	*0.49*	0.33	0.36	0.39	*0.37*	0.15	0.24	0.21	*0.18*
PIT	0.41	0.50	0.48	*0.35*	0.29	0.36	0.38	*0.24*	0.13	0.23	0.20	*0.10*
PJM	0.44	0.49	0.48	*0.49*	0.35	0.36	0.40	*0.36*	0.17	0.25	0.23	*0.19*
PJT	0.42	0.48	0.47	*0.48*	0.33	0.36	0.39	*0.34*	0.15	0.23	0.21	*0.16*
PJW	0.42	0.47	0.46	*0.54*	0.34	0.35	0.37	*0.33*	0.13	0.21	0.19	*0.15*

NZSC	WCsat (v/v) Saxton and Rawls (2006)	WCsat (v/v) Wösten et al. (1999)	WCsat (v/v) Wey-nants et al. (2009)	WCsat (v/v) ***S-map data***	WC -10kPa (v/v) Saxton and Rawls (2006)	WC -10kPa (v/v) Wösten et al. (1999)	WC -10kPa (v/v) Wey-nants et al. (2009)	WC -10kPa (v/v) ***S-map data***	WC -1500kPa (v/v) Saxton and Rawls (2006	WC -1500kPa (v/v) Wösten et al. (1999)	WC -1500kPa (v/v) Wey-nants et al. (2009)	WC -1500kPa (v/v) ***S-map data***
PPJX	0.43	0.47	0.47	*0.49*	0.34	0.35	0.38	*0.38*	0.14	0.22	0.20	*0.19*
PPX	0.42	0.47	0.46	*0.48*	0.33	0.35	0.37	*0.36*	0.13	0.22	0.19	*0.18*
PXM	0.42	0.47	0.46	*0.49*	0.33	0.35	0.37	*0.37*	0.13	0.21	0.19	*0.17*
PXMJ	0.42	0.47	0.46	*0.49*	0.33	0.35	0.38	*0.37*	0.14	0.22	0.19	*0.18*
RFMW	0.40	0.52	0.48	*0.52*	0.27	0.35	0.37	*0.37*	0.11	0.20	0.18	*0.15*
RFT	0.39	0.51	0.47	*0.45*	0.17	0.32	0.32	*0.24*	0.06	0.17	0.14	*0.08*
RFW	0.39	0.52	0.48	*0.45*	0.23	0.35	0.36	*0.29*	0.10	0.21	0.17	*0.11*
ROW	0.40	0.51	0.48	*0.47*	0.28	0.36	0.38	*0.34*	0.12	0.22	0.19	*0.13*
RXT	0.40	0.52	0.49	*0.34*	0.28	0.37	0.39	*0.17*	0.13	0.24	0.21	*0.05*
WW	0.39	0.48	0.44	*0.34*	0.10	0.23	0.20	*0.13*	0.03	0.09	0.05	*0.03*

Table 10.

Comparison of soil moisture generated via NB_PTFs toolbox using FSL soil map together with WISE soil database vs. weighted average of individual S-map sibling soil moisture for selected soils.

NZSC	FAO WRB	WCsat (v/v) Saxton and Rawls (2006)	WCsat (v/v) Wösten et al. (1999)	WCsat (v/v) Wey-nants et al. (2009)	WCsat (v/v) ***S-map data***	WC -10kPa (v/v) Saxton and Rawls (2006)	WC -10kPa (v/v) Wösten et al. (1999)	WC -10kPa (v/v) Wey -nants et al. (2009)	WC -10kPa (v/v) ***S -map data***	WC -1500 kPa (v/v) Saxton and Rawls (2006)	WC -1500 kPa (v/v) Wösten et al. (1999)	WC - 1500 kPa (v/v) Wey -nants et al. (2009)	WC -1500 kPa (v/v) ***S -map data***
BFA	Cambisols (Dystric)	0.42	0.47	0.47	*0.47*	0.31	0.37	0.37	*0.34*	0.18	0.19	0.22	*0.15*
BOA	Ferralic Cambisols (Dystric)	0.42	0.47	0.47	*0.44*	0.31	0.37	0.37	*0.32*	0.18	0.19	0.22	*0.14*
BOT	Ferralic Cambisols	0.42	0.47	0.47	*0.53*	0.31	0.37	0.37	*0.40*	0.18	0.19	0.22	*0.17*
EOC	Chernozems/ Phaeozems	0.45	0.40	0.43	*0.51*	0.36	0.36	0.36	*0.36*	0.20	0.20	0.22	*0.17*
EODC	Chernozems/ Phaeozems	0.45	0.40	0.43	*0.51*	0.36	0.36	0.36	*0.36*	0.20	0.20	0.22	*0.17*
EVM	Vertisols	0.51	0.46	0.48	*0.48*	0.43	0.43	0.43	*0.39*	0.30	0.22	0.31	*0.29*
GOT	Gleysols	0.41	0.52	0.49	*0.53*	0.29	0.41	0.41	*0.41*	0.16	0.26	0.23	*0.19*
GRT	Gleyic Fluvisols	0.41	0.45	0.45	*0.48*	0.29	0.35	0.35	*0.34*	0.15	0.17	0.20	*0.12*
PIM	Ruptic Planosols	0.39	0.43	0.43	*0.49*	0.22	0.32	0.32	*0.37*	0.10	0.16	0.16	*0.18*
PIT	Ruptic Planosols	0.39	0.43	0.43	*0.35*	0.22	0.32	0.32	*0.24*	0.10	0.16	0.16	*0.10*
PJM	Luvic Planosols/Lixic Planosols	0.39	0.43	0.43	*0.49*	0.22	0.32	0.32	*0.36*	0.10	0.16	0.16	*0.19*
PJT	Luvic Planosols/Lixic Planosols	0.39	0.43	0.43	*0.48*	0.22	0.32	0.32	*0.34*	0.10	0.16	0.16	*0.16*

NZSC	FAO WRB	WCsat (v/v) Saxton and Rawls (2006)	WCsat (v/v) Wösten et al. (1999)	WCsat (v/v) Wey-nants et al. (2009)	WCsat (v/v) ***S-map data***	WC -10kPa (v/v) Saxton and Rawls (2006)	WC -10kPa (v/v) Wösten et al. (1999)	WC -10kPa (v/v) Wey-nants et al. (2009)	WC -10kPa (v/v) ***S-map data***	WC -1500 kPa (v/v) Saxton and Rawls (2006)	WC -1500 kPa (v/v) Wösten et al. (1999)	WC - 1500 kPa (v/v) Wey-nants et al. (2009)	WC -1500 kPa (v/v) ***S-map data***
PXM	Fragic Planosols	0.39	0.43	0.43	*0.49*	0.22	0.32	0.32	*0.37*	0.10	0.16	0.16	*0.17*
RFM	Fluvisols	0.41	0.45	0.45	*0.52*	0.29	0.35	0.35	*0.37*	0.15	0.17	0.20	*0.15*
RFT	Fluvisols	0.41	0.45	0.45	*0.45*	0.29	0.35	0.35	*0.24*	0.15	0.17	0.20	*0.08*
RFW	Fluvisols	0.41	0.45	0.45	*0.45*	0.29	0.35	0.35	*0.29*	0.15	0.17	0.20	*0.11*
ROW	Regosols	0.39	0.43	0.43	*0.47*	0.22	0.31	0.31	*0.34*	0.12	0.13	0.16	*0.13*

Conclusions

The guidelines with 151 PTFs and the associated NB_PTFs toolbox are designed to provide decision trees to aid users in obtaining best-practice soil hydraulic information in different geoclimatic and data availability contexts. The toolbox contains 43 PTFs for a wide range of climates including temperate, tropical and arid climate with a user-friendly GUI interface and detailed help text. The toolbox's functionality was demonstrated in two contrasting case studies. The VMD case study represents a tropical, flat area with limited soil information and the Hurunui catchment case study represents a temperate, hilly area with better availability of soil information. Information on soil hydraulic properties, produced using NB_PTFS including point values, value ranges as well as their spatial distribution, can be used for a number of modelling purposes, such as hydrological, irrigation schedule, crop and ecosystem service modelling etc. at multiple scales. Users and developers with limited access to specialist knowledge can use the guidelines and the toolbox to quickly estimate model parameters in an inexpensive way, balancing budget limitations and desired accuracy of model parameters. In addition, the guidelines and toolbox assist users in getting more accurate soil hydraulic properties for their study areas instead of guessing amidst very broad value ranges or using default deterministic values in models. As soil hydraulic properties play such a critical role in determining the accuracy and uncertainty surrounding hydrological modelling prediction, significant improvements in resolving soil hydraulic properties are needed. For the new generation of highly spatially-resolved models, such as Nature Braid, a simple and effective method is critical.

The guidelines and toolbox will allow users who are new to the use of soil hydraulic properties to quickly select an appropriate PTF for their study area, turning a task that would otherwise take many days to weeks to minutes to hours instead. Results from different PTFs also can be combined and normalised to get the most representative soil hydraulic properties for the soil characteristics of a study area. Finally, although it is becoming common to use global soil databases to parameterise the physical and chemical properties of local soils, we warn that this can be highly inaccurate unless a good understanding of local soils has already provided information for the databases. Drawing further on locally-sourced literature and soil samples may enhance this understanding and help ensure soils selected from the global soil database adequately represent local soils.

These guidelines and tools are being released and published now as we feel they are timely and needed. We believe they add significant value to what already exists as they stand, but that significantly more value can be added. We intend to work to actively update and enhance them over forthcoming years. We plan to update guidelines and the NB_PTFs toolbox to include further point and parametric PTFs and also explore the utility of machine learning algorithms, such as Artificial Neural Networks (ANNs) and Supervised Vector Machine (SVM) learning to generate PTFs. We would also like the toolbox to be transferred to QGIS or developed as stand-alone software to reach users who have cost or other limitations precluding them accessing ArcGIS.

Acknowledgements

We are grateful for the funding support provided by Victoria University of Wellington's Victoria Doctoral Scholarship and the Marina van Damme Scholarship (University of Twente) to Dang Anh Nguyet and for the support from the Holdsworth Charitable Trust provided to Stephanie Tomscha. We would like to thank Manaaki Whenua Landcare Research for granting us the access to S-map data of the Hurunui catchment.

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Supplementary materials

Suppl. material 1: Supplementary Material S1 doi

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Endnotes

*1 Richards equation (1930) is the most popular physics-based equation to describe sub-surface water movement and is often coupled with crop models linking plant transpiration to soil moisture status amongst other things.

*2 Plant available water: Water held between field capacity and wilting point.

*3 Popular infiltration models are Green Ampt (1911), Kostiakov (1932), Horton (1940), Philip (1957)

*4 pF = $\log_{10}$ [-head (cm of water)]

*5 the difference between saturation and field capacity moisture content

*6 The soil dataset was developed by Landcare and is owned by Environment Canterbury. At the time of writing, the last update to it was carried out in 2017 and information on methodology was accessible at https://apps.canterburymaps.govt.nz/lrisupport/provenance.html (accessed 29 Jun 2021). The soil map and soil information of Canterbury can be found at: https://apps.canterburymaps.govt.nz/lrisupport/ (accessed 29 Jun 2021).