Parameterising and Adapting Ecosystem Service Models in Data Sparse Regions: Gaps, Guidelines, and an Application in the Vietnamese Mekong Delta

By

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Abstract

The *Ecosystem Services* concept – "the benefits people obtain from ecosystems" received wide attention after the United Nations launched the *Millennium Ecosystem Assessment (MEA)* (2005b). Since the MEA, there has been an increasing number of research focusing on ecosystem services (ES) assessment to support evidence-based decision-making. ES assessments provide useful information, i.e., quantifications and maps of ES biophysical and economic values, for decision-makers to understand ecosystem health status, to contrast current and potential future ES available for different groups of people, and to compare management options.

Among ES assessment methods, ES modelling has been demonstrated as an effective decision-making support tool. Models used for ES assessment include discipline-specific models, such as hydrological models, ecological-environmental models, habitat distribution models, statistical models, etc. which were not generally designed for ES assessment. This type of model is mostly useful for single ES assessment due to their discipline-based approach. To support multi-criteria decision-making, relationships and interactions between multiple ecosystem services need to be considered. Multi-ecosystem service models that link service provision and trade-offs have been rapidly developing within the last two decades, such as InVEST, ARIES, LUCI etc., hereafter referred to as ES models. These models were specifically designed to cover multiple disciplines and provide assessment for multiple ES and their interactions at different scales, from national to catchment to sub-catchment.

Demand for applying ES models in decision-making has increased across the world. However, despite advances in modelling approaches for ES, adopting either discipline-specific models or more holistic multi-ES models is time and data intensive, especially in data sparse areas and areas where ES modelling has not been well established. Many of the main challenges are rooted in model parameters/assumptions and processes biased to specific ecosystem, policy, and data contexts for which ES models were initially developed or established. ES modelling, therefore, needs to be improved to cover wider ecosystem, policy, and data conditions, and fast enough for use during decision-making timeframes.

Spatially explicit ES models have been widely used in many parts of the world. However, their applications are still limited in some rich biodiversity and economically important regions due to data constraints and lacking guidance on ES model application. These regions include the Southeast Asia (SEA) region which possesses four of the thirty-six global biodiversity hotspots according to the Conservation International. The region also has one of the highest proportions of tropical forests and coral reefs of the world. In terms of economy, the region is one of the largest suppliers of forest,

agriculture, and fishery products in the world. There are also very few numbers of spatially explicit ES model applications in deltas, one of the most populated and productive areas of SEA and global ecosystems. Deltaic regions have specific ecological processes i.e., river-floodplain and land-sea interactions as well as typical economic activities, i.e., rice and aquacultural production, which have not been well covered in previous ES modelling studies. Further explorations of ES modelling in SEA and deltas are needed to understand the advantages and disadvantages of current ES models when applying in these regions. From that, ES modelling can be enhanced for improving uptake in wider nature, policy, and data contexts.

Given the above background, the aim of this research is to facilitate ES model parameterisation and adaptation to enhance ES model applicability, especially in data sparse areas and areas where ES modelling has not been well established. It will ultimately reduce efforts required to produce ES modelling and assessments. This aim is achieved by fulfilling four objectives. The first objective is to review current literature on ES assessments to understand the diversity of assessment methods to date as well as the limitations and obstacles for implementing these methods. The focus is on the Southeast Asia (SEA) region but with a view to contributing to global needs. Through the review, we found that methodologies used in ES assessments in SEA are diverse with increased stakeholder participation and a growing number of spatially explicit assessments. ES modelling has gradually gained more attention from scientists and decision-makers in SEA. Data constraints, limited capacity building and lack of detailed guidance are the main obstacles of ES assessment and ES modelling in SEA.

Recognising the importance of stakeholder participation to achieve effective ES assessments, the initial second objective of this study is to explore stakeholder engagement in ES modelling in the Vietnamese Mekong Delta (VMD), which represents a tropical deltaic region in SEA. However, due to the Covid pandemic and travel restrictions, this objective could not be achieved, and the focus was shifted. From our review, there are many other issues needed to address for improving ES assessment in the VMD, SEA, and around the world. Among the issues, the lack of data and knowledge regarding ES related biophysical processes is a huge obstacle to implementing ES models in SEA and across the world. Enhancing data acquisition for ES modelling, therefore, becomes the second objective of this study.

Many of the most modelled ES have strong dependencies on land use/land cover data but also soil data. Among soil data, soil hydraulic properties information is generally required. However, finding information regarding soil hydraulic properties remains one of the greatest challenges for modellers because the data are generally not available and difficult to measure directly. In addition, using hydraulic properties information for ES model requires a sound understanding of hydraulic properties, which is an obstacle for users having limited access to specialist knowledge. To improve the reliability of model outputs supporting ecosystem-based policies, this issue of lacking information and knowledge on soil hydraulic properties needs to be addressed. In response to this, this study developed guidelines and an associated spatially referenced toolbox, LUCI_PTFs, to obtain soil hydraulic parameters e.g., those defining soil moisture pressure relationships and hydraulic conductivity. The guidelines and toolbox can assist in acquiring key soil hydraulic properties for different geoclimatic and data rich/sparse regions in a quick and inexpensive way. Examples of using the guidelines and toolbox were presented in two case studies, the Vietnam Mekong Delta (VMD) and the Hurunui catchment in the Canterbury region of New Zealand. The case studies are very different in natural conditions and data availability. The VMD represents a tropical, flat location with limited information on soil physical, chemical, and hydraulic properties. The Hurunui catchment case study shows the use of the guidelines and toolbox in a semi-arid and hilly area with detailed soil information.

The review of ES assessment also highlighted the importance of improving spatially explicit ES modelling and mapping in data sparse regions and regions where ES modelling has not been well established. Accordingly, the third objective of this research is to explore the capacity of ES model, applying the Land Utilisation & Capability Indicator (LUCI), to map multiple ES (flood mitigation, agriculture/aquaculture productivity, climate regulation) in the Vietnamese Mekong River Delta (VMD). The VMD characterises a deltaic region with rich ecosystems, but data are sparse and ES model application has not been well established. The VMD is an agricultural region focusing on rice and aquaculture production, which are also the important economic activities of SEA and Asia broadly. Rice fields and aquaculture lands are special wetlands providing multiple ecosystem services besides their food provision, i.e., flood mitigation, biocontrol, pollination, and nutrient cycling as well as cultural diversity and aesthetics/beauty. Rice and aquaculture cultivation in deltas were adapted to seasonal flood conditions hence the relationship between flooding and agriculture/aquaculture in deltas is temporally and spatially dynamic. The spatial configurations of these agro-hydrological characteristics are best to be presented through spatially referenced modelling. Among ES spatially explicit modelling tools, the LUCI model has particular strengths in spatial connectivity and ability to map ES at multiple scales. The model also possesses the unique trade-off tool to map the interactions between ES.

This is the first fine (5 by 5 m) spatially explicit multiple ES modelling conducted in the VMD with ~ 1500 million elements processed for a single run. The application of LUCI for the VMD will provide instructions on ES model parameterisation and recommendations to improve the model's structure/algorithms to better adapt to the VMD as well as other tropical deltaic areas. In addition, this study demonstrates the practical implementation of ES biophysical modelling results for spatially explicit economic value mapping to support nature-based solutions (Nbs) in the upper stream VMD. The author of this thesis notes that although she is now part of the LUCI development team, she specifically chose to study with the team because of her belief that LUCI was among the most applicable models to the VMD context and needs. The LUCI model has rebranded as Nature Braid (next-gen LUCI). The Nature Braid model includes all the original algorithms that were contained within LUCI's modules and functions with additional algorithms and new updates.

The last objective of this thesis is to suggest recommendations to improve LUCI and other models to better meet the needs of ES modelling in SEA and deltaic regions. Detailed guidance on model parameterisation plays an important role in enhancing ES modelling performance in these areas. In addition, model structure improvements to cover specific environmental conditions, biodiversity, and cultural values are important to increase uptake of LUCI as well as other ES models in SEA and deltaic regions. The outputs of this thesis are expected to contribute to the development of more robust ES modelling and help ES modelling become more approachable for decision-makers and scientists in data sparse regions and particularly in tropical delta areas.

Statement of own work

I hereby certify that this submission is my own work. All literature reviews, data collection, and analysis for the thesis were led by me with advice and guidance provided by my supervisors. The code behind the LUCI_PTFs tool was implemented by Dr. Rubianca Benavidez, but the implemented methodologies were collated, and results were analysed by myself with advice and guidance provided by Dr. Benavidez and my supervisors.

Chapter 2 “Review of ecosystem service assessments: pathways for policy integration in Southeast Asia” is published in the journal Ecosystem Services, 49, 101266, 2021, led by me and co-authored with Dr. Bethanna Jackson (primary supervisor), Dr. Stephanie Tomscha (secondary supervisor) and Dr. Rubianca Benavidez (LUCI team, VUW).

Chapter 3 “Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling” is published in the journal One Ecosystem, 7, e76410, 2022, led by me and co-authored with Dr. Bethanna Jackson (primary supervisor), Dr. Stephanie Tomscha (secondary supervisor), Dr. Rubianca Benavidez (LUCI team, VUW), Dr. Kremena Burkhard (Leibniz University Hannover), Dr. Linda Lilburne (Manaaki Whenua – Landcare Research), Dr. Dung Duc Tran (Vietnam National University) and Dr. Long Hoang Phi (Wageningen University).

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Acronyms and Abbreviations

Acronym or Abbreviation	Meaning
ADB	Asian Development Bank
ASEAN	Association of Southeast Asian Nations
BC	Brooks and Corey model
BD	Bulk density
Cl	Clay
DEM	Digital Elevation Model
DW	Drainable water
ES	Ecosystem services
EU	European Union
FAO	Food and Agriculture Organization
FC	Field Capacity
FSL	The New Zealand Fundamental Soil Layers
GIZ	German Corporation for International Cooperation (Deutsche Gesellschaft für Internationale Zusammenarbeit)
GSO	General Statistics Office of Vietnam
HCC	Hydraulic conductivity curve
HG	Hydroscopic water
IPBES	The Intergovernmental Science Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
K_{sat}	Saturated hydraulic conductivity
LUCI	Land Utilisation and Capability Indicator
LULC	Land use land cover
MRC	Mekong River Commission
MvG	Mualem van Genuchten model
NGOs	Non-governmental organization
NRAW	Not readily available water
NZ	New Zealand
NZSC	New Zealand Soil Classification
OM	Organic Matter
PAW	Plant Available Water
PES	Payment for ecosystem service
PTFs	Pedotransfer Functions
PWP	Permanent Wilting Point
RPAW	Readily Plant Available Water
Sa	Sand
SEA	Southeast Asia
SEEA	System of Environmental Economic Accounting
Si	Silt
SMRC	Soil moisture retention curve
TEEB	The Economics of Ecosystems and Biodiversity
UK	United Kingdom
UN	United Nation
USA	United States
USD	United States Dollars
VG	Van Genuchten model

Acronym or Abbreviation	Meaning
VMD	Vietnamese Mekong Delta
WB	World Bank
WSC	Stomatal closure point
WWF	World Wildlife Fund

Glossary

Term	Definition used in this thesis
Biomass	Organic material both aboveground and belowground, and both living and dead, e.g., trees, crops, grasses, tree litter, roots etc. (IPCC, 2006)
Carbon flux	Transfer of carbon from one carbon pool to another in units of measurement of mass per unit area and time (IPCC, 2006).
Carbon sequestration	The process of removing carbon from the atmosphere and depositing it a carbon pool (UNFCCC, 2022).
Carbon stock	The quantity of carbon contained in a carbon pool (IPCC, 2006).
Carbon pool	A system which has the capacity to accumulate or release carbon. Examples of carbon pools are forest biomass, wood products, soils and the atmosphere (IPCC, 2006).
Cultural services	The non-material benefits of ecosystems – from recreation to spiritual inspiration to mental health (TEEB, 2010b).
Ecosystem Services	The benefits people obtain from ecosystems (MEA, 2005b)
Habitat or Supporting Service	The services underpin almost all other services. Ecosystems provide living spaces for plants and animals – and maintain their diversity (TEEB, 2010b)
Hydraulic conductivity curve	The relationship between hydraulic conductivity and pressure
Nature-based solutions	Actions and policies to reconnect river and floodplains
Pedotransfer functions	Equations which statistically correlate soil hydraulic properties with more easily measured soil variables or readily available soil properties, for example sand, silt, clay, bulk density etc.
Provisioning Service	The materials that ecosystems provide such as food, water and raw materials (TEEB, 2010b)
Regulating Service	The services that ecosystems provide by acting as regulators. This includes regulation of air and soil quality, as well as flood and disease control (TEEB, 2010b)
Soil hydraulic properties	Properties control water movement in soil
Soil moisture	Quantity of water stored in soil
Soil moisture retention curve	The relationship between soil moisture and pressure

1 Introduction

1.1 General overview and context

1.1.1 Ecosystem service approach to support decision-making

Since the *Millennium Ecosystem Assessment (MEA)* (2005b), the *Ecosystem Services* (ES) concept - the benefits people obtain from ecosystems - has been gaining continual traction in decision-making processes, such as conservation and broader land-use planning and development strategies (IPBES, 2016). The European Union (EU) has considered ecosystem services in many of their planning documents including the *EU Biodiversity Strategy to 2020* which encourages the nature-based solutions for balancing economic development and the potential of natural capital (Maes et al., 2012). The United States of America (USA) has integrated ecosystem services into natural resources management through the memorandum on *Incorporating Ecosystem Services into Federal Decision Making* issued by the Executive Office of the President (EOP, 2015). The ecosystem services approach is also widely introduced to support environmental policies in the United Kingdom (Hodge, 2017), Australia (Pittock et al., 2012) and New Zealand (Greenhalgh et al., 2015).

The UN Sustainable Development Goals (SDGs) launched in 2016 will be the key shared target for many governments globally to develop national strategies by 2030. The central idea of SDGs is improving human well-being while protecting environment from degradation which is also the core purpose of the *Ecosystem Services* concept (UN, 2015). Wood et al. (2018) conducted a survey with more than 500 experts in both ecosystem services and development communities to assess the linkage of ecosystem services with the SDGs. The survey confirmed the important role of ecosystem services to underpin all SDGs. The ecosystem services approach would maintain their essential position in supporting governments to achieve the SDGs (IPBES, 2016; Geijzendorffer et al., 2017; Rieb et al., 2017). In the last few years, ecosystem services (ES) frameworks, including the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES) and the System of Environmental Economic Accounting Experimental Ecosystem Accounting (SEEA EEA) have been working on how national accounting systems integrate the value of ecosystems and their services into national planning and monitoring progress towards the SDGs (Bordt et al., 2018)

This growth in policy attention toward ecosystem services has led to the increased demands in ecosystem service assessments, specifically ecosystem service modelling, mapping, and economic valuation (Daily et al., 2009). Figure 1 presents the framework developed by Daily et al. (2009) to integrate ecosystem services into decision-making. The framework shows the essential role of ES assessments in supporting decision-making. Maps of biophysical and economic ES values provide information on ecosystems and their services. Based on this information, policymakers can make evidence-based decisions that harmonise social needs with natural assets.

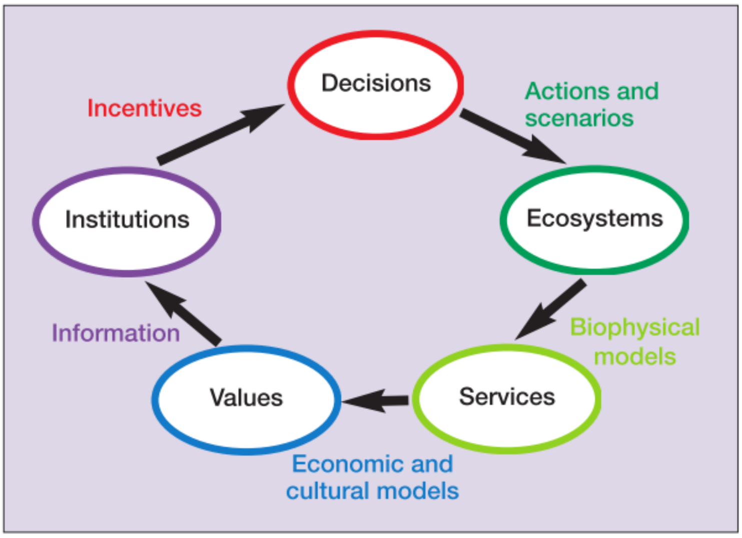


Figure 1 A framework to integrate ecosystem services into decision-making
Source: Daily et al. (2009)

Diverse methods have been continuously developed to map ES biophysical and economic values, ranging from simple matrix-based approaches to ES models. Among ES assessment tools, assessment of ES through spatial modelling plays a key role in ecosystem accounting (Daily et al., 2009; Martínez-Harms et al., 2012; Schröter et al., 2015; Francesconi et al., 2016). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) also expressed that models of biodiversity and ecosystem function are critical to policymakers' capability to predict and understand responses to environmental change (IPBES, 2016). Modelling tools integrate many components that make up natural and human-induced processes as well as interactions among these processes to quantify ES supplies, changes, and flows (Bagstad et al., 2013a).

Models used for ES assessment include discipline-specific models and ES models. Discipline-specific models such as hydrological models, ecological-environmental models, habitat distribution models, statistical models, etc., were not generally designed for ES assessment but are suitable for ES assessment purposes. ES models, such as InVEST, ARIES, LUCI, etc., were designed, as decision-support tools, for multi-ES modelling in space and time. Although ecosystem service models are newly developed over the last two decades, they have demonstrated their potential to effectively support decision-making (IPBES, 2016). They provide information to investigate trade-offs and synergies between multiple ecosystem services which are not available in the more established discipline-specific models (Bagstad et al., 2013b). Compared with discipline-specific models, ES models tend to be more accessible to non-experts while still providing a good general picture of discipline-specific ES (Vigerstol et al., 2011). Most ES models are open-source and continuously evolving (Burkhard et al., 2017). The use of ES models in real-world decision support frameworks has become the focus of a rapidly growing body of research (Bagstad et al., 2013b; Shoyama et al., 2017).

Due to their constant evolution and applicability to many contexts, reviews of ES models can be found in many places, notable ones include Burkhard et al. (2017); La Notte et al. (2017); IPBES (2016); Vigerstol et al. (2011); Bagstad et al. (2013c). These reviews summarised states, trends, achievements, and limitations in ES modelling to date. Despite advances in modelling approaches, ES modelling is still largely driven by data and requires sound knowledge to understand ES processes (Egoh et al., 2012; Crossman et al., 2013; Schröter et al., 2015; IPBES, 2016). The operational time of a spatially explicit ES model may take hundreds of working hours by an experienced analyst (Bagstad et al., 2013c; Burkhard et al., 2017). Challenges are also rooted in model's parameters/assumptions and processes biased to specific nature, policy, and data context for which an ES model was initially developed or well established. ES models need to be improved to be widely applicable for different landscapes, scales, policy, and data conditions, and fast enough for use during decision-making timeframes (Bagstad et al., 2013c).

Land use/land cover and soil data are fundamental inputs for most biophysical models. Among soil data, soil hydraulic properties (e.g., soil moisture pressure relationships and hydraulic conductivity) are required by a wide range of environmental models including ES models. Information on soil hydraulic properties has become more important as more complex representations of soils are being built into environmental models. However, this information is generally most explored in hydrology and crop models and does not consider the needs of broader ES modelling (Nemes et al., 2003; Timlin et al., 2004; Vereecken et al., 2015; Wösten & Tamari, 1999). Soil hydraulic properties, therefore, are often written with discipline-specific language causing difficulties in uptake by ES modelers and users who have limited access to specialist knowledge. In addition, direct measurements of soil hydraulic properties are both labour intensive and expensive (Wösten et al., 1999b; Nemes et al., 2003; Pachepsky et al., 2004). It is also impossible in practice to measure soil hydraulic properties for large scale hydrological applications such as for catchment or regional hydrological models (Twarakavi et al., 2009; Pechlivanidis et al., 2011; Ket et al., 2018). 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). Previous studies in hydrological modelling attempted to overcome the issue of data limitations in data-sparse regions (Neal et al., 2012; Hawker et al., 2017). However, these studies focused only on topography and river channel data enhancement, not soil hydraulic properties.

ES assessment, specifically ES modelling, has been well established in Europe (Maes et al., 2012), the United Kingdom and the United States (Grêt-Regamey et al., 2017), and some parts of Asia Pacific i.e. China (Shoyama et al., 2017) and Australia (Alamgir et al., 2014). Nevertheless, applications of ES models are still constrained in some biodiversity rich and economically important regions of the world, specifically the Southeast Asia region (Dang et al., 2021a). Southeast Asia (SEA) is one of the world's biodiversity hotspots with four of the thirty-six global biodiversity hotspots according to the Conservation International and three of the seventeen global megadiverse countries (Indonesia, Malaysia, and the Philippines) (von Rintelen et al., 2017). SEA possesses the most diverse coral reefs and tropical forests of the world (von Rintelen et al., 2017). Regarding economic importance, Southeast Asia is one of the largest suppliers of forest, agriculture, and fishery products in the world (Hall, 2004; Clarete et al., 2013). Ecosystems of the region are currently being rapidly degraded due to intensive human activities for economic development (Estoque et al., 2019). ES assessment has been considered as a potential tool to support sustainable natural resources management in the region, however, ES modelling is still limited in the region with only a few published applications of the InVEST model (Dang et al., 2021a).

In SEA, a large portion of the region’s population lives in deltaic areas, i.e., the Upper Mekong delta of Cambodia, the Chao Phraya delta and the Bang Pakong river basin of Thailand, the Ayeyarwady delta of Myanmar, the Lower Mekong delta and Red River delta of Vietnam. Deltas and estuaries are also the most populated areas of the world where 22 of the 32 largest cities in the world are located (Miththapala, 2013). The river deltas in SEA and Asia are rich in biodiversity and highly productive, specifically suitable for rice and aquaculture production. With high population densities and large dependencies on agriculture, these regions are extremely vulnerable to climate change and natural disasters, i.e. floods, storm surges, salinity intrusion, and other hazards (Szabo et al., 2016). Quality information on ecosystem health, as well as interactions between people and nature, are important for deltas’ sustainable development strategies. Recently, several applications of InVEST were conducted in deltaic regions of China (Ding et al., 2021; Dou et al., 2021; Zhang et al., 2021a; Zhang et al., 2021b). Some of the limitations of the INVEST model identified by these studies are the lack of consideration for topography and surface run-off in water yield quantification (Zhang et al., 2021b); subjective parameter setting (Ding et al., 2021); bias due to the use of empirical formulae to calculate plant available water content (PAWC) and reference evapotranspiration ET_0 (Dou et al., 2021) and the assumption that underground water resources stayed stable (Deng et al., 2019). Therefore, INVEST does not seem appropriate to model ES in coastal areas. Although showing limitations of current ES modelling, these studies did not give detailed recommendations on how ES models can be improved for better uptake in deltaic areas.

The demand for applying ES models in evidence-based decision-making has increased across the world (Seppelt et al., 2011; Maes et al., 2012; Martínez-Harms et al., 2012; Crossman et al., 2013; IPBES, 2016). To become widely used, ES models' parameters/assumptions and algorithms need to be improved for different ecosystems, scales, policies, and data contexts. In addition, ES modelling processes need to be accessible and fast enough for use during decision-making timeframes. To reduce the time required for robust ES modelling, more detailed guidelines for appropriate applications of ES decision support tools in different data availability and geoclimatic contexts are needed (Vigerstol et al., 2011; Bagstad et al., 2013c; IPBES, 2016; Ochoa et al., 2017).

1.1.2 Ecosystem service approach to support nature-based water management in the Vietnam Mekong Delta

The Vietnamese Mekong Delta (VMD) is the downstream part of the Mekong which is one of the world's greatest rivers (MRC, 2016). The total area of the delta is 39,000 km^2, occupying about 12% of the total natural area of Vietnam (GSO, 2019). The VMD represents a mega-delta with more than 17 million people, accounting for ~ 20% of the population of Vietnam. The VMD is an important agriculture region of Vietnam, producing half of the national rice production and nearly 60% of aquaculture of Vietnam (GSO, 2019)

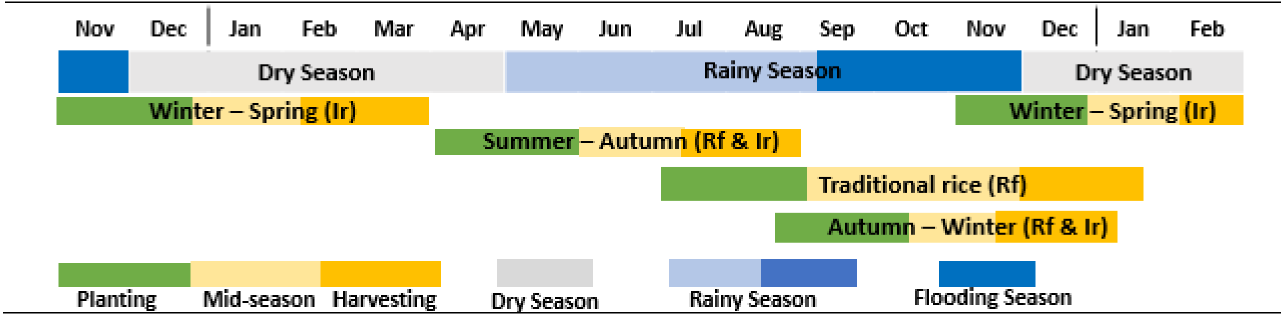
The VMD has flat terrain, an average elevation of 0.8 m, and an elevation range of 0.5-5m above sea level (MDP, 2013). Located in a tropical monsoon climate, the VMD has two distinct seasons. The dry season is from December to the end of April, and the rainy season is from May to November (Hung et al., 2012). Floods typically occur during the monsoon, with inundation lasting up to 3 months (Hung et al., 2012). Flooding is a natural process bringing many benefits to the delta (Tri, 2012; Hoang et al., 2018; Tran et al., 2018). Floodwaters wash away sulphates and salts, and bring alluvial sediment which helps maintain soil fertility (Hoa et al., 2008; Hung et al., 2014b; Manh et al., 2014; Tong, 2017), provide fresh water for crop irrigation and replenish groundwater stores (Le et al., 2009). The population in the VMD has generally adapted their lives to live with floods (Le et al., 2009; Loc et al., 2016). In the dry season, flow in the Mekong is insufficient to prevent saline intrusion and extensive salinisation of waterways occurs in the lower Delta (Hoa et al., 2008). Saltwater affects about 45% of the delta in the dry season (Tri, 2012).

Water flows of the VMD are largely influenced by the intensive hydropower development in the upstream Mekong river. In total, 187 hydropower plants are existing or planned in the Mekong basin (Hecht et al., 2019). The construction of dams can reduce the flood peaks but increase water-level fluctuation affecting the productivity of seasonally inundated floodplain agriculture and fisheries (Arias et al., 2014). Dry-season drawdowns for maximum power production may cause 40% loss of water volume when the Mekong river reaches Vietnam (DHI, 2015). In addition, hydropower reservoirs obstruct fish migration and reduce sediment transport to the VMD (Kondolf et al., 2018). It was estimated that 96% of the historical sediment load of the pre-dam period would be trapped (Kondolf et al., 2014).

In the VMD, extensive artificial water control infrastructures have been constructed for the past two decades, including dike systems with the main purpose of protecting rice fields from flooding (Hung et al., 2014b). At first, the majority of dikes constructed were low dikes or “August” dikes which provide protection against flood peaks arriving around mid-July to mid-August, ensuring the farmers can grow double rice cropping (two rice crops) per year in many parts of the VMD (Triet et al., 2017). The crests of low dikes were designed to just equal the maximum water level in August (Thanh et al., 2020). Double rice cropping systems can be divided into: (1) double-rainfed (“Summer-Autumn” and “Autumn-Winter”) and (2) double-irrigated (“Winter-Spring” and “Summer-Autumn”) rice cropping (Table 1). Double-irrigated rice cropping systems dominate in the upper part of the delta while rainfed systems are mostly found in the coastal areas (Sakamoto et al., 2006). The Vietnam government released Resolution No. 63/NQ-CP in 2009 to insure rice purchases from farmers. As a result, farmers were incentivised to increase production by shifting from double- to triple-irrigated rice cropping with three main rice seasons, i.e. “Winter-Spring” and “Summer-Autumn”, “Autumn-Winter” (Table 1) (Chapman et al., 2016; Tran et al., 2018). This led to the large expansion of high dike systems in the upper parts of the VMD’s floodplains to facilitate the third rice crop during the flood season (Chapman et al., 2016; Tong, 2017; Tran et al., 2018). High dikes were designed around the maximum water level of the extreme flood in 2000 (crest levels ~ 4.0 – 6.0m above sea level), the historically highest flood in the recent 60 years (Le et al., 2009). The total length of high dikes in the VMD is about 1,300 km, and that of low dikes is 13,300 km (Hung et al., 2014b; Triet et al., 2017). They are equipped with sluice gates and often with additional pumping systems which is the only linkage of floodplains with channels and the river.

Table 1 Main rice seasons and rice cropping systems in the VMD, adapted from Lam et al. (2017)

Rice cropping system	Rain-fed/Irrigated	Rice season
1. Single rice crop	Rainfed (Rf)	Traditional rice
2. Double rice crop	Rainfed (Rf)	Summer-Autumn and Autumn-Winter
	Irrigated (Ir)	Winter-Spring and Summer-Autumn
3. Triple rice crop	Irrigated (Ir)	Winter-Spring, Summer-Autumn and Autumn-Winter
4. Rice shrimp system	Rainfed (Rf)	Traditional rice



* The rice seasons were named based on traditional understanding of seasons in Vietnam (a year has four seasons: Spring, Summer, Autumn and Winter), not really based on temperature.

Adding high dikes to the VMD system for triple-rice cropping ultimately threatens the delta's sustainability. Recent studies have proved that triple-rice cropping only brings a short-term benefit of increasing rice production while the adverse impacts can be significant and long-lasting (Manh et al., 2014). High dike systems interrupt the connectivity between rice fields and the rivers and channels hence decreasing the benefits of floodwater. As important sediment-bound natural nutrients could not be delivered by floodwaters, soil degradation increased and fertilizer use increased, resulting in the net benefit of triple rice cropping ultimately being reduced through time (Tran et al., 2018). In addition, high dikes block fish migration – an important nutrient source for local people during the flood season. Poor farmers are the most vulnerable groups because they heavily depend on natural resources for their basic needs and income in the flood season (Chapman, & Darby, 2016). Another key effect of the high dike systems is a change in the natural flooding and inundation regimes. Inundation water levels tend to be higher in downstream areas with increased flood risks in unprotected parts of the VMD (Hoa et al., 2008; Vu et al., 2014a; Triet et al., 2017).

Recognising that preventing flooding by hard infrastructure (e.g. stop-banks, dikes, weirs, etc.) has mixed effects, WWF (2004) suggested governments and policy-makers should work with floods rather than against them. Nature-based solutions (Nbs) that aim to reconnect rivers with their floodplains have emerged as an economic and ecological way forward to both restore floodplains' capacities and reduce flood risks (Moss et al., 2007; Michael et al., 2014; Hudson et al., 2015). Conservation of natural flood protection to keep the benefits of natural inundation has been identified as the key component of the Mekong Delta Plan (MDP, 2013). Hoang et al. (2018)

reviewed flood risk management strategy in the VMD and concluded that the current technology-centric flood management approach is insufficient in the context of rapid socio-ecological changes. As the dike system has been well established and provided essential protection in the VMD, the combination of maintaining current water engineering infrastructure with appropriate Nbs is a suitable solution for the delta.

Efforts to reconnect the delta with the Mekong River have been carried out in the upper stream of the VMD (Tran et al., 2017; Tran et al., 2021). The first effective policy on Nbs in the VMD is the 8 crops in 3 years scheme (3-3-2 cycle) introduced by An Giang province in 2007 (Chapman et al., 2016; Tran et al., 2017). The paddy field under a high dike system is left fallow to fully flood in the 9th crop over three continuous years (or the third crop of the third year over three continuous years). The aim of the 3-3-2 scheme is to reconnect the delta with the Mekong River to increase the soil fertility by sediment brought by floodwater (Tran et al., 2017). However, the 3-3-2 scheme has not succeeded to date because farmers have not seen benefits from letting their fields be flooded (Tran et al., 2017; Tran et al., 2021). There are also some demonstration projects by the International Union for Conservation of Nature (IUCN) sponsoring flood-based crops in low dike areas which are protected against flood peaks arriving around mid-July to mid-August. Within these projects, farmers still gain income while floodwater storage and retention areas can be maintained. Nevertheless, these projects are scattered and carried out at small scales so will not have significant regional impacts unless much broader uptake can be enabled.

Ecosystem services assessment has demonstrated its capacity to assist the implementation of nature-based solutions (Nbs) (Fisher et al., 2014), specifically in deltas (Nicholls et al., 2018). Maps of multiple ES obtained from Nbs are important to improve the understanding of farmers and decision-makers about the spatial heterogeneity of ES. In addition, ES maps can help prioritise areas for Nbs implementation and assist in the establishment of a payment for ecosystem service schemes to maintain Nbs. Among ES assessment tools, ES modelling has been demonstrated as an effective tool for supporting Nbs (Ronchi et al., 2019; UNDRR, 2020; Gupta et al., 2021). In Vietnam, spatially explicit ES models were also introduced in a framework for ecosystem-based adaptation (Ministry of Natural Resources and Environment Vietnam, 2013).

In recent years, a number of studies focusing on ecosystem services have been conducted in the VMD (Berg et al., 2012; Burkhard et al., 2015; Quoc Vo et al., 2015; Loc et al., 2016; Berg et al., 2017; Loc et al., 2017; Quyen et al., 2017; Tekken et al., 2017; Loc et al., 2018a; Loc et al., 2018b). Despite the potential of ES modelling in improving the information on ecosystem health and assisting the implementation of Nbs, there has not been any research that applies this approach in the VMD to date. In terms of floodplain ecosystem services, much of the literature has focussed on flooding and flood dynamics (Hoa et al., 2008; Dung et al., 2011; Kuenzer et al., 2013; Duc Tran et al., 2017; Hawker et al., 2017; Triet et al., 2017; Dang et al., 2018c) and suspended sediment dynamics during the flood season (Hung et al., 2014b, 2014a; Manh et al., 2015; Dang et al., 2018b). No studies have attempted to map multiple ecosystem services as well as their synergies and trade-offs in the whole VMD. These gaps should be addressed by exploring the application of ES models in the VMD and other deltaic regions, and what information ES modelling could provide to accelerate the design of Nbs.

1.2 Aims and objectives

The aim of this research is to improve ecosystem services modelling in data sparse regions and regions where ecosystem services modelling has not been well established. Through facilitating model parameterisation and suggesting model adaptation, the effort needed to produce ES assessments can be reduced. This research focuses on Southeast Asia (SEA) and a tropical deltaic region of SEA, the Vietnamese Mekong Delta. But these results can contribute to the development of ecosystem service modelling. This aim is achieved by fulfilling the following objectives:

Objective 1: To review current literature on ES assessments to gain a better understanding of the diverse assessment methods to date as well as limitations and obstacles for the implementation of these methods in Southeast Asia where ES modelling has not been well established, with a view toward global needs.

Objective 2: To develop guidelines and an associated spatially referenced toolbox to obtain soil hydraulic parameters, which are commonly required in biophysical models but generally not available and difficult to measure directly.

Objective 3: To explore the use of the Land Utilisation & Capability Indicator (LUCI) model (rebranded as Nature Braid, next-gen LUCI) to map multiple ES as well as their synergies and trade-offs in the VMD and provide suggestions on model enhancements to improve ES modelling in the VMD and other tropical and/or deltaic regions; and somewhat account for the economic drivers which need to be considered alongside biophysical valuations for practical implementations of ES maps for nature-based solutions in the upstream VMD.

Objective 4: To give recommendations to improve LUCI and other models to better meet the needs of ES modelling in SEA, deltas, and data spare regions.

1.3 Thesis structure

The thesis is presented in five chapters in which the three main chapters (Chapter 2, Chapter 3, and Chapter 4) have been written as scientific papers and address the first three objectives respectively. Therefore, the words "paper" and "chapter" are sometimes interchangeable within this thesis. As these are stand-alone works in their own right, some repetition, particularly around the overview of the VMD, exists in this chapter (Chapter 1), Chapter 3, and Chapter 4.

Chapter 2 reviews literature on ES assessments with a focus in Southeast Asia. ES assessments have been recognised as an important information source to support decision-making in natural resources and biodiversity but still face many obstacles. From the review results of 118 ES assessment case studies in Southeast Asia, key gaps in current ES assessments were identified and pathways for policy uptake of ES assessments were discussed. This chapter has been published at the time of thesis submission.

From the review of ES assessments, lacking data and expertise-knowledge in ecosystem and environmental processes are one of the main obstacles for policy uptake of ES assessments. Among required data for biophysical models of ES, soil hydraulic properties are an important input. 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. However, information on soil hydraulic properties is generally not available and difficult to measure directly. To address this issue, Chapter 3 presents guidelines and the associated toolbox to support modellers and practitioners in getting soil hydraulic properties in a quick and inexpensive way. That will ultimately reduce time and cost required for an ES assessment research/project. In this chapter, two case studies in the Vietnamese Mekong Delta and New Zealand Hurunui catchment were conducted to demonstrate the use of the guidelines and the toolbox in different geo-climatic and data availability contexts. 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 significantly higher availability of detailed soil information.

Chapter 4 focuses on how to use the Land Utilisation and Capacity Indicator (LUCI) model to map three ES i.e., flood mitigation, agriculture/aquaculture productivity, and carbon sequestration, and their synergies and trade-offs across the Vietnamese Mekong River Delta. Some results of soil hydraulic properties of the VMD (plant available water, drainable water, hydraulic conductivity etc.) obtained from chapter 3 were used for soil parameterisation in this chapter. From the LUCI application in the VMD, model enhancements were drawn out to improve the applicability and utility of LUCI in the VMD as well as other tropical and/or deltaic regions. This chapter also demonstrates the practical implementation of ES maps for nature-based solutions (Nbs) in the upstream VMD. ES maps can assist in prioritising areas for Nbs and inform the design of financing incentives for Nbs.

Chapter 5 discusses and summarises the findings of the research and presents recommendations for further research and model development, including recommendations to adapt and improve LUCI and other models to better meet the needs of ES modelling in SEA, deltas and data sparse regions, the objective 4 of this thesis.

2 Review of ecosystem service assessments: pathways for policy integration in Southeast Asia[1]

2.1 Introduction

Ecosystem service (ES) assessments provide systematic information to mainstream ES into decision-making (Erik et al., 2009; Seppelt et al., 2011; Maes et al., 2012; Martínez-Harms et al., 2012; Crossman et al., 2013; Alkemade et al., 2014; IPBES, 2016). They allow policy-makers to contrast the ES available for different groups of people and to compare management options (Bagstad et al., 2013a; Hanna et al., 2018). The growing number of ES assessments globally demonstrates their importance. Over the last two decades, numerous reviews have synthesised ES assessments by highlighting global distributions of ES economic valuation (Costanza et al., 1997; de Groot et al., 2010; de Groot et al., 2012; Schägner et al., 2013) and ES mapping and modelling (Erik et al., 2009; Egoh et al., 2012; Martínez-Harms et al., 2012; Burkhard et al., 2013; Schägner et al., 2013; Malinga et al., 2015; Posner et al., 2016). Some reviews have focused on ES assessments at continental scales, for example, Europe (Maes et al., 2012) and Asia (Shoyama et al., 2017).

Southeast Asia (SEA) is a region of rich biodiversity. SEA includes four of the thirty-six global biodiversity hotspots according to the Conservation International (Myers et al., 2000; Turner et al., 2016a). The region comprises eleven countries in which five nations (Cambodia, Laos, Myanmar, Thailand, and Vietnam) are on the mainland and the remaining six (Brunei, Timor Leste, Indonesia, Malaysia, Philippines, and Singapore) are spread across thousands of islands (Samek et al., 2012). Agriculture, fisheries, and forestry play important roles in the economies of many SEA countries (ADB, 2009; Carrasco et al., 2016). Nearly 15% of the world's tropical forests are in SEA (Estoque et al., 2019) and SEA was one of the world's biggest providers of forest products in 2004 (ADB, 2009). The region also supplied an estimated 21.6% of the global fishery production (42.2 million metric tonnes) in 2014 (Lieng et al., 2018) and accounted for ~7.7% and 15% of the agricultural production in the world and Asia respectively in 2016 (IFPRI, 2019). Other important economic activities in the region include offshore oil and gas production and tourism (IPBES, 2018). With many of these economic activities depending directly on nature, people in the region rely heavily on ES for their wellbeing. Rapid population growth in recent decades has escalated conflicts between natural resource conservation and economic development. From 1990 to 2015, SEA has undergone dramatic shifts in land use with a 12.9% reduction in forest cover, largely due to an increase in timber extraction, large-scale bio-fuel plantations and the expansion of intensive agriculture and shrimp farms (IPBES, 2018). SEA also has experienced high deforestation rates with an average net

[1] This chapter has been published as: Dang et al. (2021a)

loss of 1.6 million ha yr^{-1} (0.6% yr^{-1}) (Estoque et al., 2019). This is problematic because SEA also has exceptional levels of species richness and endemism (ICIMOD, 2007; Carrasco et al., 2016). Estimates suggest that habitat loss in SEA is among the highest and most severe in terms of biodiversity loss (Estoque et al., 2019). Due to these massive changes, ecosystems are projected to degrade further over this century in SEA (Estoque et al., 2019).

ES assessments increasingly aspire to inform policies in SEA (Carrasco et al., 2016). For instance, such assessments provided evidence for weighing the costs and benefits of conservation alternatives and economic growth in Indonesia (van Beukering, 2009) and for land use and spatial planning in Cambodia (Watkins et al., 2016) and Myanmar (Mandle et al., 2017). As another example of ES informing policies in SEA, an index based on ES economic values was introduced in Vietnam to help decision-makers improve the current land pricing method to better capture actual land profitability which includes ES values (Loc et al., 2017). In a developing region like SEA, ES provisions are widely assumed to contribute to poverty alleviation - the first Sustainable Development Goal (Suich et al., 2015). Therefore, integrating ES assessments, especially assessments that highlight economic values of ES for impoverished people, into socio-economic policy is important to support poverty reduction efforts (Suwarno et al., 2018). Another example of how ES assessments can inform legislation is by providing information for climate policy. With long coastlines and reliance on agriculture and fisheries, SEA countries are highly vulnerable to climate change (ADB, 2009). ES contribute significantly to climate change mitigation and adaptation (carbon storage capacity, soil and water retention capacity of forests, coastal protection by mangroves, etc.) (Locatelli, 2016). Hence, ES should be integrated into climate change mitigation and disaster risk reduction portfolios, particularly in developing countries (Munang et al., 2013; Locatelli, 2016). Despite their potential to inform policy, the breadth and characteristics of ES assessments available for informing policy decisions in SEA have not been detailed in previous reviews in Asia (Shoyama et al., 2017) nor in reviews at the global scale (Seppelt et al., 2011; Malinga et al., 2015). To date, there are no comprehensive reviews of ES assessments in SEA or analysis of how ES assessments communicate with SEA policy, which limits our understanding of what evidence is required by policymakers. By identifying information gaps, ES assessments can be matched to policy and decision-making needs, illuminating pathways for better uptake.

Recognising gaps in the spatial and temporal scales of ES assessments may show pathways for ES assessments to inform policy and decision-making in SEA. With policymakers increasingly making evidence-based decisions, ES information is needed at multiple spatial (extent and resolution) and temporal scales (Turner et al., 2016b). Assessments with large spatial extents are important for sub-provincial, provincial, and national natural resources management. However, a limitation of large-scale analysis is that landscape continuity and heterogeneity are unresolved, and thus, these large-scale analyses may miss important ES from small ecosystems, such as small wetlands (Fischer et al., 2008; Malinga et al., 2015). Detailed decisions at local levels or site-scales (e.g., farm, small wetland, sub-catchment) may require ES assessments at finer resolutions (Egoh et al., 2012; Bagstad et al., 2013c; Malinga et al., 2015). Concomitantly, decisions made at one spatial or temporal scale may affect natural resources at other scales (Pelosi et al., 2010). ES assessments also should be adaptable across different ecological (e.g., watershed) and administrative (e.g. provincial) scales, as these scales may not align. Moreover, appropriate temporal resolutions may vary for different contexts. Historical ES assessments inform trends of ES supply and demand while future scenarios compare different opportunities (Kandziora et al., 2013; Rau et al., 2020). Therefore, multi-spatiotemporal scale ES assessments are essential to enable better multiscale management practices (Malinga et al., 2015). However, the operational and methodological pathways for multiscale ES assessments are still lacking (Brown et al., 2015).

In addition to gaps in assessments at different spatial and temporal scales, previous reviews of ES assessments across Asia and at the global extent have found gaps in data availability, which may have multiple consequences for ES assessments. One of the major data gaps is the limited availability of spatially-explicit data for ES assessment and modelling (de Groot et al., 2010; Shoyama et al., 2017). These gaps mean spatial models may be poorly parameterised leading to inaccurate maps of ES (de Groot et al., 2010; Shoyama et al., 2017). Limited data availability may also lead to problematic oversimplification of ES assessments by using proxy methods (via land use/land cover or vegetation indices), which means the information they provide may not be accurate enough for decision-making (Eigenbrod et al., 2010). Furthermore, limited data availability means many ES assessments are not validated. This lack of validation can lead to distrust in assessment results, limiting the uptake of ES assessments results by both academia and decision-makers (Englund et al., 2017). Data gaps may also be responsible for the lack of ES assessments focusing on cultural and supporting services (Shoyama et al., 2017). Quantification methods for intangible cultural or supporting services are less straightforward than methods for provisioning services or regulating services (Wolff et al., 2015), in part, because cultural services assessment normally requires primary data that is often not readily available and the collection of such information is often resource-intensive (Maes et al., 2012).

To date, ES assessments poorly capture interactions among different ES (e.g., trade-offs and synergies) as well as interactions at the interface of ecosystem processes and humans (Seppelt et al., 2011; Stephens et al., 2015; Englund et al., 2017). For example, gaps in ES assessments include a lack of stakeholder involvement, which limits our understanding of ES demand. In addition to improving uptake of management plans, involving stakeholders would enhance our understanding of how people interact with services (Seppelt et al., 2011; Shoyama et al., 2017; Hanna et al., 2018). Furthermore, many ES assessments lack trade-off analysis between ES, which limits their ability to inform our understanding of different future scenarios (Seppelt et al., 2011). Exploring how these common gaps at process interfaces affect ES assessments in SEA may uncover suitable advancement targets.

We reviewed published quantitative ES assessments in the SEA region. These publications used diverse methods including economic valuation, mapping, and other quantitative assessments. We also reviewed publications that assess stakeholder perceptions with quantitative and semi-quantitative outputs, for example, economic values, maps, and scores table, to ascertain the level of stakeholder involvement in ES assessments and decision-making processes in SEA. Therefore, in our paper, the term “ES assessments” includes both these suites of methods. We compared ES assessments in SEA to understand the following characteristics: (1) geographical distribution, (2) ecosystem and ES types studied, (3) spatial scale and resolution, (4) temporal scale and resolution, (5) data sources, (6) linkages among different ES assessment approaches, and (7) linkages between ES assessments with policy and decision-making. The first six characteristics provide the big picture of the current state of ES assessments in SEA. These characteristics demonstrate the trends and gaps in current ES assessments. Finally, linkages between ES assessments and policy and decision-making address how likely different ES assessments were implemented in policy and decision-making in SEA.

2.2 Methodology

2.2.1 Search strategy and publications selection process

Our search strategy included both online database searches and searches in reference lists of key review publications. First, we searched on ISI Web of Science with the following keywords: SEA countries AND “ecosystem service*” in the title, keyword, and abstract, and published prior to September 2019. The search strategy is as follows: *TS = (Ecosystem service* AND Vietnam*) OR TS = (Ecosystem service* AND Laos*) OR TS = (Ecosystem service* AND Cambodia*) OR TS = (Ecosystem service* AND Thailand*) OR TS = (Ecosystem service* AND Myanmar*) OR TS = (Ecosystem service* AND Malaysia*) OR TS = (Ecosystem service* AND Singapore*) OR TS = (Ecosystem service* AND Brunei*) OR TS = (Ecosystem service* AND Indonesia*) OR TS = (Ecosystem service* AND Philippines*) OR TS = (Ecosystem service* AND Timor Leste*).* Figure 2 summarises the publications selection and review process which can be used by readers to quickly visualise the process. We obtained 823 publications including journal articles, book chapters, conference proceedings, reviews, and editorial material. The search results were refined to journal articles, book chapters, and conference proceedings, which reduced the total publications to 795 (~250 publications in Indonesia, ~130 each in Vietnam and Thailand; ~100 each in Malaysia and the Philippines, and the remaining 100 publications were attributed to Cambodia, Laos, Myanmar, and Singapore). Of those, we screened the publication's abstract to select publications focusing on ES assessments with quantitative and semi-quantitative results and outputs in SEA. Where the abstract did not clearly describe methodology, we screened the publication's content. We eliminated publications that consisted of conceptual or theoretical analyses only and publications that assessed the effectiveness of policy programmes without conducting a formal ES assessment (e.g., payment for ES schemes, conservation programmes and ES governance options). We also excluded publications that were conducted at the global scale and those that mentioned SEA countries without a clear case study in the region. Publications which quantified benefits but that did not explicitly self-identify as having quantified an "ecosystem service" were not included, as we focused on the body of literature that self-identifies as ES research. After this screening, only 129 publications remained. A second search with the same search parameters in Scopus resulted in 795 publications and a third search in Science Direct resulted in 285 publications. The source title lists, and publication title lists of both were compared with the Web of Science search. All publications had already been identified through the Web of Science search.

To avoid missing important publications and grey literature, we also reviewed the reference lists of *The Economics of Ecosystems and Biodiversity for Southeast Asia (ASEAN TEEB)* (TEEB, 2012) and the following ES reviews: Englund et al. (2017), Shoyama et al. (2017) (with the online platform IPBES Catalogue of Assessments on Biodiversity and Ecosystem Services: http://catalog.ipbes.net/, accessed on 10/12/2017), Turner et al. (2016b), Andrew et al. (2015), Brown and Fagerholm (2015), de Araujo Barbosa et al. (2015), Bunse et al. (2015), Malinga et al. (2015), Suich et al. (2015), Wolff et al. (2015), Crossman et al. (2013), Schägner et al. (2013), Barbier (2012), Egoh et al. (2012), Martínez-Harms et al. (2012), Seppelt et al. (2011) and de Groot et al. (2010). We selected reviews through Google Scholar searches that specifically overviewed ES assessment approaches, e.g., economic valuation, assessments of human perception, mapping, or modelling. By searching through the reference list of those reviews, we identified important grey literature. Much of the ES work in SEA is carried out by NGOs, governmental organisations and/or consultancies which traditionally do not publish in academic outlets. This "grey literature" provides information and evidence around data, studies and policy in the region that is not captured through traditional academic sources. Cross-checking the reference lists of the existing reviews helped corroborate our methods, providing an additional procedure to identify important quantitative ES assessments. From the reference lists of the above reviews, 113 publications on ES in SEA were identified. The result is presented in Appendix A1.

Of the total 242 publications (129 from online database search plus 113 from ES reviews), we eliminated 78 duplicates. The remaining 164 were read thoroughly. 56 of those remaining were excluded from detailed analysis due to their lack of clear ES assessment methodology and quantitative results. The final number of publications selected for detailed review was 108 of which 6 publications included multiple case studies. Our analysis therefore includes a total of 118 case studies. Our full list of publications and their code is in Appendix A2. Review results were recorded and organised in an Excel database. The database's structure is shown in Appendix A3. The aim of Appendix A3 is to present the structure of the database which can support other authors who are planning to do a similar review of ES assessment.

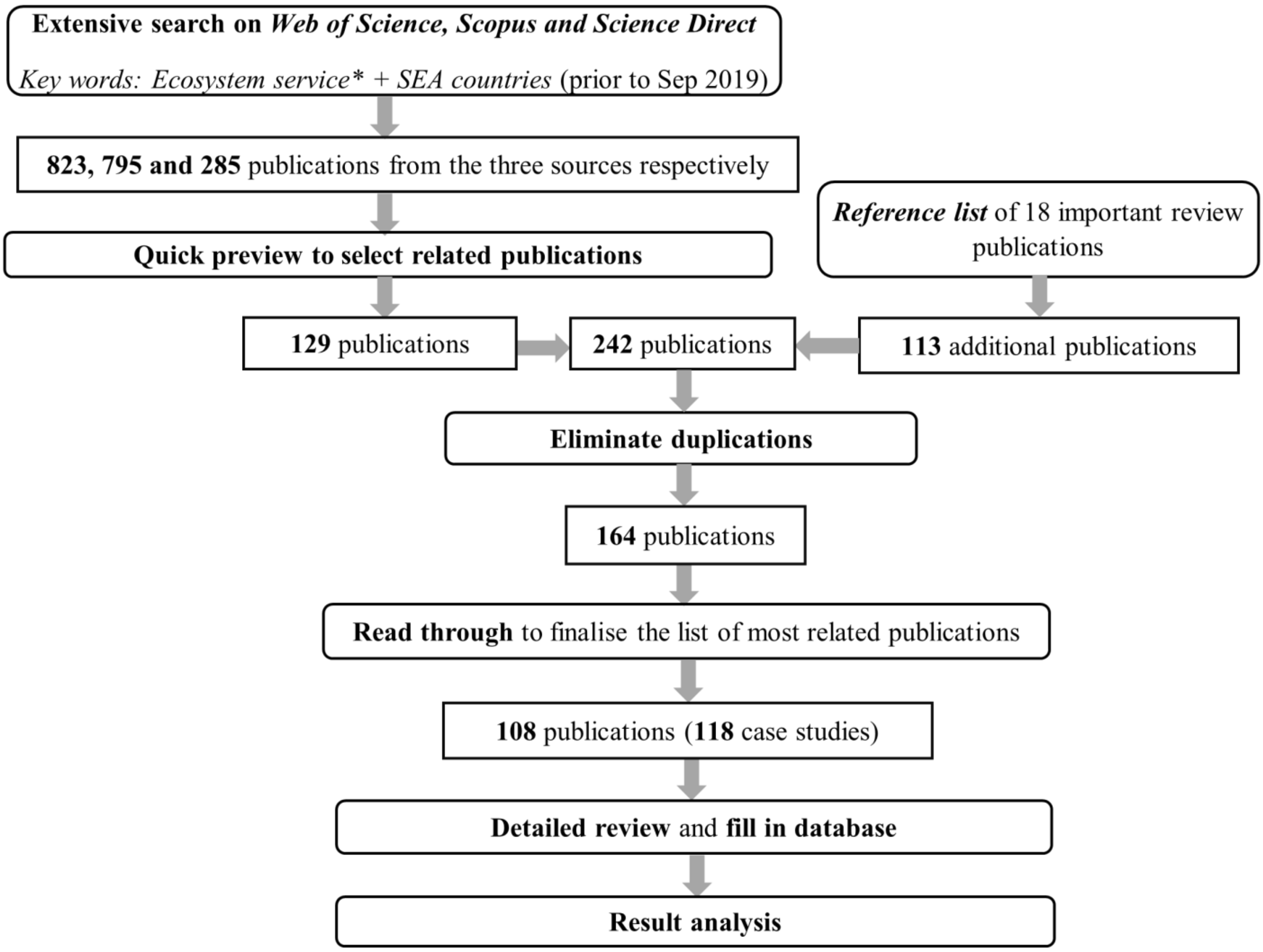


Figure 2 Publication selection and review process

2.2.2 Review framework for ecosystem service and ecosystem categories

This section defines the ES and ecosystem categories used for our review.

2.2.2.1 Ecosystem types

Ecosystems (biomes) were classified based on the ecosystem classification of The Economics of Ecosystems and Biodiversity (TEEB) (TEEB, 2010a) with minor modifications: (1) combining *marine* and *coastal* ecosystems and (2) separating TEEB's *cultivated ecosystem* into *agriculture* and *agro-forest* to better represent cultivation systems in SEA. Therefore, the ecosystems classification used in this review include: (1) *agriculture* (rice, vegetation, and other crops etc.), (2) *agro-forest* (oil palm, rubber etc.), (3) *forest*, (4) *inland water* (lakes & rivers), (5) *marine/coastal/island* (coral reefs, seagrass, shores), (6) *urban*, (7) *wetland* (coastal wetland: mangrove & marsh and inland wetland: peatland & swamp), (8) *mixed* (research/publication comprises more than one ecosystem).

2.2.2.2 Ecosystem services

Publications follow different ES classification systems, therefore an important step is to select an appropriate and consistent ES classification for our review. Re-categorising ES into the same ES classification allows for easier comparison and analysis of relationships between ES and other parameters. In the literature, several ES classification systems have been used, including those used in Costanza et al. (1997), the Millennium Ecosystem Assessment (MEA) (MEA, 2005a), Burkhard et al. (2009), TEEB (TEEB, 2010a) and the European Common International Classification of Ecosystem Services (CICES) (https://cices.eu/, accessed on 16/11/2019). A comparison of different ES classification systems can be found in Table 3 of Englund et al. (2017) and Section 2.4. in Burkhard et al. (2017).

To select a suitable ES classification system, we screened the classifications used in previous review papers and our database of SEA publications. Of the review papers, only 50% clearly indicated which ES classification system was used. The screening showed that TEEB (2010a) was widely used in previous reviews including de Groot et al. (2010) and Egoh et al. (2012). Malinga et al. (2015) used TEEB's classification with some modifications. *The blueprint for mapping and modelling ecosystem services* by Crossman et al. (2013) also used classification systems of TEEB (2010a). Most of the collected SEA publications in our review did not clearly mention which ES classification system was used. Instead, they directly used indicators such as carbon stock/storage, water yield or habitat quality, etc. for their assessment. There were some publications that mentioned the use of the *MEA classification* i.e. Mathe et al. (2015), Sumarga et al. (2015), Estoque et al. (2012), Watkins et al. (2016), Tekken et al. (2017), Thiagarajah et al. (2015); *Burkhard et al. (2009)'s classification* i.e. Kaiser et al. (2013) and Burkhard et al. (2015); *CICES classification* i.e. Feurer et al. (2019); and *TEEB classification* i.e. Sumarga et al. (2015) and TEEB (2012).

After reviewing ES classifications used in previous review papers and publications in SEA, we decided to use the TEEB classification for two main reasons: (1) TEEB was widely used in previous reviews, so our review is comparable with their work, and (2) SEA is an important hotspot for global biodiversity, and TEEB includes consideration of the importance of "habitat services" (habitat services were assessed in about 30% of our reviewed publications). Table 2 describes how we categorised ES in our review. The chosen categories were based on a combination of TEEB (2010a) and Malinga et al. (2015) classifications. ES identified in our reviewed studies were each placed in one of these categories. We also noted that there are several ES that can fall under different ES categories, therefore ES mentioned in reviewed publications were noted carefully for further study/analysis using different categories.

Although there is still an ongoing debate on whether biodiversity is an ES (Malinga et al., 2015), we included biodiversity in the classification because biodiversity has been prominent in ES assessments in SEA.

Table 2 ES classification based on TEEB

Category	**Service**	**Service mentioned in publications**
Provisioning Service	Food	food, food production, agriproducts, rice yield, rice production, vegetable, fruit, agricultural products, crops, cash crops, palm sugar, nutmeg, candle nut, cinnamon, honey, vanilla, bird nest, cocoa, wildlife products, wild food (meat, plant), fish, fishery product, aquaculture products, shrimp, crab, seafood, livestock, fodder
	Raw materials	raw material, timber, rattan, forest products, forest materials, firewood, construction material, wood, fibres, palm oil, energy, fertiliser, fuel, oil
	Water	water, water yield, ground water recharge, water supply, irrigation water, fresh water
	Genetic resources	genetic resource, seed
	Medicine	medicine, aromatic oil, medical plants, medical herb
	Ornamental resources	ornamental resources, ornamental plants, artisanal mining, handicraft materials, pet animal
Regulating Service	Erosion prevention	erosion prevention, erosion control, landslide control, sediment retention
	Climate regulation	climate regulation, carbon stock, carbon sequestration, carbon storage, carbon emission reduction, above ground biomass
	Biological control	biological control, disease prevention, illness prevention, natural enemy of crop pests and diseases, disease regulation
	Pollination	pollination, pollinator, seed disperser
	Air quality regulation	air regulation, shade, maintenance of clean air and wind break, gas regulation, fresh air, air purification
	Maintenance of soil fertility	soil formation, soil conservation, nutrient cycling, nutrient regulation, nutrient retention
	Regulation of water flows	water regulation, drought mitigation, drought prevention, hydrology, water service, reservoir function, flow regulation, control of sediment in stream, stream flow distribution, saline intrusion prevention

Category	Service	Service mentioned in publications
	Regulation of extreme events	flood control, flood prevention, flood risk reduction, coastal protection, shore protection disturbance regulation, fire prevention, protection from disasters, storm protection, wave protection, mitigation of water conflict
	Waste treatment	waste treatment, pollution prevention, depollution, water quality, water purification, environmental protection, wastewater treatment
Cultural Service	Aesthetic information	aesthetic information, landscape beauty, scenery, aesthetic value
	Recreation and tourism	recreation, tourism, ecotourism, hunting
	Inspiration for culture, art, design	inspiration, culture, rural lifestyle, myth and legend, festival, social relation
	Spiritual experience	spiritual and religious value, cultural belief, ritual, magic aspects, places to perform religious rites and celebrations
	Information for cognitive development	information, education, research, biodiversity for research, scientific value
Supporting/Habitat Service	Maintenance of life cycles	habitat quality, nursery service, refuge, nursery habitat, habitat connectivity
	Maintenance of genetic diversity	genetic maintenance, wildlife conservation, biodiversity, biodiversity conservation, conservation value

2.2.2.3 Ecosystem service assessment approach

A range of methods are available for assessing ES, from mapping and modelling the supply and demand of ES to evaluate their economic and non-economic importance (Harrison et al., 2018). In this paper, assessment approaches were divided into four main categories:

(1) *Economic valuation* included contingent valuation, travel cost, market price, choice experiment, replacement cost, damage cost, benefit transfer, net present value, resource rent, and other economic valuation methods. Definitions of each approach can be found in Burkhard et al. (2017).

(2) *Mapping* included five categories: ES models (e.g., InVEST); other modelling approaches (e.g., hydrological models, species distribution models, agent-based modelling); statistical models (e.g., regression models); proxy mapping (e.g., matrix-based approaches or look-up tables to present ES based on land use/land cover maps); and other mapping approaches (e.g., deliberative mapping, spatial interpolation). Our classification was developed based on *the categories used for selecting methods for ES assessment* by Harrison et al. (2018). Originally, these categories included ES modelling, biophysical modelling, agent-based modelling, integrated modelling, simple matrix mapping, advanced matrix mapping, simple GIS mapping, and deliberative mapping. However, we grouped biophysical modelling, agent-based modelling, and integrated modelling into ‘other modelling approaches’. Furthermore, we grouped simple matrix mapping, advanced matrix mapping, and simple GIS mapping into the ‘proxy mapping’ group. Deliberative mapping was grouped into ‘other mapping approaches’.

(3) Assessments of human perception included questionnaire surveys, interviews, and focus groups. To be included in this review, studies must have delivered quantitative results such as maps, economic values, or semi-quantitative results as scores or grading scales.

(4) Other quantitative assessments included methods based on biophysical parameters and involve field measurements, monitoring, and modelling but do not generate a map or valuation of ES. From our database, the following methods are in this category: water balance models, dynamic coupled vegetation and global hydrology models, simple score tables, Bayesian Belief Networks, and value quantification from interviews or references.

2.2.2.4 Data use

For publications clearly mentioning data sources, information about data sources were collected and divided into primary and secondary data. Primary data includes questionnaires, interviews, and focus groups. Secondary data includes land use/land cover (LULC) maps, DEMs, soil maps, topographic maps, hydrological maps, road maps, evapotranspiration data, precipitation data, temperature, population density, soil properties, statistical data, and results from previous studies.

2.2.2.5 Spatial scale and resolution

Geographic scale of case studies (total area of study site) was divided into five main categories: Local/Patch/Village scale (<100 km^2); District/Sub-provincial scale (100-10^3 km^2); Provincial/State or Sub-national scale (10^3-10^5 km^2); National scale (10^5-10^6 km^2) and Multi-national scale (>10^6 km^2). For ES mapping resolution, we categorised mapping resolution into five groups: <10m, 10-50m, 50-200m, 200-1000m and >1000m. These same categories of spatial scale and resolution were used in the review of Schägner et al. (2013).

2.2.2.6 Time scale

Publications were divided into four time scales: those considering historical change (change over historical time), a single point in time, short- and medium-term future scenarios (scenario <50 years) and long-term futures (scenario >50 years).

2.2.2.7 Linkage with policies

To identify the linkage between ES assessment and policies in SEA, we reviewed the publication objectives as well as their discussions and conclusions. The policies/strategies that each ES assessment aimed to support was recorded. From our database, the main policies recorded were land use policy/planning, waste management, conservation strategy, risk management, climate change mitigation, and sustainable management.

2.3 Results

2.3.1 General characteristics

2.3.1.1 Geographic distribution

There were 108 publications (with 118 case studies) selected for detailed review and analysis. Our review revealed a bias in geographic distribution, with a larger number of studies in Indonesia (36) and Vietnam (25), followed by Thailand (14), Malaysia (13), Philippines (13) and few studies in Laos (4), Myanmar (4), Cambodia (3) and Singapore (2) (Figure 3a). There were three studies at the SEA scale and one at the Lower Mekong scale. No ES assessment publications were found for Brunei and Timor-Leste. The bias in geographic distribution was also seen in the search results presented in methodology section.

2.3.1.2 Ecosystems

Most case studies covered a single ecosystem (93 cases), while 20 cases dealt with multiple ecosystems. *Forest*, *wetland*, *agriculture,* and *marine/coastal/island* ecosystems have been the most extensively studied (Figure 3b). *Inland water* ecosystems, such as rivers and lakes have received relatively little attention although in several important cases (e.g., the Lower Mekong case study), they are recognised as facing severe threats to their ecological functioning.

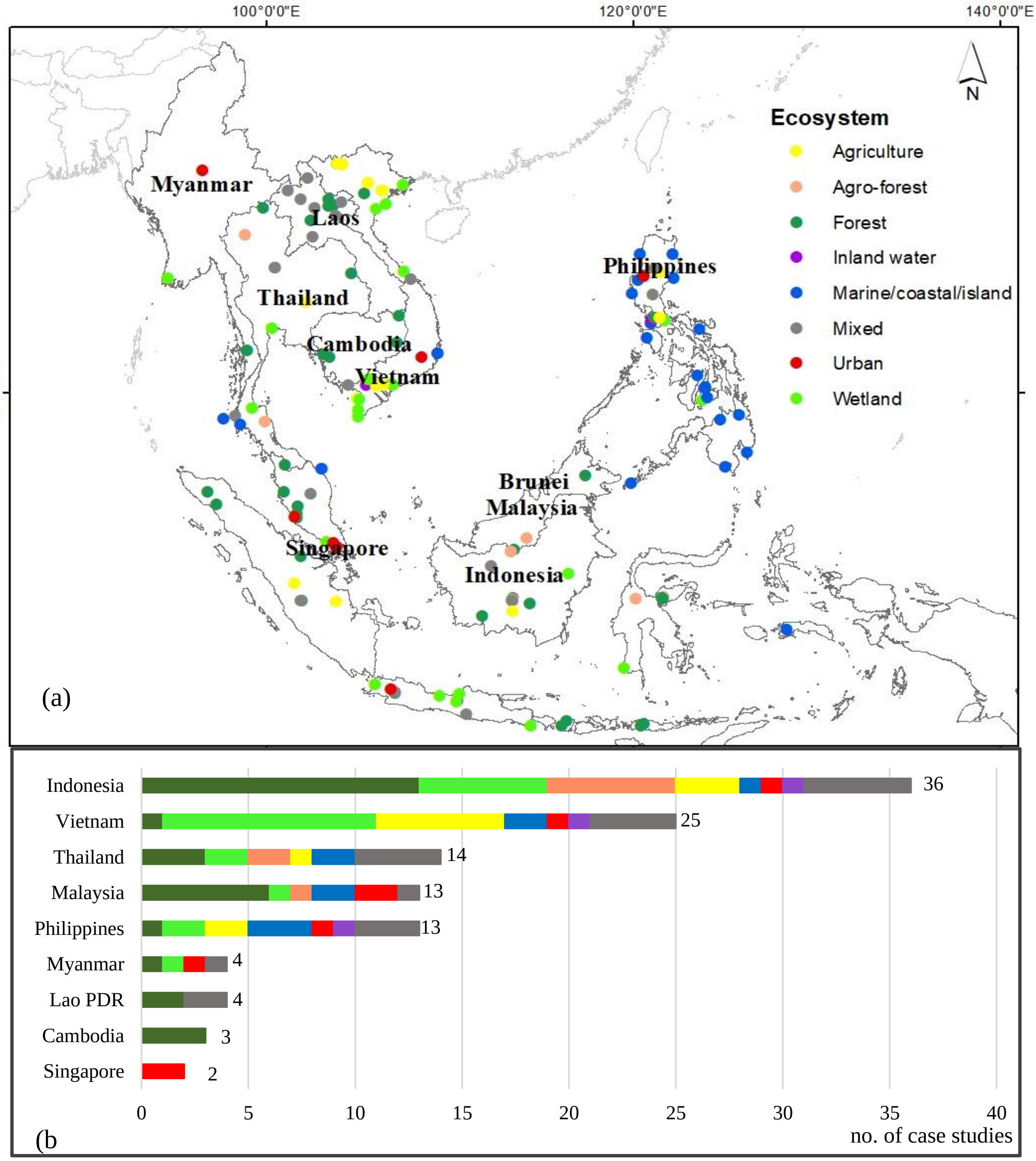


Figure 3 (a) Location of case studies and ecosystem types, (b) Case studies of each countries and ecosystem types *(Colour reflects ES types and location of study was recorded from study area description)*

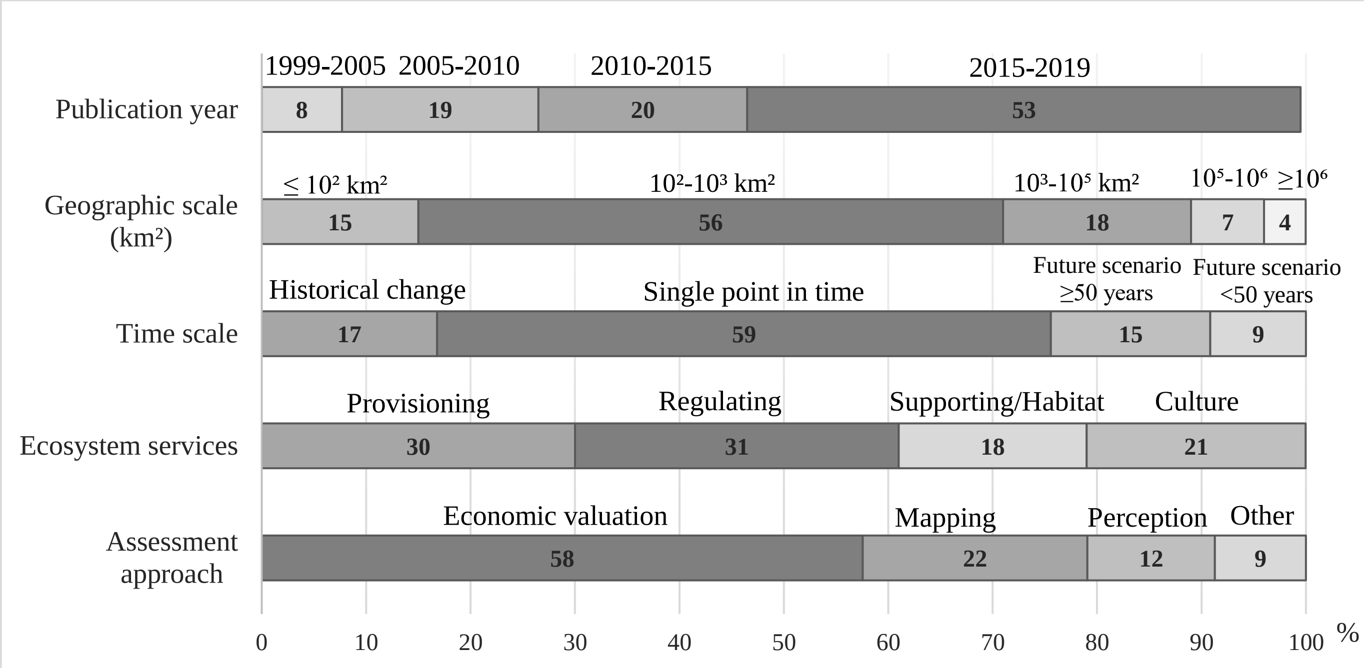


Figure 4 Overview of publication year, geographic scale, time scale, ES categories and assessment approach

2.3.1.3 Publication year

More than half of our reviewed publications (53%) were released in the period of 2015-2019 (Figure 4). The first publication on ES assessment in SEA was founded in 1999, with a rapidly increasing number of publications since 2005 following the Millennium Ecosystem Assessment (Figure 5). Results from 2019 are excluded from Figure 5 as the search was limited to publications prior to September 2019.

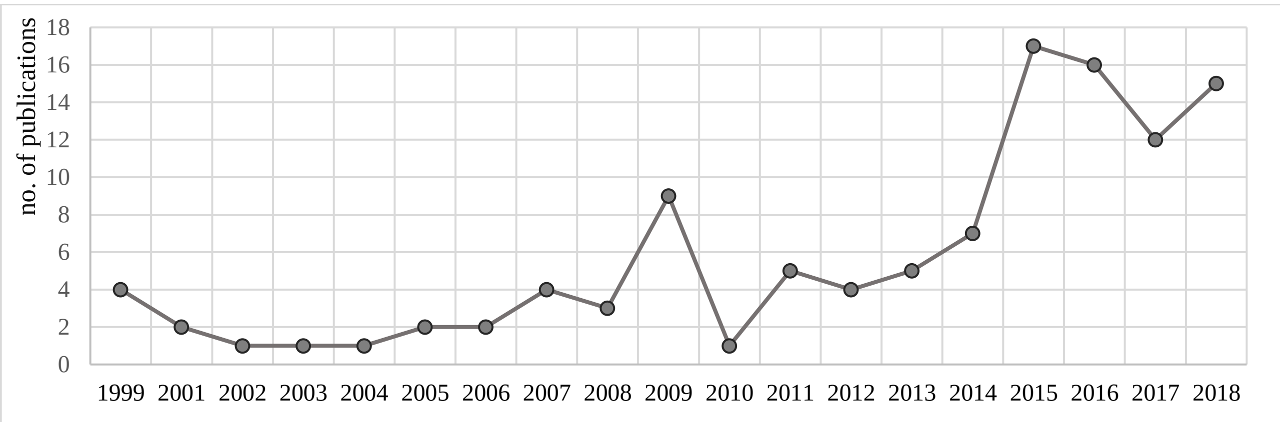


Figure 5 Number of publications through time

2.3.1.4 Geographic scale

Most of studies were done at large scales, 56% at district or sub-provincial scales (10^2 -10^3 km²) and 18% at provincial/state or sub-national scales (10^3-10^5 km²) (Figure 4). The case study with the smallest extent (2.8 km²) was an assessment of human perception in a village in Indonesia

(Muhamad et al., 2014). The largest case study was an economic valuation of mangroves and coral reefs for the whole of SEA (TEEB, 2012). All the case studies reviewed were at a single scale, and no research was conducted at multiple scales.

2.3.1.5 Time scale

More than half of the publications reviewed assessed ES at a single point in time (59%), while 17% considered historical change over time (Figure 4). Of the publications that predicted future outcomes, most examined the short-term to medium future (<50 years), 15% of total publications, while 9% analysed the long-term future (>50 years).

2.3.1.6 Ecosystem services

In general, for ES categories, regulating and provisioning services received the greatest attention, accounting for 31% and 30% of total number of publications, respectively (Figure 4). Twenty-one percent of publications assessed cultural services. Supporting/habitat services received the least attention with 18% of studies assessing them. The number of case studies per sub-ecosystem service category for each country are presented in Figure 6. As for specific ES, the most frequently assessed are food and raw materials (provisioning services), climate regulation (regulating services) and recreation and tourism services (cultural services).

Among provisioning services, food received the greatest attention in Indonesia, Vietnam, Philippines while water was the most assessed in Thailand and raw materials were the most assessed in Malaysia. Other countries with significantly fewer existing studies showed the same pattern with similar concerns surrounding food and raw material including Laos, Cambodia, and Myanmar. Climate regulation received high levels of concern in Indonesia, Vietnam, the Philippines, and Thailand. Myanmar focused on regulation of water flows. Studies in Singapore only focused on cultural services.

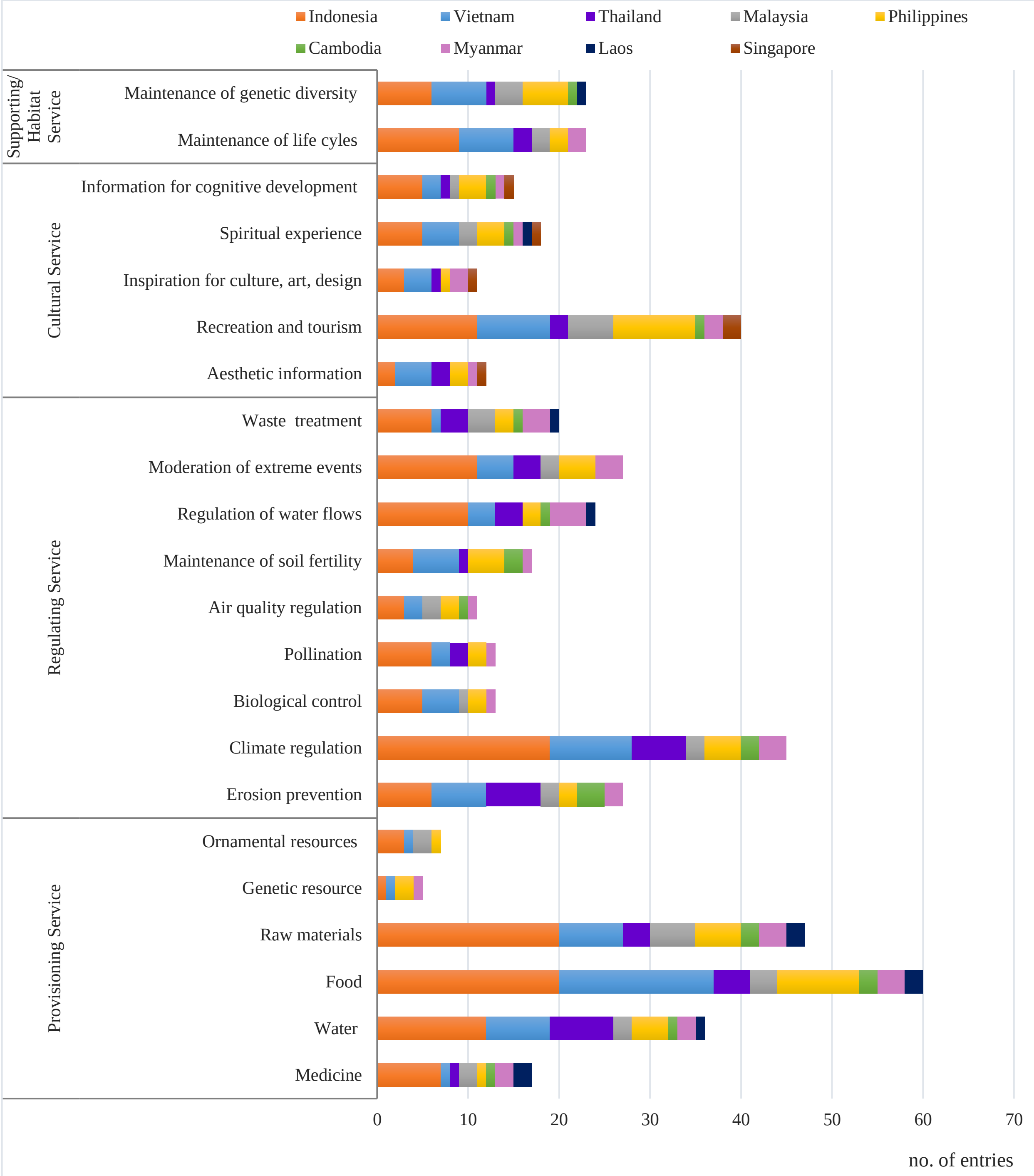


Figure 6 Number of case studies of each country per sub-ecosystem service categories

2.3.2 Ecosystem service assessment methodology

Before 2009, most studies focused on monetary valuation of ES, but trends in ES assessments in SEA have changed since 2009 with an increasing number of studies employing other assessment approaches (ES mapping, modelling, assessments of human perception and other quantitative assessments) and integrated approaches (economic valuation & mapping, assessments of human perception & mapping, economic valuation & other quantitative assessments) (Figure 7).

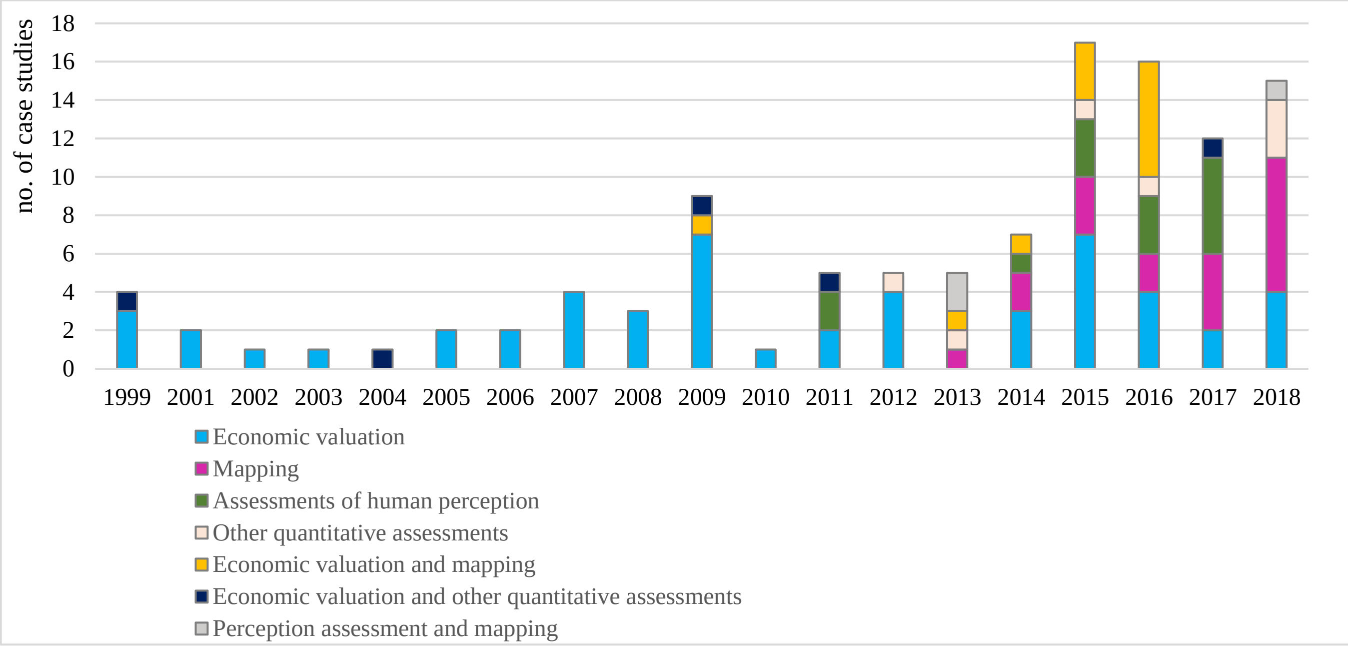


Figure 7 ES assessment (main categories) developments through time

Contingent valuation, market price and benefit transfer are the economic valuation methods with the highest usage frequency in SEA research (Figure 8). Contingent valuation is usually used for cultural services (recreation and tourism) and supporting/habitat services (Figure 9). Contingent valuations use surveys or questionnaires to directly question individuals on their willingness-to-pay for a good or service. The prominent use of contingent valuation is presumably due to its perceived flexibility and ability to estimate total value, including none-use or passive use value (Carson et al., 2001). Market price is mostly used for money valuation of provisioning services and benefit transfer is mostly used for regulating services (climate regulation) (Figure 9). Market price of provisioning services, e.g., food, fish, timber, can be obtained easily at a low cost. Hence this method is useful for estimating the economic value of provisioning services, especially where data are scarce (McElwee, 2012). Market price provides rapid comparisons of the cost of allocating resources for competing uses (de Groot et al., 2012). Conducting empirical economic valuation studies is always time consuming and costly. Benefit transfer is an alternative by transposing value estimates from one location to another. The main advantage of benefit transfer is that it provides a relatively quick assessment of the economic value of ES (Costanza et al., 1997).

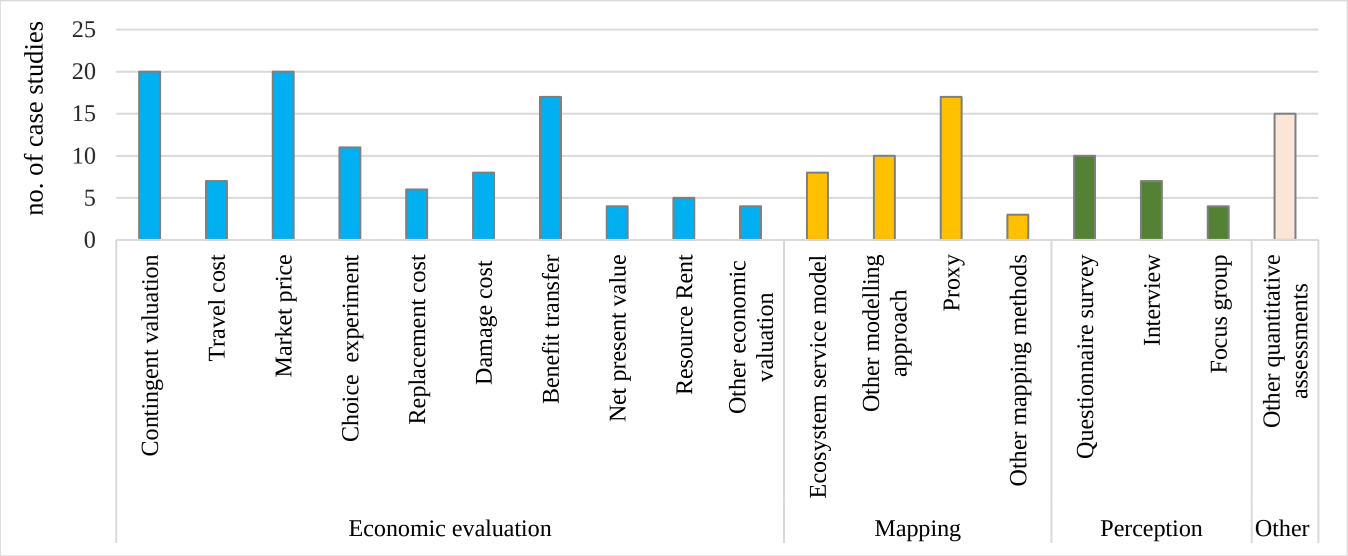


Figure 8 Distribution of ES assessment sub-categories

There have been an increasing number of ES mapping and modelling studies in SEA. The mapping method most often used in SEA is proxy mapping (based on LULC cover maps) (Figure 8). This method has been applied to almost every category of ES in SEA (Figure 9). Recently, ES modelling with spatially comprehensive and self-identified ES assessment approaches (using the Integrated Valuation of Ecosystem Services and Trade-offs (InVEST) model) have received more attention with three case studies in Thailand (Arunyawat et al., 2016, 2018; Thompson et al., 2019), one in Indonesia (Bhagabati et al., 2014), one in Vietnam (Dang et al., 2018a), one in Cambodia (Watkins et al., 2016), one in Myanmar (Estoque et al., 2018) and one in Lower Mekong Region (Trisurat et al., 2018).

In some of current SEA's ES assessments, trade-offs were analysed among different land use or development scenarios (Ron et al., 1999; Steffan-Dewenter et al., 2007; Hall et al., 2012; McDonough et al., 2014; Zavalloni et al., 2014; Sumarga et al., 2015; Neang et al., 2019). Synergies and trade-offs among ES were mainly identified using Pearson's correlation coefficient (Langerwisch et al., 2018), Spearman's Correlation Analysis (Loc et al., 2018a) or scoring methods (Feurer et al., 2019). We did not find any spatially-explicit ES modelling of synergies and trade-offs among ES in SEA.

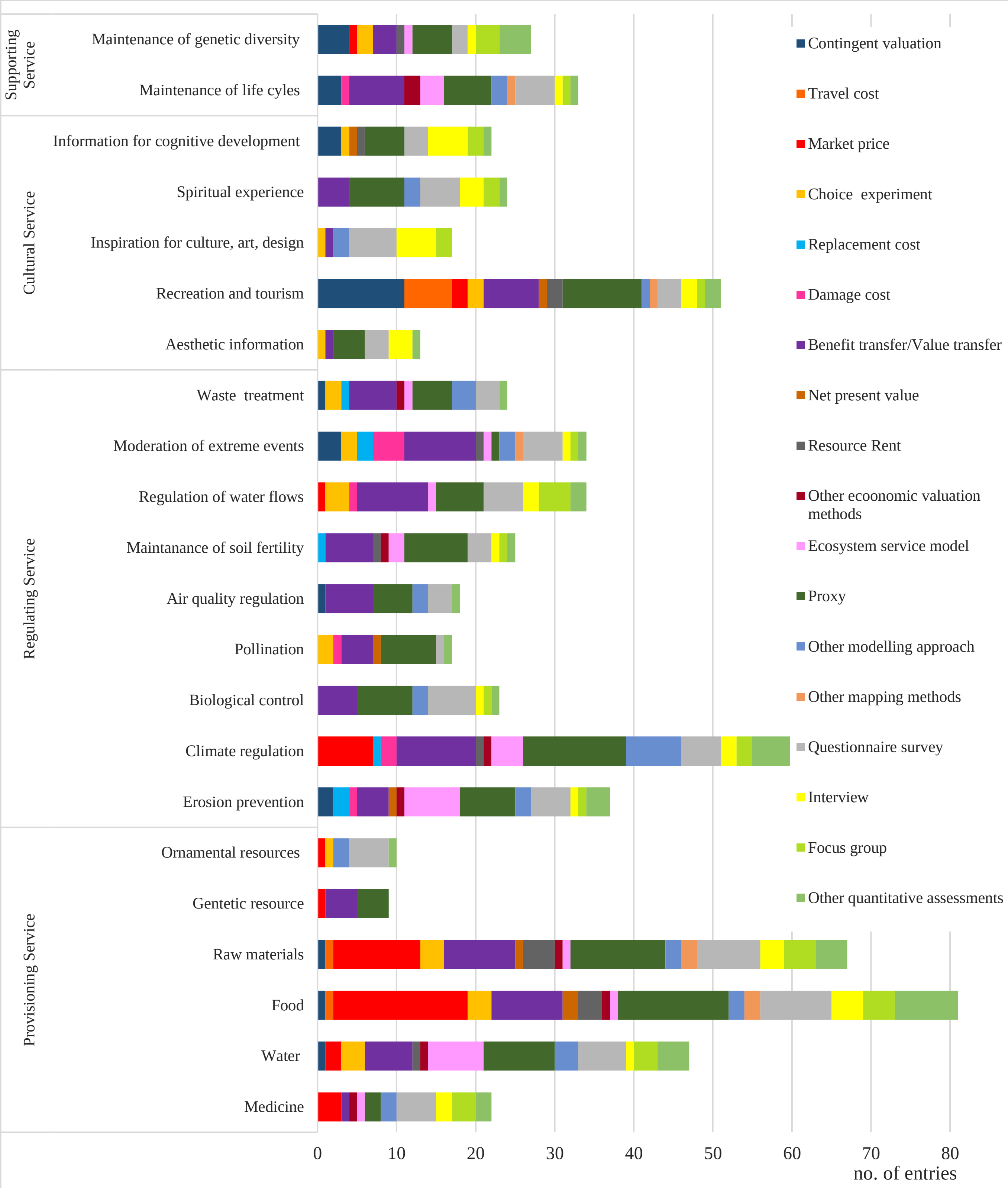


Figure 9 Methods used to assess individual ES are highly diverse. Bar height shows the number of times each ES was assessed, while colours show the methodology used

ES are mostly mapped at the resolution of 10-50m (Figure 10). Methods used to map ES at 10-50m are ES model and proxy methods. The finer scale studies (≤10m) in SEA were mapped only using proxy methods. The coarse scale studies (>1000m) were mapped using regression models.

Only 8 out of the 27 mapping cases reviewed validated their results (we excluded cases that used participatory mapping from these numbers). Validation was most common for climate regulation (using Root mean squared error to compare estimated value of biomass/carbon stock with field-measured data or applying Monte Carlo Simulation) (Pham et al., 2017; Kitayama et al., 2018; Suwarno et al., 2018) and water yield (using Nash-Sutcliffe efficiency coefficient to calculate the normalised relative variance of predicted water yields in comparison with the measured data) (Trisurat et al., 2016; Trisurat et al., 2018). Other validation methods applied in SEA are cross-validation for validating spatial interpolation of timber, rice, and oil palm provisioning (Sumarga et al., 2014) and social validation with stakeholders (Suwarno et al., 2018). Most of the cases using proxy methods (12/17) did not contain result validation.

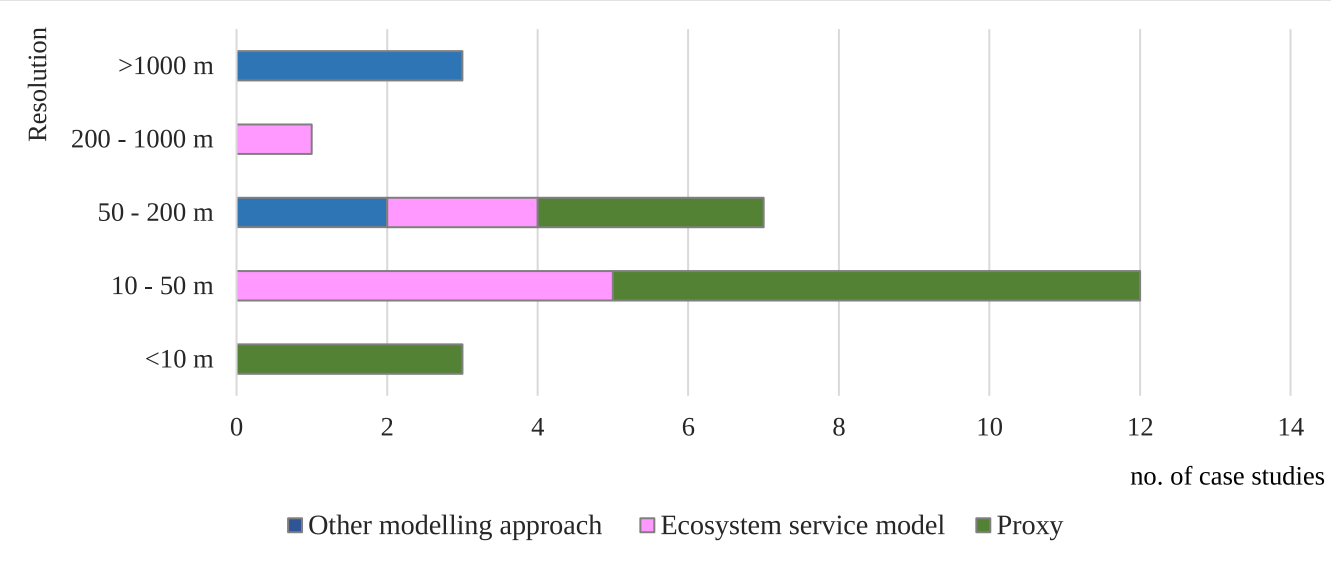


Figure 10 Resolution of ES mapping studies

There were no publications assessing stakeholders' perception before 2011 (Figure 7). Assessments of human perception have been used to identify how preferable different ES were in the context of supporting sustainable management and land use policies in Indonesia (Pfund et al., 2011; Muhamad et al., 2014; Mathe et al., 2015; Villamor et al., 2016), Malaysia (Barau, 2015), Vietnam (Berg et al., 2017) and Philippines (Tekken et al., 2017). They have also been used to identify key ES in a study area (Thiagarajah et al., 2015; Quyen et al., 2017; Feurer et al., 2019). In recent years, assessments of human perception have been integrated with ES mapping to make more realistic future scenarios for ES assessments in Indonesia (Kim et al., 2018). Spatially-explicit information on local perceptions of ES in Malaysia and Indonesia were used to inform land use planning and to identify where people are directly affected by the decline in ES due to land use change (Abram et al., 2014).

Since 2009, an increasing number of studies have integrated multiple methodologies into their assessment (Figure 7). The largest number of linkages were found between economic valuation and mapping (Figure 11). Other linkages can be seen in Figure 11.

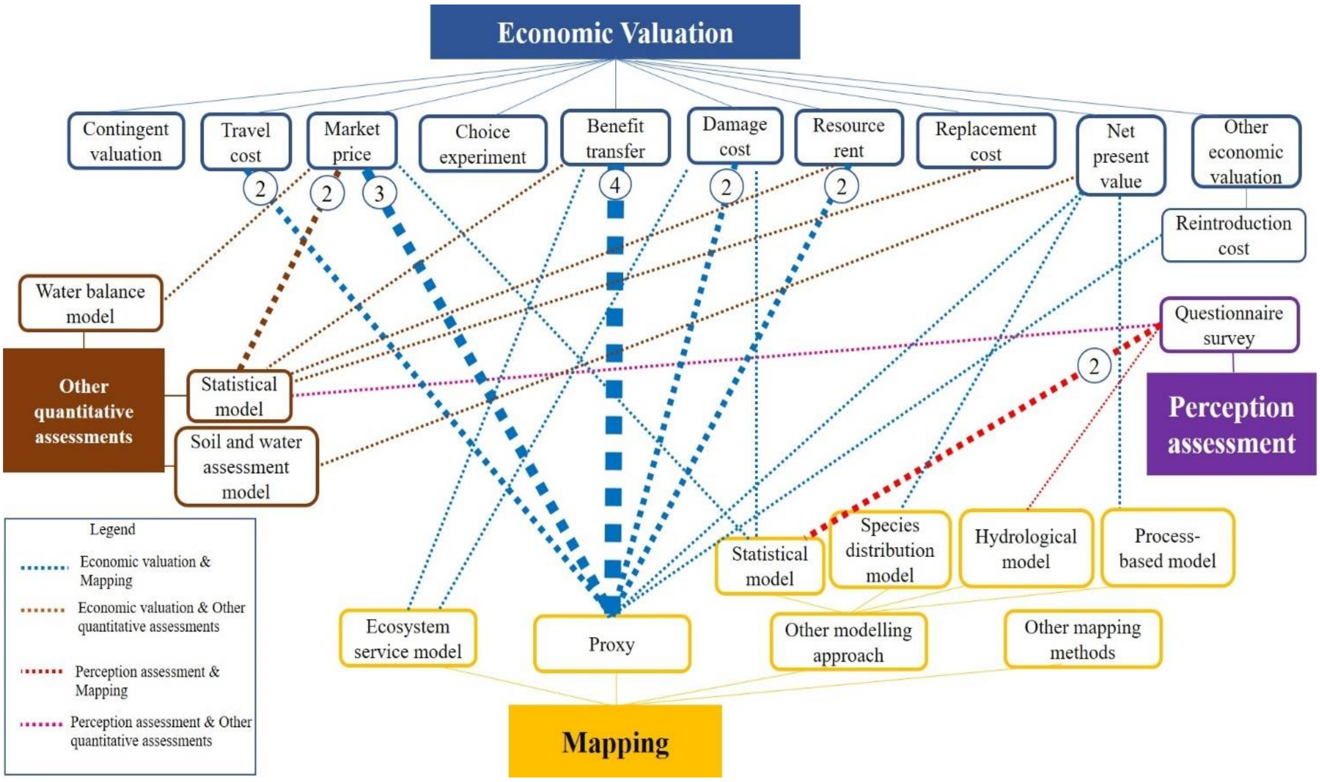


Figure 11 Method interlinkages among ES assessments *(thickness of linking line represents the number of linkages, the thicker the line the greater number of linkages, lines without numbers mean 1 linkage)*

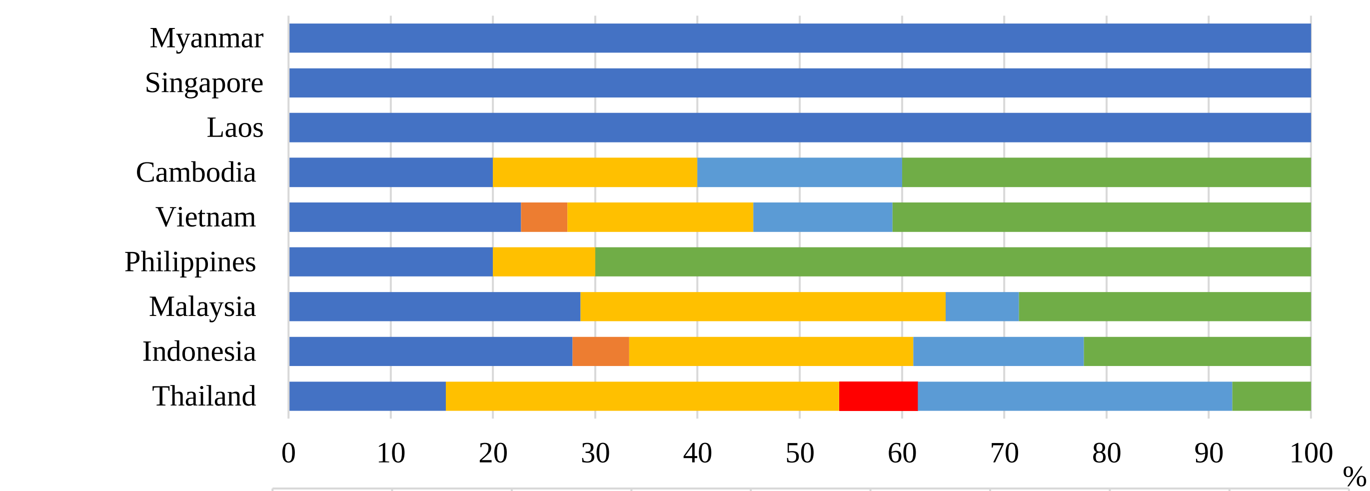
Table 3 presents the main input data used in ES assessments in SEA. Among data used, primary data from questionnaire surveys, interviews, and focus groups are the most important input, particularly for economic valuation. The most used secondary data for ES mapping is LULC maps. However, LULC sources in SEA studies mostly came from satellite images (34 case studies: 17 use Landsat, 10 use SPOT and 7 use MODIS). In a data sparse region like SEA, remotely-sensed products are very important data sources, especially open-source images like Landsat and MODIS. Upon screening through data sources, we found several studies used data from third parties. For example, NGOs (Bhagabati et al., 2014; Suwarno et al., 2018), international organisations (Arias et al., 2011) or foreign universities (Sumarga et al., 2014) and institutes (Bhagabati et al., 2014; Arunyawat et al., 2018; Kim et al., 2018), were common sources of data. Some studies also mentioned the use of unpublished data (Pfund et al., 2011; Sumarga et al., 2014). A number of studies used globally available data to fill data needs for their research (Naidoo et al., 2009; Yacob et al., 2011; Abram et al., 2014; Bhagabati et al., 2014; Mandle et al., 2017; Trisurat et al., 2018; Dang et al., 2019).

Table 3 Main input data used for ES assessments

Data	Assessment method	**Economic valuation**	**Economic valuation and Mapping**	**Economic valuation and Other quantitative assessment**	**Mapping**	**Other quantitative assessment**	**Assessments of human perception**	**Assessments of human perception and Mapping**	**Total**	**% total case studies**
Primary data	Questionnaire, interview, focus group	34	8	2	14	5	7	1	**71**	61
	Field data collection				1			1	2	2
Secondary data	Land use/land cover map	7	11	1	16	6	5	3	**49**	42
	DEM		1	1	6	3		2	13	11
	Soil map		1	1	5	3			10	9
	Topographic map	1			2	1	1		5	4
	Hydrological map								0	0
	Road map			1	3			2	6	5
	Evapotranspiration data				6	1			7	6
	Precipitation data	1			4	4		2	11	9
	Temperature					3		2	5	4
	Population density	1	1		1	1		2	6	5
	Soil properties	1			4	1			6	5
	Statistical data	7							7	6
	Result of previous studies	8				2			10	9

2.3.3 Ecosystem service assessment and linkage with policy decision-making

Although assessments of ES are increasing in number in SEA, how well they integrate into the decision-making process is yet undocumented (Förster et al., 2015). Although 93 among the total 118 case studies mentioned their aim to support policy in objectives or conclusions, only 13/118 case studies linked with current government policies. From our database, the main policies recorded were land use policy/planning, waste management, conservation strategy, risk management, climate change mitigation and sustainable management (Figure 12). For Thailand, Indonesia and Malaysia, conservation strategy attracted the most concern from ES assessments while in Vietnam, Philippines, Cambodia and Laos sustainable management was most commonly supported. Land use policy/planning was the main reason for ES assessment in Singapore and Myanmar. Regarding ES assessment approaches, economic valuation was mostly used to support ‘conservation strategy’ (34% of case studies) and ‘sustainable management’ (34%) while mapping approaches and assessments of human perception mainly supported ‘land use policy/planning’, 53% and 43% respectively.



	Thailand	Indonesia	Malaysia	Philippines	Vietnam	Cambodia	Laos	Singapore	Myanmar
Land use policy/planning	15	28	29	20	23	20	100	100	100
Waste managemt	0	6	0	0	5	0	0	0	0
Conservation strategy	38	28	36	10	18	20	0	0	0
Risk management	8	0	0	0	0	0	0	0	0
Climate change mitigation	31	17	7	0	14	20	0	0	0
Sustainable management	8	22	29	70	41	40	0	0	0

Figure 12 Percentage of policy groups targeted in SEA's ES assessments shows linkage of ES assessment and policies in SEA.

Among the 118 case studies, 13 mentioned links with current government policies (Bann, 1999; Naidoo et al., 2009; van Beukering, 2009; Nguyen et al., 2013; Bhagabati et al., 2014; UNEP, 2015; Arunyawat et al., 2016; Trisurat et al., 2016; Watkins et al., 2016; Loc et al., 2017; Mandle et al., 2017; Arunyawat et al., 2018; Suwarno et al., 2018), three studies were funded by the World Wildlife Fund (two in Indonesia: Naidoo et al. (2009) & Bhagabati et al. (2014) and one in Cambodia: Watkins et al. (2016)). WWF used the studies' results to work with planners, provincial officials, and governments to support the integration of ES assessments into the spatial planning process (Watkins et al., 2016). Information on ES supply and demand at the national scale for Myanmar by the Natural Capital Project were shared with a range of ministries in Myanmar including the Ministry of Natural Resource and Environmental Conservation (Mandle et al., 2017). By highlighting areas where loss of natural ecosystems may have negative consequences for Myanmar's people, the national assessment can guide land use planning for agricultural expansion and resettlement plans, as well as inform the location and design of infrastructure projects (Mandle et al., 2017). The final draft of the National Environmental Policy of Myanmar emphasised the importance of natural capital and ES (Mandle et al., 2017). In 2015, the United Nations funded a four-year case study in Vietnam, ProEcoServ, with the aim to mainstream ES concepts into policy-planning and decision-making. Through this project, the ES concept was successfully implemented in land use planning for Ca Mau National Park (UNEP, 2015). Comprehensive reviews of Vietnam's legal documents to examine integration of ES concepts into their legal frameworks found that the inclusion of relevant keywords, e.g. "ecosystem service", "payment for ecosystem service" and "natural capital", demonstrates increasing recognition of the importance of natural capital and ES in Vietnam's policy (Loc et al. (2017). However, it seems that only studies conducted by leading international organisations e.g. UN, WWF, the Natural Capital Project, are likely to reach policymakers. Although Singapore was assessed as has been successful in implementing ES in its planning process for water services, ES is still not quantified systematically in Singapore (Loc et al., 2020). Loc et al. (2020) could not find evidence that ES is monetised as part of the decision-making process in Singapore. It may due to top-down policy in Singapore. Singapore has decided that strong environmental stewardship is needed for their people and no evidence is needed. The small number of ES assessment case studies in Singapore found through this review aligns with the findings of Loc et al. (2020).

Although poverty reduction remains a priority in SEA, there were only few studies mentioning linkages among ES assessments with poverty alleviation (WorldFish, 2008; Suwarno et al., 2018). Three publications provided a general discussion on poverty alleviation and ES without in-depth analysis under specific policy contexts (Muhamad et al., 2014; Berg et al., 2017; Suwarno et al., 2018). Another three publications included a poverty index in ES assessments, however they did not analyse how ES assessments supported poverty alleviation (Glenk et al., 2006; Barkmann et al., 2008; Abram et al., 2014). The only publications that developed suitability maps considering trade-offs between ES and poverty reduction were two case studies in Thailand and Indonesia under the REDD+ programme (Ferraro et al., 2015).

ES assessments in SEA currently attract more funding from the international community than from SEA countries themselves. From the 88 cases studies that clearly acknowledged research funding, only 15 studies were funded by SEA countries, 62 were funded by international organisations (TEEB Southeast Asia, LEGATO, UN, WWF etc.) and 11 were part of PhD or post-doc research conducted in countries outside SEA.

2.4 Discussion

2.4.1 Trends and achievements of ecosystem services assessment in SEA

Our review demonstrates an increasing number of ES assessments are used for the wide variety of ES in SEA. The review includes both academic papers and grey literature as NGOs and foreign aid agencies play an important role in ES assessments in the region. Including grey literature avoids missing important evidence of linkage between ES assessment and decision making in SEA. Assessment approaches are becoming more diverse and include greater use of ES modelling, assessments of human perception and integrated approaches since 2005. These patterns match trends of ES assessments highlighted in Asian and global reviews (Egoh et al., 2012; Shoyama et al., 2017). They signal greater uptake of ES concepts in science and policy in SEA. Furthermore, the growth of ES modelling aligns with the rapidly growing body of ES modelling research found in other parts of the world.

Several positive signals suggest mainstreaming ES into decision-making in SEA with 13/118 case studies (4 from grey literature and 9 from academic papers) linking their result with current government policies. While relatively rare, these examples show how ES assessment can support decision-making and provide a foundation for future integration of ES information in related policies in SEA countries. In particular, some examples show how policymakers may benefit from using scenarios analysis of future alternatives from modelling tools (IPBES, 2018). For example, the InVEST model was used to estimate total losses in peat carbon over 50 years, which in turn supported government-led spatial planning and strategic environmental assessments in central Sumatra, Indonesia (Bhagabati et al., 2014).

An increasing number of studies have integrated ES perception assessments with spatially-explicit ES mapping. These integrations make ES assessments more problem-oriented and relevant to decision-making in the region. Furthermore, the expansion of integrated ES assessments indicates improvements in ES assessment capacity and inter-disciplinary cooperation among SEA researchers. As supply and demand for ES can occur in different locations, spatially-explicit values of services provide policymakers with a better understanding of ES flow between ES supply and demand. Information on these ES flows, as well as gaps in these flows, identify how ES can support human well-being (Burkhard et al., 2013; Crossman et al., 2013; Andrew et al., 2015). Furthermore, a multi-method approach may fulfil different needs at different stages of an assessment (Bagstad et al., 2013c; Wolff et al., 2015). For example, proxy mapping, benefit transfer and assessments of human perception can be a screening tool to evaluate and identify ES of importance and ES modelling can give more in-depth analysis of drivers, underlying processes, and interactions among ES for decision-making at more detailed scales. This diversity shows positive prospects for the development of more systematic ES assessments in SEA.

Our work corroborates the increasing recognition globally that stakeholder participation in ES assessments is an important tool for relating ecosystem function to human well-being (Seppelt et al., 2011). Particularly when interwoven with biophysical assessments, this integration of stakeholder participation can enhance applicability of ES assessments in SEA. Despite advancement in SEA in integrating stakeholders into ES assessments (Abram et al., 2014; Kim et al., 2018), new approaches integrating biophysical and socioeconomic methods are needed to address the gaps of spatially-explicit ES monetary valuation in SEA. For example, integration of biophysical mapping and economic valuation of ES, where economic valuation represents ES demand and biophysical mapping can represent ES supply, provides critical information for policymakers to understand natural systems (Daily et al., 2009). Systematically integrating multiple methodologies is a significant undertaking, requiring interdisciplinary collaboration. A framework that demonstrates multi-method integration is the System of Environmental Economic Accounting Experimental Ecosystem Accounting (SEEA), which the United Nations and partners are developing to bring economic and environmental information into a common framework to facilitate informed decision-making (SEEA, 2014).

2.4.2 Gaps and limitations in ecosystem services assessment in SEA

2.4.2.1 Geographical bias

There is a bias in the number of publications on ES assessments associated with individual countries in SEA. This bias may reflect both differences in international concern (and resultant international funding) and individual country's priorities. For example, there are two global biodiversity hotspots located in Indonesia (Sundaland and Wallacea) and the whole countries of Vietnam, the Philippines and Malaysia are identified as biodiversity hotspots (Myers et al., 2000). These hotspots have received significant funding from the International Union for Conservation of Nature (IUCN), the Critical Ecosystem Partnership Fund (CEPF), as well as other funding sources. This funding may have prompted evaluations of the investment efficacy and encouraged scientific partnerships, resulting in a higher number of ES publications in Indonesia, Vietnam, Thailand, the Philippines, and Malaysia compared to other SEA nations.

Vietnam and Indonesia have been progressively operating Payment for Ecosystem Services (PES) programmes (Suhardiman et al., 2013; Suich et al., 2017). The government of Vietnam endorsed PES implementation through their Government Decree on the Policy on Payment for Forest Environment Services (24 September 2010). The decree stated the implementation of PES in 26/64 provinces in Vietnam (Suhardiman et al., 2013). In 2009, the total revenue derived from service buyers, mostly hydropower and water supply companies, was 77 billion Vietnam Dong (VND) (approximately US $4 million) (To et al., 2012). PES was introduced in Indonesia since 2002 and was stated in the Indonesian Law on Environmental Protection and Management (Law No. 32/2009) established in 2009 (Fauzi et al., 2013).

Indonesia and the Philippines have engaged in the Wealth Accounting and the Valuation of Ecosystem Services (WAVES) partnership led by World Bank. The aim of WAVES is to promote sustainable development by ensuring that natural resources are mainstreamed in development planning and national economic accounts. Furthermore, Indonesia, Malaysia and the Philippines were in the list of the nations with presence of an environmental-economic accounting programme based on the *Global Assessment of Environmental-Economic Accounting and Supporting Statistics* (SEEA, 2017). The SEEA aims to provide a framework for countries to incorporate natural capital into their accounting systems. These also can explain the high number of ES assessments in Indonesia, Vietnam, Philippines, and Malaysia.

Although Laos, Cambodia and Myanmar are also identified as biodiversity hotspots, the current number of ES assessments in these countries does not reflect their importance. Moreover, Myanmar was indicated as a nation with presence of an environmental-economic accounting programme (SEEA, 2017). The whole countries of Laos, Cambodia and Myanmar are also identified as biodiversity hotpots (Myers et al., 2000). Therefore, expanding ES assessments in Laos, Cambodia and Myanmar will provide extra evidence for policy in the countries as well as SEA's common strategy. There is only one transborder study identifying as an ES assessment in SEA in the Lower Mekong region. Although a number of studies in SEA have focused on transboundary water management and haze pollution, they are not included in this review because they did not self-identify as ES. Regional and transboundary management of ES is important to produce benefits beyond national borders (IPBES, 2018). The lack of cooperation in transborder ES assessments may limit the region's capability to address transborder ES related issues.

2.4.2.2 Thematic gaps

Bias was also seen in ecosystem types in ES assessments. A larger number of studies focused on *forest, wetland, agriculture,* and *marine/coastal/island,* presumably reflecting high policy concern surrounding the degradation of these ecosystems in the SEA region. Although inland water is important and recognised as facing severe threats to their ecological function, adequate attention has not been paid to this type of ecosystem. The review results coincide with earlier findings of TEEB (2012). The bias may be because each country has unique natural resources, and the distribution of ES assessments for different ecosystem types reflect these differences. For instance, Indonesia and Malaysia are the largest producers of palm oil in the world, together contributing 85 to 90% of palm oil globally (IPBES, 2018). Hence, research in Indonesia and Malaysia focused on forest and agro-forest systems (Figure 3). The Philippines' rich coral reef systems (IPBES, 2018) were the subject of numerous coral reef ES assessments, while high concentrations of mangroves in Indonesia, Vietnam, Thailand, and Myanmar led to a large number of studies on mangrove ES.

Some ES have also gained more attention than others. It is possible that the selection of ES assessed in existing publications reflects the degree of policy concern or relative economic importance of these services in each country. Food security is a special challenge in the SEA region (ADB, 2013), hence food has been extensively focused in ES assessments in SEA. Tourism is the important industry in many SEA countries which correlates with a large number of recreation and tourism services assessments. Another possibility is that the data available for several ES (e.g., food, materials, and climate regulation) is more accessible compared to other services.

ES mapping and modelling mostly focused on provisioning and regulating services. Despite SEA's concentration on ecological diversity as well as the importance of cultural services, mapping cultural services and supporting/habitat services is still lacking in SEA. Further ES assessments that include diverse ES types, especially cultural and supporting/habitat services, are needed for policymakers to properly assess trade-offs among different values that ES bring to different groups of stakeholders. Supporting/habitat and cultural ES in SEA were mostly assessed through economic valuation approaches such as willingness to pay or stakeholder's perception assessment. However, mapping supporting/habitat and cultural ES and their value will better support policymakers to manage and preserve these services in SEA.

There are still gaps in the policies that ES assessments have supported in SEA. At the present, ES assessments mainly focus on supporting general sustainable management, land use policies/planning and conservation strategies. There is a lack of analyses that link risk assessments and climate change mitigation, which are important topics for SEA as a region vulnerable to climate change. Additionally, the relationship between ES and human well-being is stressed by MEA (2005a). Poverty alleviation is one of the main issues of SEA countries and the first priority in the Sustainable Development Goals (SDGs); however, not many ES assessments in SEA address poverty alleviation or provide evidence of their contribution to poverty alleviation. Those limitations may link to the difficulties in poverty data collection in developing countries (Ferraro et al., 2015) and the difficulties in hydrological and broader integrated modelling in data-sparse regions like SEA (Hawker et al., 2017; Mandle et al., 2017).

Alongside these gaps in the research we evaluated, we also acknowledge our paper may have missed studies and reviews that are not included in online databases or where titles, abstracts and keywords did not highlight an explicit ES focus. In addition, focusing only on publications that explicitly self-identify as having quantified an "ecosystem service" captures only research after the development of this terminology. Future work which expands search strategies to more available databases as well as additional key words will add valuable understandings about ES assessments and decision making in SEA. A deeper review on current ES policies in SEA would also be useful to reveal better ways toward integrating ES assessments into policy for the region.

2.4.2.3 Data limitations and gaps

While spatially-explicit ES monetary valuation is an important information source for decision-making, improvements in current approaches are needed to improve its reliability for this purpose (Burkhard et al., 2013; Crossman et al., 2013; Andrew et al., 2015). Through our linkage analysis among ES assessment approaches, we found ES values were primarily mapped using proxy methods. The prominence of proxy methods is also found in ES mapping in Asia (Shoyama et al., 2017), Europe (Maes et al., 2012) and global ES mapping because data required are easy to obtain (Schägner et al., 2013). Proxy-based ES assessments present the same value for each land use/land cover (LULC) class at different locations, not the actual distribution of ES values. However, ES are not only determined by LULC but also by other factors such as soil type, topography or water availability and human demand. For example, Rasmussen et al. (2016) found through their survey that primary forests were not the most important source of provisioning services (e.g., wild vegetables, wild meat, fodder, and medicinal plants) for people in Northern Laos, which contradicted the pattern seen using LULC proxies. As such, using LULC proxies for ES may be inadequate especially for understanding ES's importance for local people (Rasmussen et al., 2016).

Using proxy-based methods can lead to uncertainty in ES value mapping. Because the same ES value is assigned to each LULC class, proxy methods usually underestimate the value of small-scale heterogeneity, for example biodiversity hotspots or priority areas for multiple services, which cannot be identified in LULC map (Eigenbrod et al., 2010). Proxy methods, therefore, are appropriate for coarse-scale planning but not for finer-scale decision-making (Eigenbrod et al., 2010). Proxy methods also risk generalisation errors and oversimplification, that can mislead decision-making processes (Seppelt et al., 2011; Stephens et al., 2015). As an example, carbon stock is considered an adequate proxy for estimating potential for emissions reduction (Larsen et al., 2010; Law et al., 2015). However, there are several ways to estimate carbon stocks, such as field-based measurements, remote sensing-based estimations, and land use/landcover based look-up tables. When considering carbon proxies in a policy or planning context, it is important to recognise that each proxy will produce different estimates, and thus, proxy choice can influence the overall performance of policies (Law et al., 2015). Spatial proxy models were also highlighted as unsuitable for mapping of cultural ES, as proxy data often underestimates the multiple socio-cultural benefits for human well-being (Kopperoinen et al., 2017). Thus, the assessments based on empirical data and evidence-based approaches could provide higher credibility for decision-making and planning processes (Ruskule et al., 2018). Moreover, our review found the majority of the cases using proxy methods in SEA did not contain result validation. The use of invalidated proxy-based mapping has been raised as a concern in previous studies (Englund et al., 2017). The limitations in result validation were attributed to the time-consuming efforts required to collect empirical data (Englund et al., 2017).

Although ES mapping and modelling approaches are increasingly being applied in SEA, data availability and parameterisation constrain these efforts. Applying ES modelling may require input data that are not readily available for SEA. For example, the InVEST-Water yield model needs information on root depth as well as other soil hydraulic properties that are either unmeasured or inaccessible in SEA. To apply InVEST in Thailand, Trisurat et al. (2016) conducted field surveys and laboratory analysis to obtain the root depth and soil characteristics in topographically complex areas. Lack of data also limited ES trade-off analysis for spatial planning in Central Kalimantan province, Indonesia (Sumarga et al., 2014). Spatial planning usually involves trade-off analysis in monetary terms for different land conversion scenarios. However, economic valuation of sufficient accuracy is not available to provide robust information on optimal land use in the province (Sumarga et al., 2014).

Data sharing is not common across SEA. Although the Mekong River Commission, the inter-governmental organisation of Mekong River Basin countries (Cambodia, Laos, Thailand, and Vietnam) provides data for the Mekong River Basin area, data are not freely available and data retrieval requires time-consuming application and approval process. There are not any open-source databases that freely provide the detailed regional data needed for ES assessments in SEA. The databases that contain up-to-date data are conducted and developed by government sources in SEA countries. Country-based spatial data are difficult to access.

Because the lack of data sharing, remote sensing or global databases are often important data sources for ES assessments in SEA. Indeed, our results show remote sensing and other globally available data are the main data sources for ES mapping and modelling in SEA. However, relying on remote sensing and global data sources is not without limitations. For example, LULC classification accuracy may be limited when conducted across broad areas, and as such, coarse resolution of remotely sensed imagery may omit of small patches with high ES values (de Araujo Barbosa et al., 2015). Furthermore, because of difficulties with data access, there is a lack of ES model-based assessments at fine resolutions (≤10m). This lack of high-resolution information may limit the ability of policymakers to make decisions in heterogeneous landscapes. In addition, multiscale analyses need to be further developed to strengthen the link between local findings with global perspectives, data, and models. ES maps and models should be validated, however, validation is difficult in data-scarce environments.

2.4.2.4 Limited coverage of spatial and temporal scales and their interactions

There is a lack of multi- spatial and temporal scale analyses in SEA. Decision-making may require analysis at multiple spatial scales as decisions made at one scale may affect services at other scales (de Groot et al., 2010; Willemen et al., 2012; Burkhard et al., 2013). Regarding temporal scales of ES assessment, ES assessments at single points in time can only deliver static information about the current state of ES the dynamic nature of ES interactions only can be obtained by multi-spatiotemporal ES assessment (Renard et al., 2015). This information may not be enough for effective decision-making. Policy- and decision-makers also need analyses regarding historical and future change of ES for assessing the impact of development actions or developing future planning (Greenhalgh et al., 2015; Rau et al., 2020). Therefore, the lack of historical and future scenarios analysis in SEA may limit effective decision-making in the region. Advantages of multi-scale ES assessments is that they can provide important insights on the mechanisms influencing ES at different scales. For example, anthropogenic activities influenced ES relationships at local scales while the physical environment (climate, hydrology and soil) controlled ES relationship at regional scales in China (Liu et al., 2017). Multi-scale analyses also show more diversity in spatial correlations among ES than single-scale analysis (Liu et al., 2017). Further ES assessments at multiple scales, therefore, can support diverse management purposes in SEA.

Most ES mapping in the region is at moderate and low resolution. Mapping resolution often depends on input data resolution and the type of ES being mapped (Egoh et al., 2012). However, in order to support decision-making, spatially-explicit ES maps need an appropriate resolution. In a data scarce region like SEA, low-resolution ES assessments can be useful for decision-making at national or regional level. Some services can be mapped at coarse resolutions e.g., climate regulation, water yield or water regulation. However, detailed analysis at the local level or site-scale (farm/landscape) requires finer mapping resolution (Egoh et al., 2012; Bagstad et al., 2013c; Malinga et al., 2015). Specifically, land management may require a more detailed understanding of landscapes and their services (Malinga et al., 2015). The finer scale studies (≤10m) in SEA were mapped only using proxy methods, which can be limited in accuracy, especially within land cover types. More ES modelling at finer resolution is needed. ES modelling at finer resolutions (<10 m) may be necessary to provide more comprehensive information for land management practice at site-scales in SEA or for management of specific ES types that have very site-specific ecological processes.

There has not been any spatially-explicit ES modelling of synergies and trade-offs among ES in SEA. Spatially-explicit information of ES synergies and trade-offs is more useful for decision-making than aspatial correlation coefficients or scores (Jackson et al., 2013; Barnett et al., 2016). As targeting one ES can affect other ES, synergy and trade-off analysis provides important information for contrasting gains and losses of ES and for finding win-win solutions to benefit policy making and the public for future plans. SEA, therefore, needs more studies that analyse synergies and trade-offs among ES.

2.4.3 Way forward for ecosystem services assessment in SEA

2.4.3.1 Data accessibility improvement

To move forward with ES assessments that inform policy, systematic and transparent data collection and use of spatially-explicit models are urgently needs. To overcome issues that arise from data constraints, each country should develop basic open-source databases organised by assessment methodology with parameterised and validated data specifically. These databases, as well as subsequent ES assessments in SEA, should follow the Findable, Accessible, Interoperable and Reusable (FAIR) Data Principles for reusing scholarly data, which ensures data quality (Wilkinson et al., 2016). A database like this would improve data accessibility, reduce time spent on data collection and parameterisation, ultimately improving the performance, and strengthening the scientific basis of the ES assessment process for policymaking and implementation. Currently, the Economy and Environment Program for Southeast Asia has the ValuAsia database which contains studies of environmental economic values within SEA. However, studies were only updated up to 2013 and their detailed contents are not accessible (accessed on 20/07/2020). Updating the ValuAsia database, therefore, would be valuable to narrow the information gap that hinders policymakers in SEA.

2.4.3.2 Use of ES models

Diversifying the ES models used for analysis may strengthen databases needed for ES assessments by providing a range of potential ES outcomes in SEA and can ultimately contribute to global ES assessment. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) has encouraged the use of modelling approaches to support policymakers (IPBES, 2016). However, InVEST is the only ES model used for existing studies in SEA. There are a number of other tools available for ES modelling that have been widely used in public- and private-sector decision-making (Bagstad et al., 2013c; IPBES, 2016). Comparative studies of different modelling tools allow decision makers in SEA to contrast and select the most suitable tool for their management purposes (Bagstad et al., 2013d; Sharps et al., 2017). For example, the Artificial Intelligence for Ecosystem Services (ARIES) model (Bagstad et al., 2013d; Villa et al., 2014), the Land Utilisation & Capability Indicator (LUCI) model, rebranded as Nature Braid (next-gen LUCI) (Jackson et al. 2013) and the InVEST model (Sharp et al., 2020) can all map some aspects of ES demand and flows, but each model has different strengths and weaknesses according to which regions and ES are being considered. In addition, different ES models have different parameterisation requirements. Employing other ES models in SEA may facilitate incorporating a greater number of ES types as well as synergy and trade-off analyses into ES assessments.

2.4.3.3 Specific guidance on ES classification for SEA

Another obstacle to mainstreaming ES assessment in SEA is rooted in the ES classification used in the SEA context. About 50% of our reviewed papers did not clearly indicate the ES classification they used for ES assessed. Widespread ES classification terms originated from developed countries and do not align well with the context of SEA countries (Loc et al., 2017). From the review results, there have not been any official documents that explain how to transfer ES concepts and classifications from developed countries to SEA. Therefore, it is important for SEA to have an official document/framework that clearly defines ES for SEA. Clear and specific definitions of the different ES are important to develop appropriate indicators and units for ES quantification so that they can be used for setting policy and management objectives as well as for natural capital accounting (Braat et al., 2012).

2.4.3.4 Boosting cooperation and engagement

Shared benefits of water, energy and land in SEA countries require close cooperation among countries and local agencies to co-develop transborder policies that faciliate sustainable development. This cooperation should include shared ES classifications, coordinated funding and the development and promotion of transboundary frameworks. Currently, there is only one transborder ES assessment in SEA, which assesses water yield services across the Lower Mekong countries (Thailand, Laos, Vietnam, and Cambodia) (Trisurat et al., 2018). Although SEA countries have developed strategic regional plans for biodiversity conservation, illegal wildlife trade, and sustainable forest management, SEA countries have not had any official common strategies for ES assessments like developed region (IPBES, 2018). The European Union has the *Biodiversity Strategy for 2020* that set the mapping and valuing of ES as an important target for each member state. EU also has detailed guidance on how mapping and assessment of ES can be done and how to adopt ES into planning and decision-making (EU, 2013, 2016). A similar effort is needed in SEA to improve ES assessments and cooperation in natural capital preservation by the Association of Southeast Asian Nations (ASEAN), the inter-governmental organisation of SEA countries. PES and valuing ES were mentioned in the ASEAN Initial Inputs to the *Post-2020 Global Biodiversity Framework* as tools and measures to achieve vision 2050 about *"Living in harmony with nature",* but there has not been any practical guidance on how to structure ES assessments. SEA countries also need to improve collaboration between governments and harmonise objectives for ES assessments (IPBES, 2018). A larger effort is needed across Asia toward policy integration of ES assessment.

Working with local agencies will help align local and regional strategies, as well as improve the local technical capacity to implement these tool and methods. However, the financial support necessary for this cooperation and capacity building is still limited. Lack of funding for ES assessments may be because ES concepts are not mainstreamed in the policy frameworks of most SEA nations (Loc et al., 2020). Governments normally allocate funding towards priorities that reflect concepts in government policies (Matzek et al., 2019). Challenges in mainstreaming ES concepts can also lead to lack of exposure to ES decision making frameworks and government silos. Science-policy frameworks that promote scientific knowledge of ES will help ES assessments garner attention (GIZ, 2012; UNEP, 2015; FAO, 2016).

To develop such policies, engaging stakeholders is critical, especially those operating at different scales including the private sector and other agencies not directly responsible for biodiversity and natural resources management (IPBES, 2018). This engagement can enhance the credibility of ES assessments. In addition, international foreign aid agencies (ADB, WB, JICA and GIZ) play an important role in mainstreaming ES in policy-making in SEA (Loc et al., 2020). Increases in funding that focus on informing policy and ensuring data collection is coordinated across countries is critical. Better empirical data collection is essential for an evidence-based approach. In addition, having freely available empirical data will encourage policy-oriented research in leading research institutes and universities in SEA. Taken together, common frameworks and additional funds will improve ES assessments, and ideally, result in policies to align natural resource conservation and economic development for SEA.

The low engagement between ES science community and policymakers in SEA countries has hampered the ability of ES assessments to access and thus influence decision-support platforms (Carrasco et al., 2016). The science-policy gap in ecosystem management in Asia Pacific may be in part attributed to inadequate capacity and lack of strategies for community participation (Avishek et al., 2012). Opening more science-policy forums or dialogues is likely to be an effective way to bring ES assessment results to policymakers. These would also assist researchers and scientists to gain more understanding of policymakers' needs and how to improve ES assessments to provide the best information for policymakers. Similar activities like the "Science-Policy Dialogues on the Assessment of Biodiversity and Ecosystem Services: Southeast Asia & Northeast Asia" should be organised more frequently in SEA and Asia. Through this forum, government officials and experts from SEA and Northeast Asia had an opportunity to discuss ways to utilise the various reports of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), especially the regional assessment for Asia and the Pacific.

2.5 Conclusion

In this paper, 108 publications (118 case studies) on ES assessments in SEA were reviewed with a focus on their assessment approaches and how their results support decision-making in the region. We highlighted achievements, gaps, and limitations in ES assessments. Since 1999, methodologies used in ES assessments in SEA have diversified with increased stakeholder participation and a growing number of spatially explicit assessments. However, ES assessments in SEA still face geographical bias, thematic bias, data constraints, and limited coverage of some spatial and temporal scales. Data constraints have led to a preference for proxy-based ES assessments, but these assessments can only provide limited information for policymakers. Lack of multi- spatial and temporal scale analyses, particularly high-resolution analyses in SEA may cause limitations for decision-making that require multiple scale information or local detailed information. Some studies have aligned results with policy needs, but their tangible influence on policy still appears limited. To better support decision-making, more evidence-based assessments with trade-off analyses and validation are needed in SEA with the support of ES modelling. Detailed guidance on how to map and assess ESs and how to adopt ES assessments into planning and decision-making may facilitate standardised ES assessments that provide such evidence. Ways forward for ES assessments to better support decision making also include improving data accessibility, creating more science-policy dialogues, enhancing engagement of stakeholders in ES assessment and facilitating more cooperation among ASEAN countries.

Among data gaps identified in this paper, the lack of soil hydraulic property information has been a big obstacle to applications of ES model in data sparse regions. The challenges arise from both limited access to specialist knowledge and difficulty to obtain and/or measure soil hydraulic properties. In response to these, guidance and an associated spatially referenced toolbox were developed in Dang et al. (2022) (Chapter 3). The guidance and toolbox provide a quick way to obtain spatially explicit soil hydraulic properties information which are not only useful for ES modelling but also for broader integrated environmental modelling.

3 Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling[2]

3.1 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 et al., 1998). Being situated at this crucial nexus means soil plays a fundamental role in the Earth's ecosystems (Vereecken et al., 2015; Adhikari et al., 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 et al., 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 et al., 1999b; Nemes et al., 2003; Timlin et al., 2004; Vereecken et al., 2015), but each type of model requires different soil hydraulic properties (Table 4). For example, lumped conceptual catchment models require soil moisture thresholds in both surface and root-zone storage (Nielsen et al., 1973; Moore, 2007; Willems, 2014; DHI, 2017a). 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) [3] (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 et al., 2019). Regional and global climate and weather prediction models also require adequate parameterisation of soil hydraulic properties (Montzka et al., 2017).

[2] This chapter has been published as: Dang et al. (2022)

[3] 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 among other things.

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[4] grid to estimate the actual evapotranspiration (Sharp et al., 2020). Average annual soil infiltration is used in ARIES floodwater sink module to find areas with different infiltration capacities (Bagstad, 2011). The Land Utilisation and Capability Indicator model (LUCI), rebranded as Nature Braid (next-gen 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 is important to implement realistic and sustainable land and water management practices (Mishra et al., 1999; Hengl et al., 2015).

Table 4 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 et al., 1973; DHI, 2017a)	- 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, 2017b)	Two-Layer UZ method: - Soil moisture content at saturation, field capacity, wilting point - Saturated hydraulic conductivity (K_{sat}) - 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
	• 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

[4] Plant available water: Water held between field capacity and wilting point

Model type	Examples	Soil hydraulic property inputs
	• 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., 2020)	- Plant available water
	• ARIES (Bagstad, 2011)	- Soil infiltration
	• LUCI (Jackson et al., 2013)	- Permeability class - Drainable water - Plant available water - Saturated hydraulic conductivity

Information on soil hydraulic properties is often not available because direct measurements are both labour intensive and expensive (Wösten et al., 1999b; Nemes et al., 2003; Pachepsky et al., 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 (K_{sat}) and hydraulic conductivity curve (HCC), is normally unavailable or insufficient in the soil databases of many countries (Jarvis et al., 2002; Patil et al., 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 et al., 2016; Abbaspour et al., 2019). For example, current land-surface models mostly (95%) use default regionally sourced soil parameters e.g. 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 behavior of complex hydrological models (Flanagan, 2004), land-surface models (Van Looy et al., 2017), agricultural systems (Castellini et al., 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 5) (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 et al., 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 et al., 2017), SOILPAR (Acutis et al., 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 5 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)	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 the literature devoted to the use and development 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 et al., 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 et al., 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 timeframe (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 unexperienced 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 when 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[5]. 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 Appendix B1.

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 getting 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 Land Utilisation and Capability Indicator (LUCI) model framework, rebranded as Nature Braid (next-gen LUCI). It is both embedded within LUCI 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.

[5] Popular infiltration models are Green Ampt (1911), Kostiakov (1932), Horton (1940), Philip (1957), Holtan (1961)

The third objective is to demonstrate the use of the guidelines and toolbox for getting soil hydraulic properties required by the LUCI model in different geoclimatic conditions and under different levels of data availability with two case studies, Vietnam Mekong Delta (VMD) and Hurunui catchment in 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; FSL soil map (Manaaki Whenua - Landcare Research, 2010) and WISE global soil properties; 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 LUCI_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 region.

3.2 Materials and Methods

The guidelines were developed based on an in-depth review of available resources (databases, tools, publications, etc.) to guide 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, LUCI_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.

3.2.1 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. Figure 13 presents an overall flow chart for the guidelines. In the current version, the guidelines contain instructions on how to get 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).

Soil hydraulic information can be obtained directly from global or local databases (Table B1.2, Appendix B1). The latest summary of *Soil Physical and Hydraulic Properties databases* is by Nemes (2011). Table B1.2 (Appendix B1) 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 contains less information. Data mostly exists in two main forms: tabular information and gridded maps. For example, SoilGrids™, 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 et al., 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 -1,500 kPa) and no hydraulic conductivity data is 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[6] 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 is available, those data can be fitted to SMRC functions using various data fitting techniques, for

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

example utilising mathematic optimisation methods like the numerical simplex or amoeba algorithms (Pan et al., 2019).

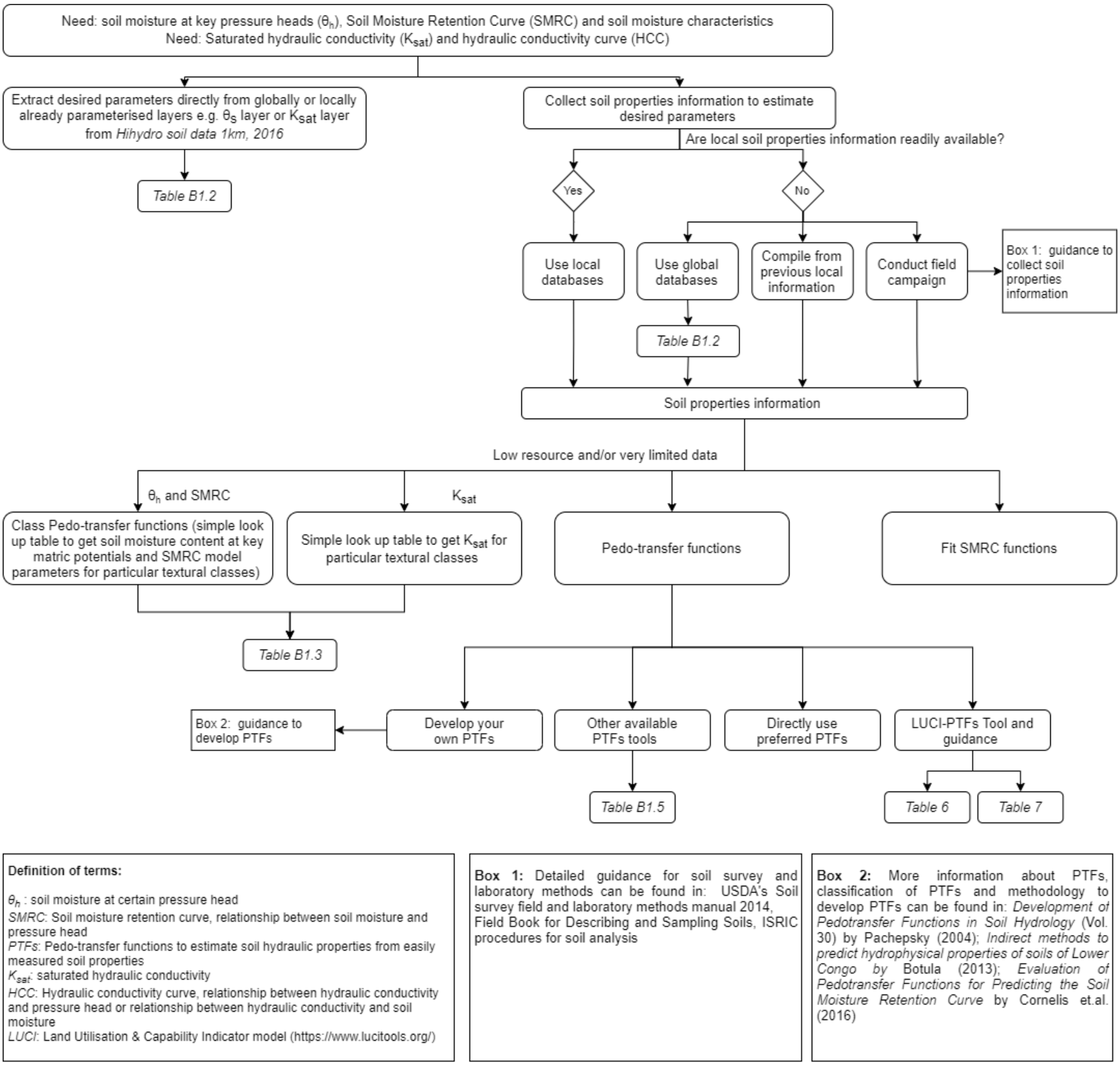


Figure 13 Overall flowchart of the guidelines for parameterising soil hydraulic properties

If it is not possible to get 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 B1.2, Appendix B1); 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"*

(Soil Survey Staff, 2014), the "*Procedures for soil analysis*" (Reeuwijk, 2009) or specific guidance for soil survey of each country is also available (Box 1, flowchart, Figure 13).

The soil data, once collected, can be used to develop PTFs or used as inputs in published PTFs to obtain 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. (1999a) 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 Neighbor methods (see Box 2, flowchart, Figure 13). 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 B1.3, Appendix B1. 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 6 and Table 7 give detailed guidance as to where the information on PTFs can be found in the Appendix B1. 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 et al. (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 developed 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 6 Guidance for finding information on soil moisture PTFs depending on data availability and climate context (Appendix B1)

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 B1.6, section Point PTFs (1)*	*Table B1.6, section SMRC (1)*	*Table B1.7, section Point PTFs (1)*	*Table B1.7, section SMRC (1)*	*Table B1.8, section Point PTFs (1)*	
2	Soil texture (Sa, Si, Cl); BD; OM/OC	*Table B1.6, section Point PTFs (2)*	*Table B1.6, section SMRC (2)*	*Table B1.7, section Point PTFs (2)*	*Table B1.7, section SMRC (2)*	*Table B1.8, section Point PTFs (2)*	
3	Soil texture (Sa, Si, Cl); OM/OC	*Table B1.6, section Point PTFs (3)*		*Table B1.7, section Point PTFs (3)*		*Table B1.8, section Point PTFs (3)*	
4	Soil texture (Sa, Si, Cl); BD	*Table B1.6, section Point PTFs (4)*	*Table B1.6, section SMRC (4)*	*Table B1.7, section Point PTFs (4)*		*Table B1.8, section Point PTFs (4)*	*Table B1.8, section SMRC (4)*
5	Soil texture (Sa, Si, Cl)	*Table B1.6, section Point PTFs (5)*	*Table B1.6, section SMRC (5)*	*Table B1.7, section Point PTFs (5)*		*Table B1.8, section Point PTFs (5)*	

Table 7 Guidance for finding information on soil hydraulic conductivity PTFs depending on data availability and climate context (Appendix B1)

No.	Data available	Temperate climate		Tropical climate		Arid climate	
		K_{sat}	**HCC**	**K_{sat}**	**HCC**	**K_{sat}**	**HCC**
1	Particle size distribution information	*Table B1.9, section K_{sat} (1)*					
2	Particle size distribution information and SMRC models parameters	*Table B1.9, section K_{sat} (2)*					
3	SWRC models parameters	*Table B1.9, section K_{sat} (3)*					
4	Effective porosity	*Table B1.9, section K_{sat} (4)*		*Table B1.10, section K_{sat} (4)*			
5	Soil texture (Sa, Si, Cl) and porosity	*Table B1.9, section K_{sat} (5)*	*Table B1.9, section HCC (5)*	*Table S1.10, section K_{sat} (5)*		*Table B1.11, section K_{sat} (5)*	
6	Soil texture (Sa, Si, Cl); BD; OM/OC	*Table B1.9, section K_{sat} (6)*	*Table B1.9, section HCC (6)*			*Table B1.11, section HCC (6)*	
7	Soil texture (Sa, Si, Cl); OM/OC	*Table B1.9, section K_{sat} (7)*					
8	Soil texture (Sa, Si, Cl); BD	*Table B1.9, section K_{sat} (8)*		*Table B1.10, section K_{sat} (8)*			
9	Soil texture (Sa, Si, Cl)	*Table B1.9, section K_{sat} (9)*		*Table B1.10, 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 - was 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 B1.5, Appendix B1). The LUCI_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 LUCI_PTFs tool and other PTFs is given in Table B1.5. More details of the LUCI_PTFs tool are described in the next section.

Tables B1.6, B1.7 and B1.8 (Appendix B1) contain 92 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 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 B1.4, Appendix B1). The collected PTFs were classified in the five groups depending on their required input parameters (Table 6). 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 the literature, and there are not many available PTFs or tools that estimate K_{sat}. Tables B1.9, B1.10 and B1.11 (Appendix B1) contain about 46 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 in nine groups representing the differences in required inputs (Table 7).

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 et al., 2004; Reichert et al., 2009; Botula et al., 2012). Hodnett et al. (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 soil moisture retention behaviors 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), among 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) among 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 different among countries. For example, New Zealand (NZ) defines silt at particle size between 0.002-0.06 mm (John et al., 2002) while United Sate (US) uses the range 0.002 – 0.05 mm (USDA, 1987) and FAO use the range 0.002 – 0.0063 to define silt (FAO, 2006). Consequently, that leads to the difference in thresholds to define sand among classification systems. The silt/clay threshold is more commonly agreed among 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 et al., 1985). In addition, textural triangles are different among countries regarding number of classes, definition of classes (ranges of particle size to define classes) and classes’ name. For example, the US’s 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, 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 necessary directly comparable even if they appear to have the same texture and classification and/or use similar input data. Where local data is not available, searching for PTFs trained on soils of similar geographic conditions is recommended.

3.2.2 LUCI_PTFs toolbox version 1.0

LUCI_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 Land Utilisation and Capability Indicator (LUCI) framework but can also be accessed as a stand-alone toolbox. The GitHub link to download LUCI_PTFs can be found at https://github.com/lucitools/LUCI_PTFs. The toolbox can be used to guide parameterisation of required soil hydraulic parameters not only for LUCI 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 selected. In the version 1.0, LUCI_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 & Corey function (Appendix B2). As for hydraulic conductivity, the toolbox has nine PTF options for K_{sat} estimation and two PTF options for parameterising the Mualem van Genuchten 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 the Appendix B1. 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. LUCI_PTFs version 1.1 will include additional point PTFs as well as PTFs for other SMRC models, e.g., 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 LUCI_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 the Appendix B2. If local soil maps and soil properties are not available, guidance from the previous section can be used to obtain 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: (1) interpolating soil properties then applying PTFs or (2) applying PTFs then interpolating the result to get catchment map of soil hydraulic properties (Picciafuoco et al., 2019). In the current version, LUCI_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 LUCI_PTFs toolbox (Table 8). 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 LUCI_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 among soil layers (topsoil and subsoil) were included.

The toolbox provides a graph of SMRC when the van Genuchten or the Brooks & 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 (Appendix B2).

Table 8 Parameters and units for LUCI_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	$g\ cm^{-3}$
CEC	$cmol\ kg^{-1}$

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 9. Those key soil moisture thresholds and soil moisture characteristics for plants are generally identified using SMRC (Figure 14). Guidance on how to identify those parameters can be found in Table 9. 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"; hence in practice SAT is often estimated as 0.95 of total measured porosity. 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 purpose, 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). 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). Readily plant available water is the water held between FC and WSC. Water held between WSC and PWP is not readily for plant, not readily available water (NRAW). Water held below PWP is hydroscopic water (HW). LUCI_PTFs toolbox has functions to extract soil moisture values at key pressure (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.

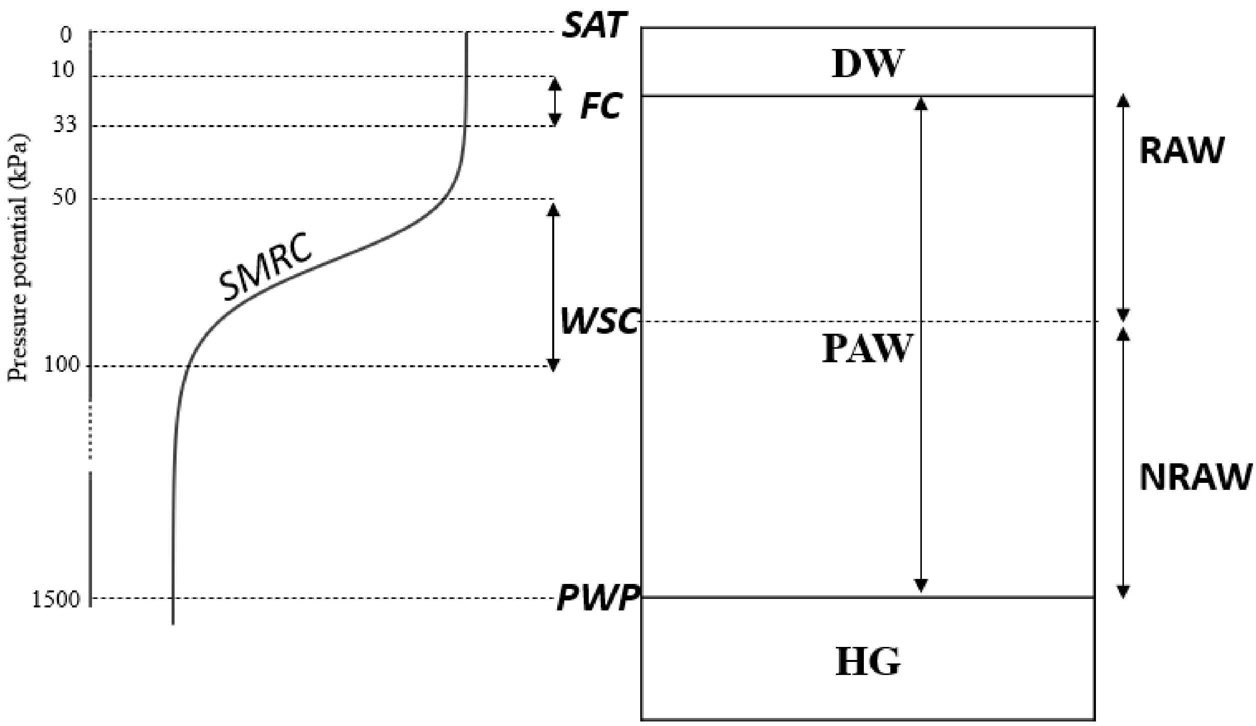


Figure 14 Key soil moisture thresholds and plant water availability thresholds can be extracted from LUCI_PTFs, explanations of parameters can be found in Table 9.

Table 9 Key soil moisture content thresholds and plant available water thresholds

Parameter	Definition	Guidance
SAT (Saturated moisture content or porosity)	- SAT present 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"; hence in practice SAT is often estimated as 0.95 of total measured porosity.
FC (Field capacity)	There are various definitions of FC: - Veihmeyer et al. (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 FC which is very important to define drainable water and plant available water. It is because, the pressure determining FC changes depending on where the water table is as well as soil texture and soil depth (Hillel, 2004). For measurement purpose, 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 critical point or refill point in some literatures (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)
DW (Drainable water)	Drainable water is water held between saturation (SAT) and field capacity (FC). 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 the permanent wilting point) to a lower limit	PAW = Field capacity (FC) – Permanent wilting point (PWP)

Parameter	Definition	Guidance
	(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.	
RAW (Readily plant available water)	Portion of the available water holding capacity is 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 LUCI_PTFs toolbox, the fraction default value is 0.5 but users can define the fraction themselves.
NRAW (Not readily available water)	HAW is water held between stomata closure point and permanent wilting point	HAW = Stomata closure point (WSC) – Permanent wilting point (PWP)
HG (Hygroscopic water)	HG is water held below permanent wilting point	

3.3 Case studies

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

3.3.1 Vietnamese Mekong Delta case study

The VMD case study encompasses a flat tropical area with extremely limited information regarding soil properties. Limited detail in soil physical, chemicals and hydraulic data is common in tropical countries (Nemes, 2011). Some results from the case study, e.g., drainable water, plant available water, saturated hydraulic conductivity, were used for the application of the LUCI to map multiple ecosystem services in the VMD (Dang et al., 2021b).

3.3.1.1 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 (Figure 15) (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 dike systems with the main purpose of protecting rice fields from flooding (Hung et al., 2014b). 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, getting 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).

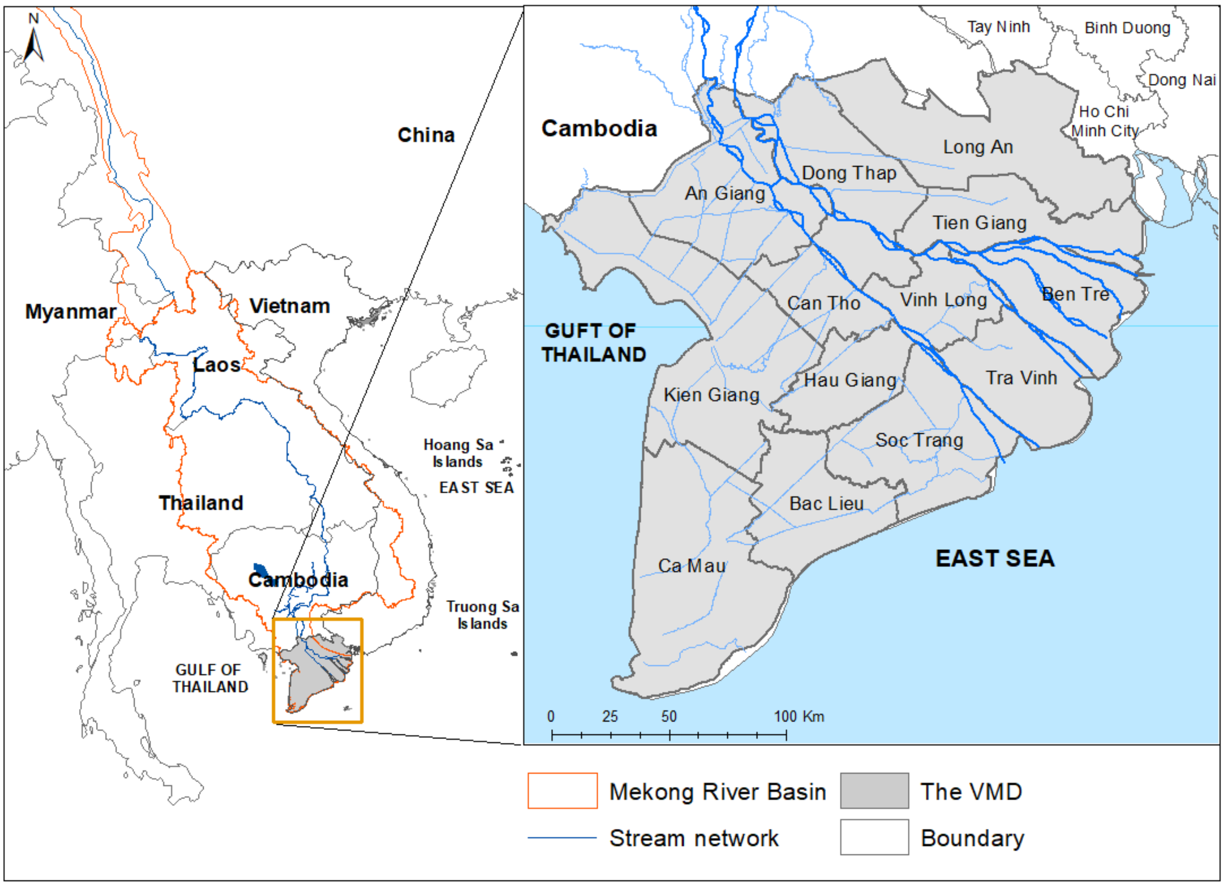


Figure 15 Location of the Vietnam Mekong Delta (VMD)

3.3.1.2 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 (Figure 16a) and soil properties using FAO-UNSESCO 1974 categorisation (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 (Figure 16b) which we linked to WISE global soil properties (Batjes, 2009); and a local soil map obtained from Dong Thap University (WISDOM project) linked to the FAO-UNESCO 1990 categorisation, referred to as the VN soil map (Figure 17) 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 models 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).

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, $CaCO_3$) was joined with the MRC and VN soil maps.

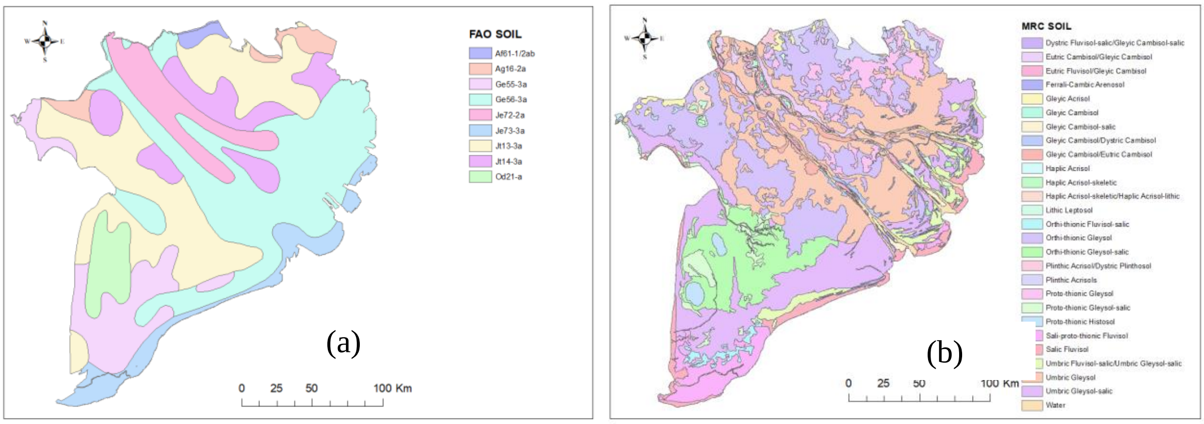


Figure 16 Soil maps obtained from (a) FAO, (b) MRC

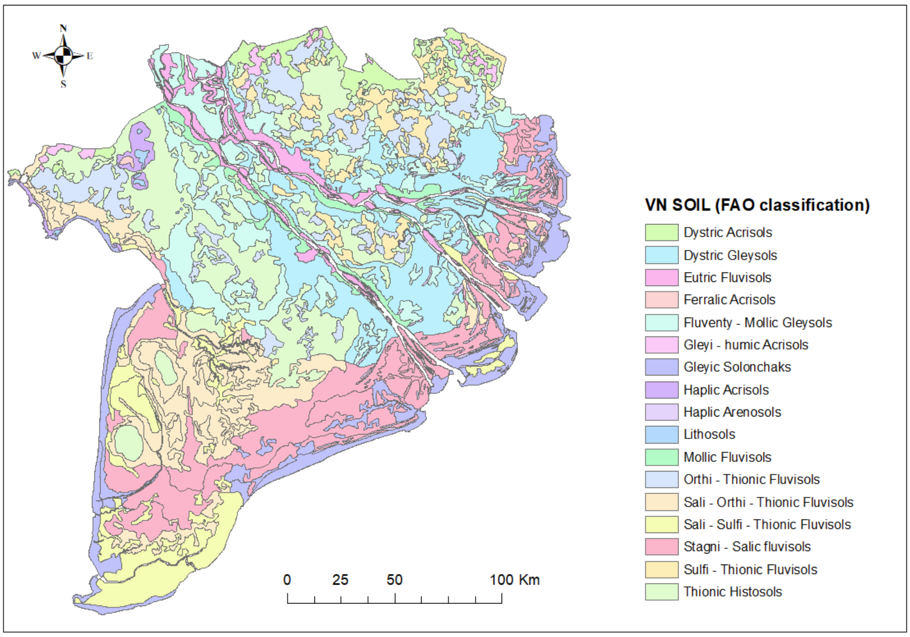


Figure 17 The soil map for the VMD using Vietnam soil classification system

3.3.1.3 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 8 pressure heads, -1kPa, -3kPa, -6 kPa, -10kPa, -20kPa, -33kPa, -100kPa, -1500kPa. In addition, PTFs by Wösten et al. (1999a) and Hodnett et al. (2002) were used to obtain van Genuchten soil moisture retention curve for the VMD. The Hodnett et al. (2002) relationship was selected for comparison because the PTFs were developed in another tropical climate (Brazil). Although the PTFs by Wösten et al. (1999a) 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 et al. (2000), based on the similarity between VMD soil properties and the datasets used to develop these two models. PTFs by Wösten et al. (1999a) and Weynants et al. (2009) were used to establish Mualem van Genuchten HCC because HCC PTFs for 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 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).

3.3.1.4 Results and discussion - the VMD case study

Using the LUCI_PTFs toolbox, shapefiles of various soil hydraulic properties can be obtained in less than 1 min. These shapefiles can be subsequently presented as maps. Figure 18 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 data sets 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.

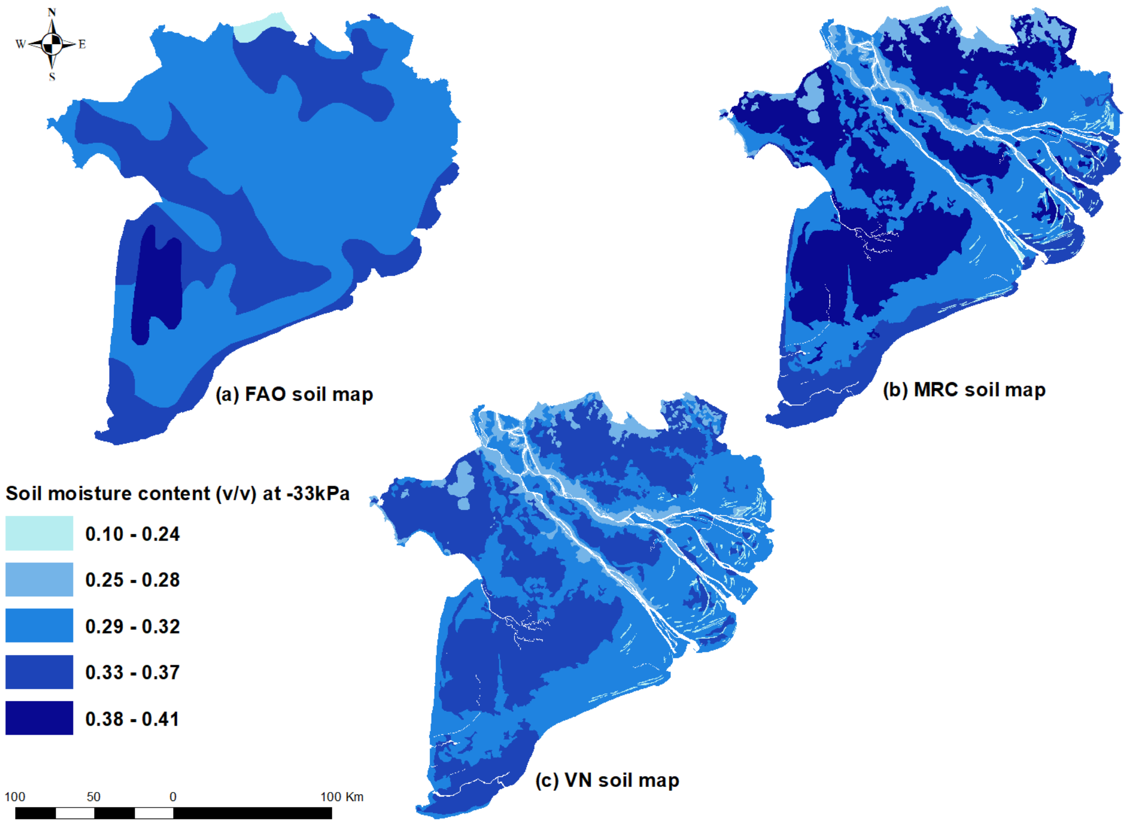


Figure 18 Maps of soil moisture content at -33kPa (field capacity) for topsoil using Nguyen et al. (2014) PTFs; (a) FAO soil map, (b) MRC soil map, (c) VN soil map

Similarly, Figure 19 presents the maps of soil moisture content at permanent wilting point using Nguyen et al. (2014) PTFs. Results of soil moisture content at permanent wilting point obtained using the three data sets 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.

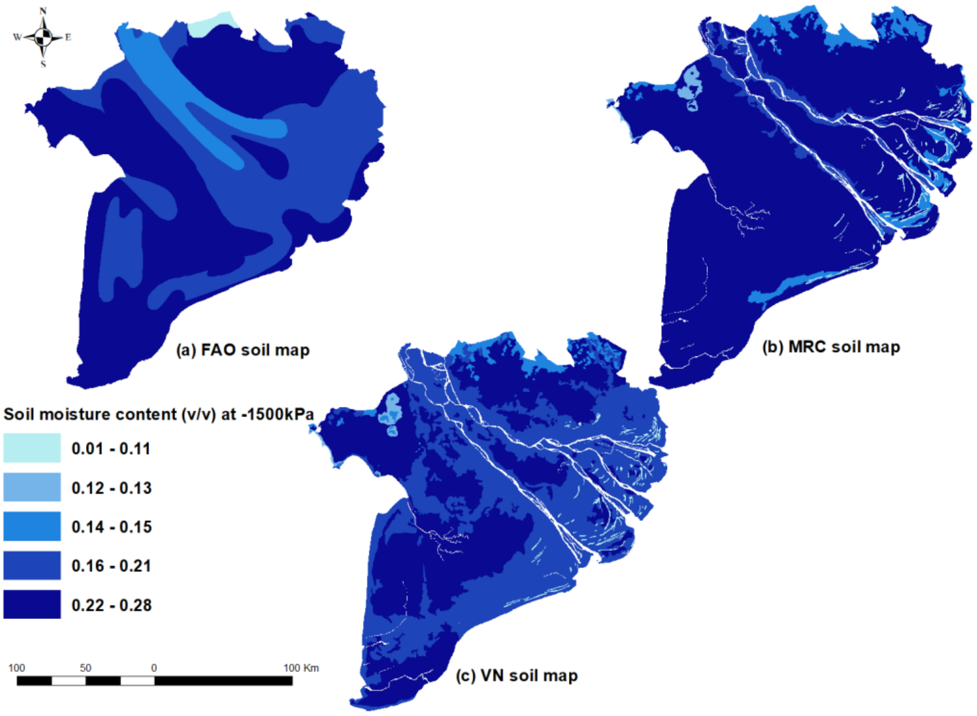


Figure 19 Maps of soil moisture content produced by LUCI_PTFs at -1500 kPa (permanent wilting point) using Nguyen et al. (2014) PTFs; (a) FAO soil map, (b) MRC soil map, (c) VN soil map

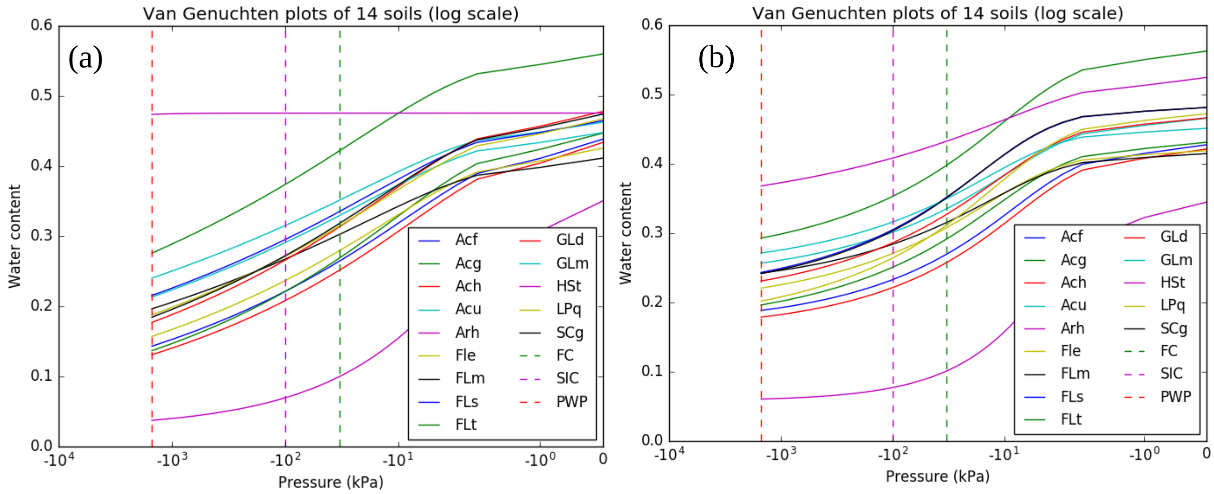


Figure 20 van Genuchten SMRCs established using VN soil map, (a) Wösten et al. (1999) PTF and (b) Hodnett and Tomasella (2002) PTF

In addition to point PTFs, SMRCs can be obtained via LUCI_PTFs. SMRCs are the required inputs for many models which solve Richards's equation. Figure 20 provides examples of van Genuchten

SMRCs obtained from the toolbox using PTFs by Wösten et al. (1999a) (developed for temperate regions, Figure 20a) and Hodnett et al. (2002) (developed for a tropical region: Brazil, Figure 20b). In Figure 21, 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. (1999a) and Hodnett et al. (2002) PTFs to understand how they compare with each other across soil types.

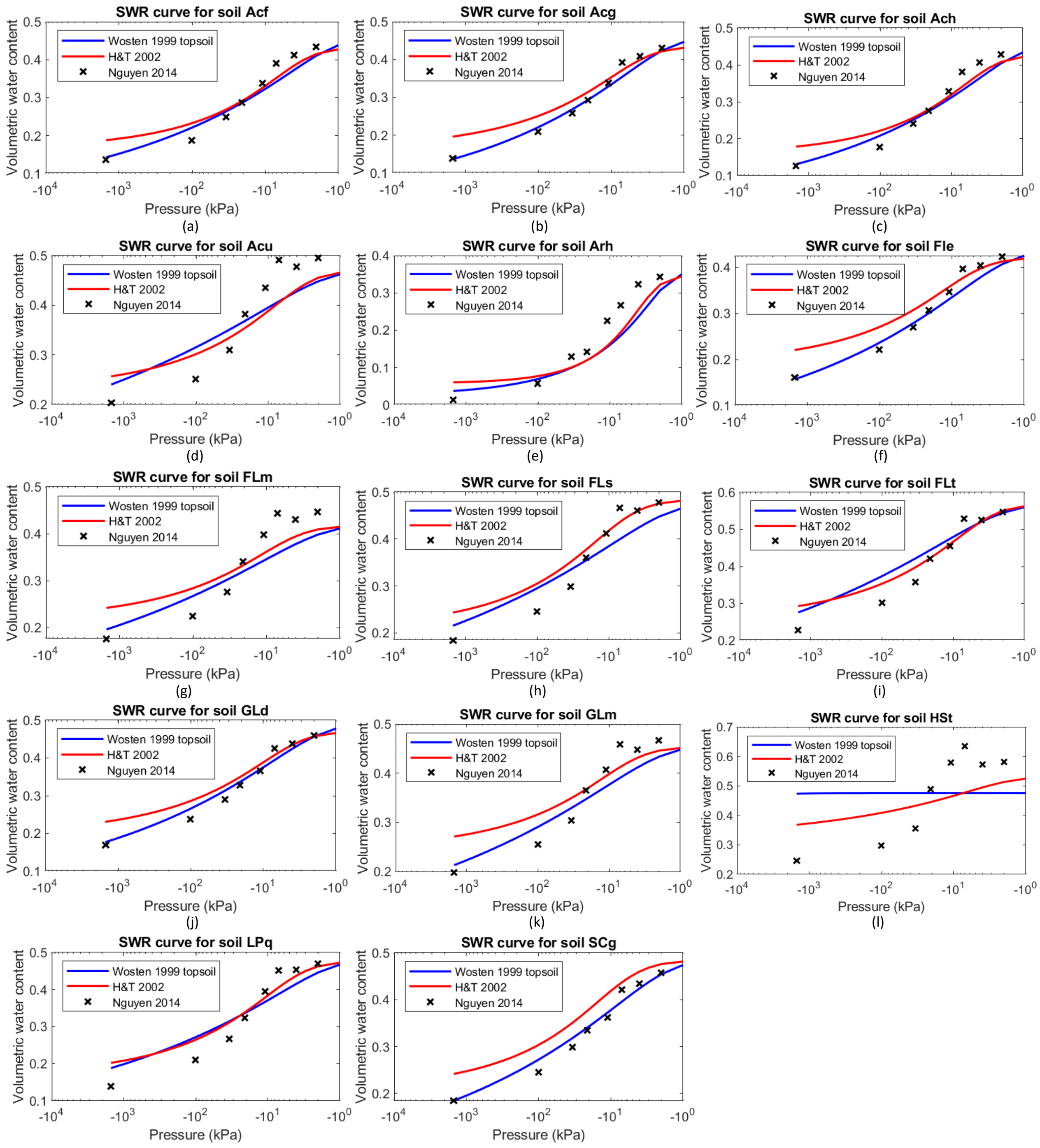


Figure 21 van Genuchten SMRCs established for 14 FAO-UNESCO 1990 soils (VN soil map) using Wösten et al. (1999a) PTFs for top soil (referred to as Wosten 1999) and Hodnett et al. (2002) PTFs (referred to as H&T 2002), and soil moisture content at eight pressures using Nguyen et al. (2014) PTFs (referred to as Nguyen2014).

Examining the results presented in Figure 21, all but one (Thionic Histosols) of the soil SMRCs obtained from the three PTFs look physically realistic. Unfortunately, there are no site-specific hydraulic property data (a problem, that in part, was the rationale behind this study). 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 (Figure 21 l). 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. (1999a) 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 et al., 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. (1999a) 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 infeasible results. We suggest extreme caution is used if applying the Wösten et al. (1999a) or similar relationships to tropical peat soils.

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 et al. (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 et al. (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 et al., 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 what PTFs are suitable for differing peats or other high OC soils in different climates and geographic settings is recommended.

Saturated hydraulic conductivity (K_{sat}) and Hydraulic conductivity curve (HCC) can also be obtained from LUCI_PTFs toolbox. Figure 22 and Figure 23 presents maps of K_{sat} using PTFs from Ahuja et al. (1989) and Minasny et al. (2000), respectively. Effective porosity for these two PTFs were estimated using SAT and FC obtained from Nguyen et al. (2014). Comparing output maps obtained from the three input data sets and the two PTFs (Figure 22a with Figure 23a, Figure 22b with Figure 23b and Figure 22c and Figure 23c), the K_{sat} maps have similar patterns when using the two different PTFs. However, the value ranges are different. The PTF from Minasny et al. (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.

If local measurement data is 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 et al. (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 et al. (2000) PTF. The K_{sat} value of the samples in the SoilKsatDB database, which have soil properties similar to *peaty acid sulphate soils*, have 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: (1) the point PTFs for estimating soil moisture content by Nguyen et al. (2014) were not established for peaty soil and (2) the K_{sat} PTFs by Ahuja et al. (1989) (Figure 22) and Minasny et al. (2000) (Figure 23) only use moisture content (*effective porosity*[7]) 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, LUCI_PTFs can support the comparison of different PTFs and find the most suitable one for different contexts.

[7] the difference between saturation and field capacity moisture content

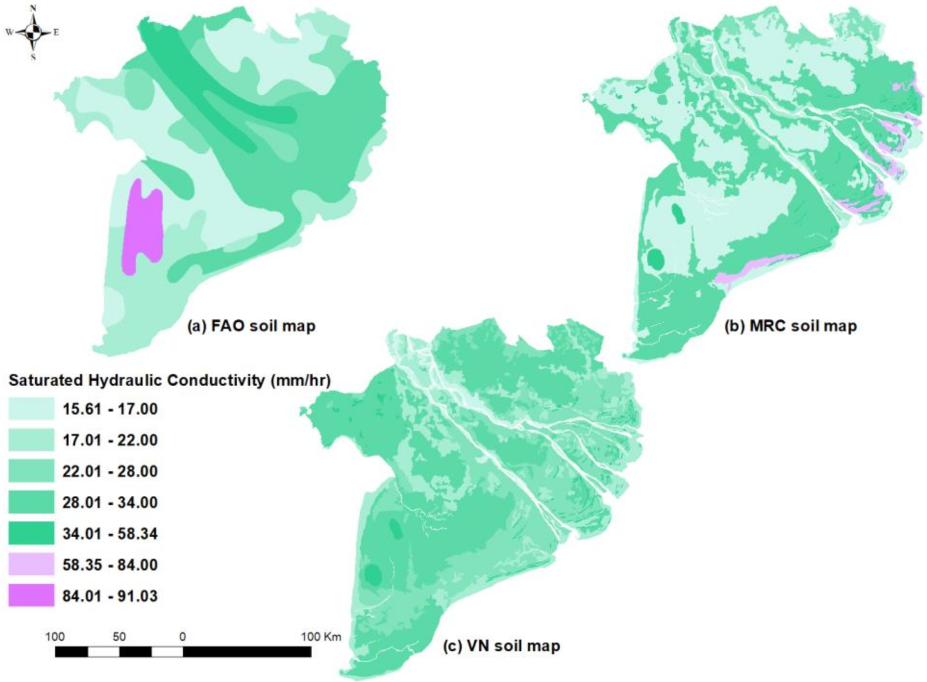


Figure 22 Maps of saturated hydraulic conductivity using Ahuja et al. (1989) PTF; (a) FAO soil map, (b) MRC soil map, (c) VN soil map

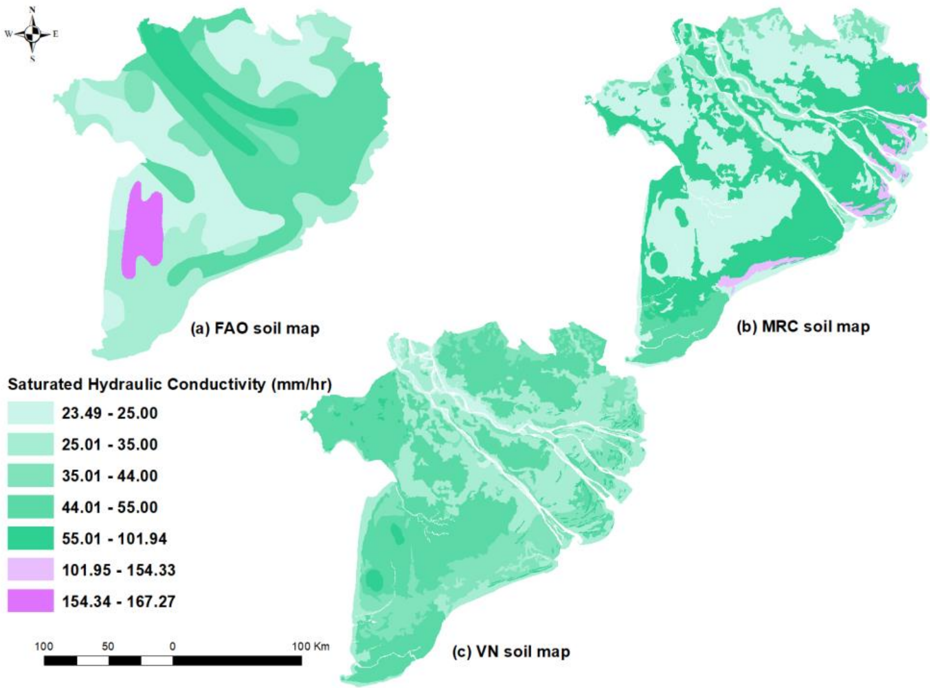


Figure 23 Maps of saturated hydraulic conductivity using Minasny et al. (2000) PTF; (a) FAO soil map, (b) MRC soil map, (c) VN soil map

The three datasets were then tested with Mualem van Genuchten PTFs by Wösten et al. (1999a) and Weynants et al. (2009). Figure 24 and Figure 25 presents K_{sat} value obtained from the two PTFs. Wösten et al. (1999a) gives a higher value range of K_{sat} compared to Weynants et al. (2009) PTF. Figure 26 presents Mualem van Genuchten HCCs. From HCCs graphs, hydraulic conductivity of almost soil types have quite similar characteristic when using the two PTFs. However, soil hydraulic conductivity values obtained from Wösten et al. (1999a) 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.

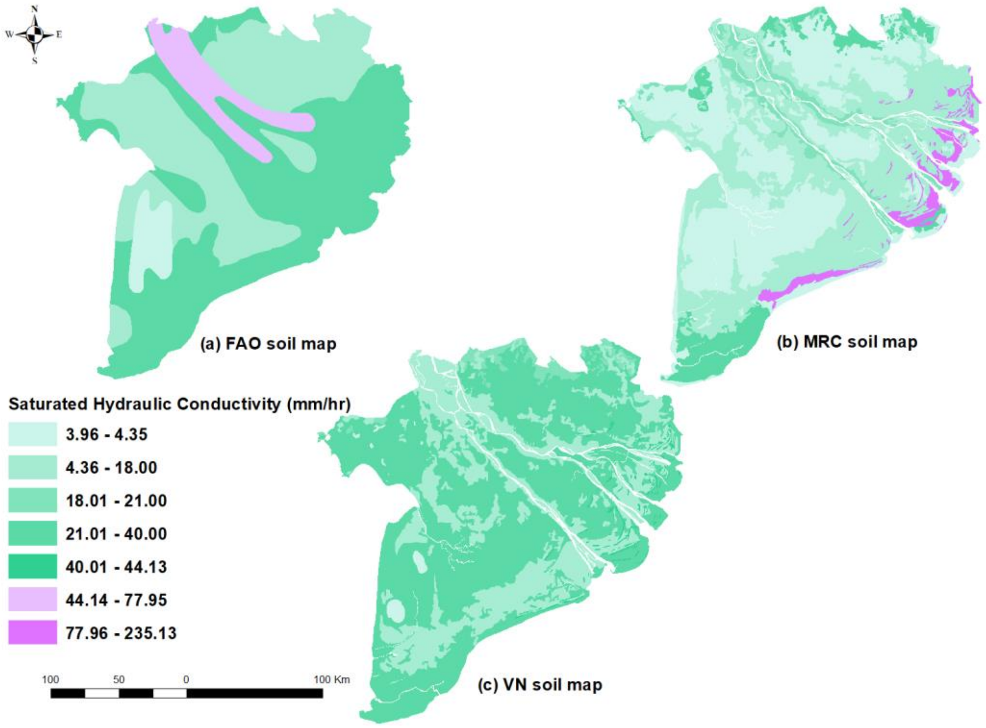


Figure 24 Maps of saturated hydraulic conductivity using Wösten et al. (1999a) PTF; (a) FAO soil map, (b) MRC soil map, (c) VN soil map

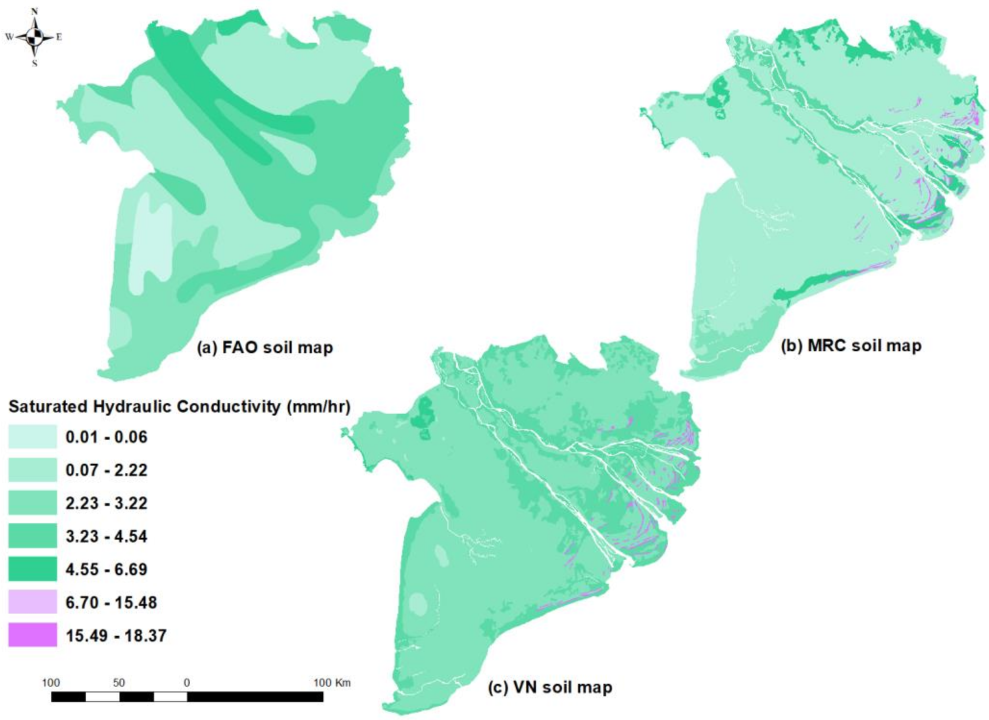


Figure 25 Maps of saturated hydraulic conductivity using Weynants et al. (2009); (a) FAO map, (b) MRC map, (c) VN soil map

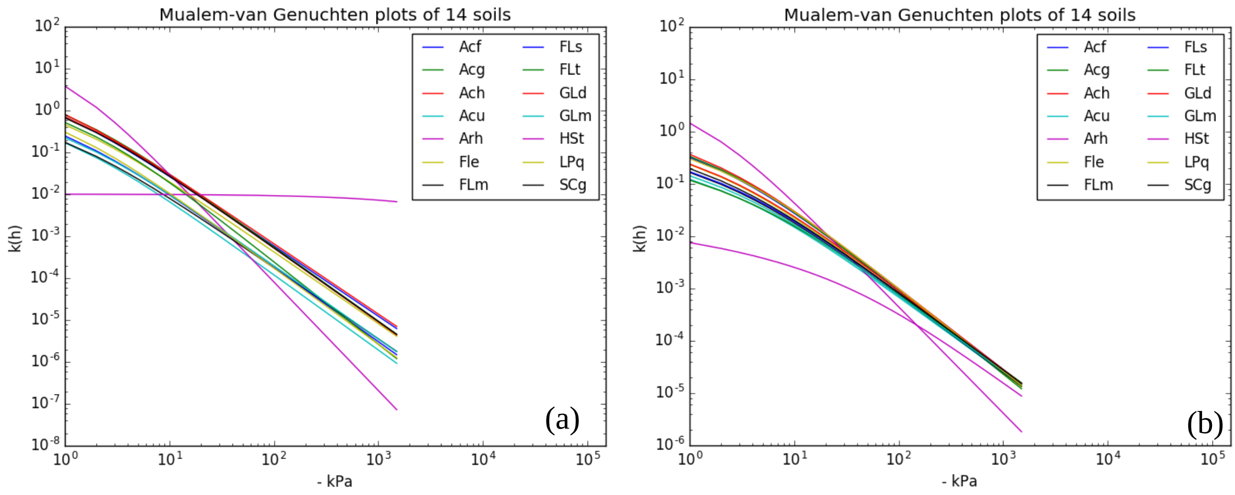


Figure 26 Mualem van Genuchten HCCs established using VN soil map, (a) Wösten et al. (1999a) PTF and (b) Weynants et al. (2009) PTF

The outputs from the LUCI_PTFs toolbox were compared with the global database, HiHydroSoil (Table 10 and Table 11). In general, soil moisture content values at saturation point and -100kPa of the LUCI_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 and 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., 1999a; Minasny et al., 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 10 Soil moisture content obtained from the LUCI_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 -1500kPa (v/v) Nguyen et al. (2014)	WC at -1500kPa (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*

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 -1500kPa (v/v) Nguyen et al. (2014)	WC at -1500kPa (v/v) ***HiHydro Soil***
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 11 K_{sat} obtained from the LUCI_PTFs toolbox using VN soil and PTFs by Ahuja et al. (1989), Minasny et al. (2000), Wösten et al. (1999a) 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*
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*

3.3.2 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 LUCI_PTFs toolbox in a hilly temperate region, where more soil information is available compared to the VMD.

3.3.2.1 Main characteristics of the Hurunui catchment

The Hurunui catchment is located in the North Canterbury region of New Zealand (Figure 27). 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. Therefore, models of soil-landscape relationships are important for mapping soils in the catchment.

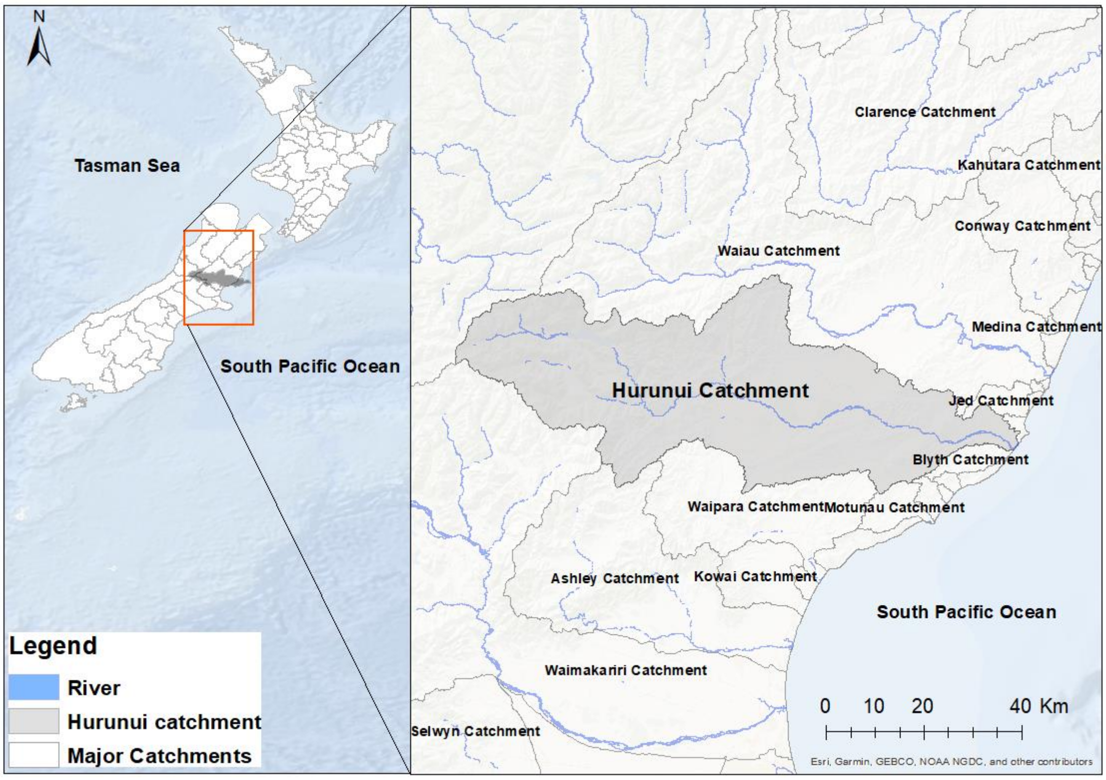


Figure 27 Hurunui catchment on New Zealand's South Island

3.3.2.2 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 data sets 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). 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 contains soil fertility/toxicity, some soil moisture properties (total plant available water and readily plant available water), topography and climate. FSL is freely accessible; 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). New Zealand Soil Classification (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, among many other things, hydraulic properties (soil moisture content at seven pressure heads including soil moisture at saturation, field capacity and permanent wilting point, plant available water), however at the time of this study S-map covers 37.1% 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 LUCI_PTFs toolbox using FAO and FSL data. We also note that in the Canterbury region where the Hurunui is located, the regional government have funded work[8] 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 this paper (Dang et al., 2022) 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. The LUCI framework (now Nature Braid - next-gen LUCI) has three options to treat multiple soil siblings, a weighted average approach, use of the most dominant sibling or random selection of a sibling (Taylor, 2018). In this case study, the weighted average approach was used to estimate a representative of individual S-map siblings in a polygon based on the sibling proportion values of each polygon. Testing the dominant sibling and random selection of sibling options was out of the scope of this study.

[8] 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).

3.3.2.3 PTFs selection

Cichota et al. (2013) tested different PTFs for New Zealand and found that the PTFs from Saxton et al. (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. (1999a) 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, three PTFs from Saxton et al. (2006), Weynants et al. (2009) and Wösten et al. (1999a) were selected 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 et al., 2018). For saturated hydraulic conductivity, the PTFs by Saxton et al. (2006) and Wösten et al. (1999a) obtained the highest correlation coefficient with the reference data (Cichota 2013). Hence, these two PTFs were tested in LUCI_PTFs toolbox.

3.3.2.4 Results and discussion - the Hurunui case study

Similar to the VMD case study, soil hydraulic properties in the Hurunui catchment were obtained from the LUCI_PTFs toolbox using different soil maps. The results demonstrate how detailed soil hydraulic properties can be derived from global soil map, general local soil map and detailed local soil map. Figure 28 presents maps of soil moisture content at -10kPa using Saxton et al. (2006) PTF with the three input data sets. 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 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 -1500 kPa (Figure 29)

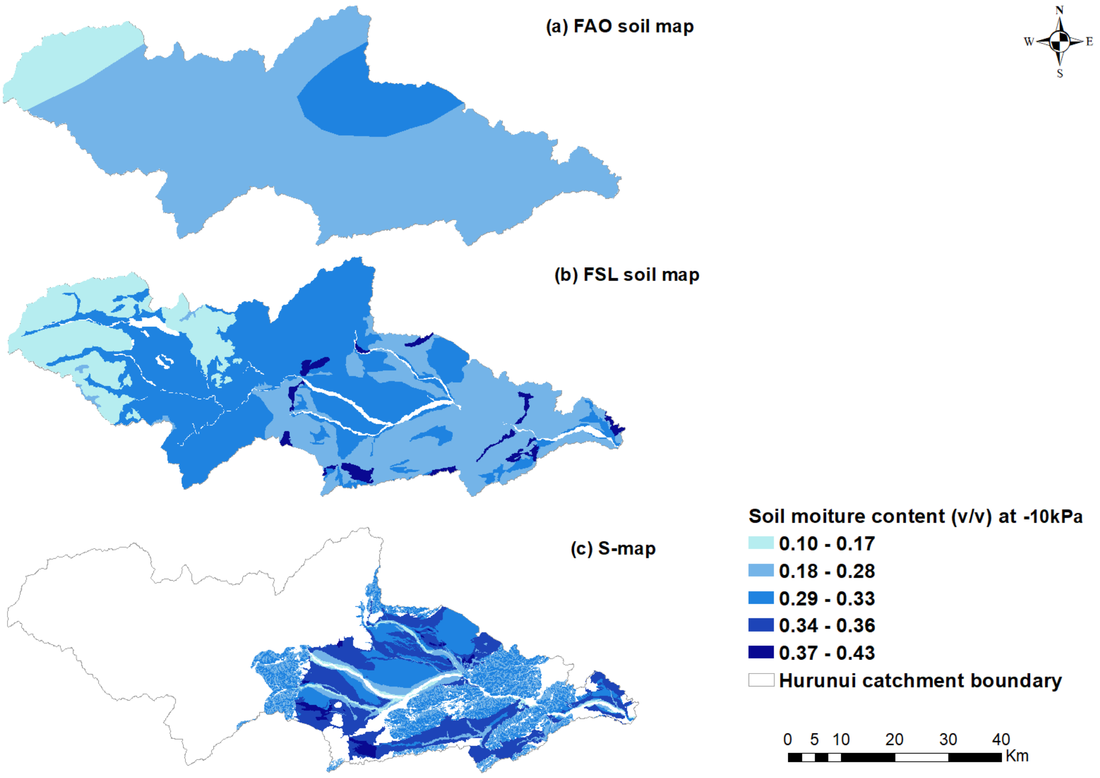


Figure 28 Soil moisture content at -10 kPa using Saxton et al. (2006) PTF; (a) FAO soil map, (b) FSL soil map, (c) S-map

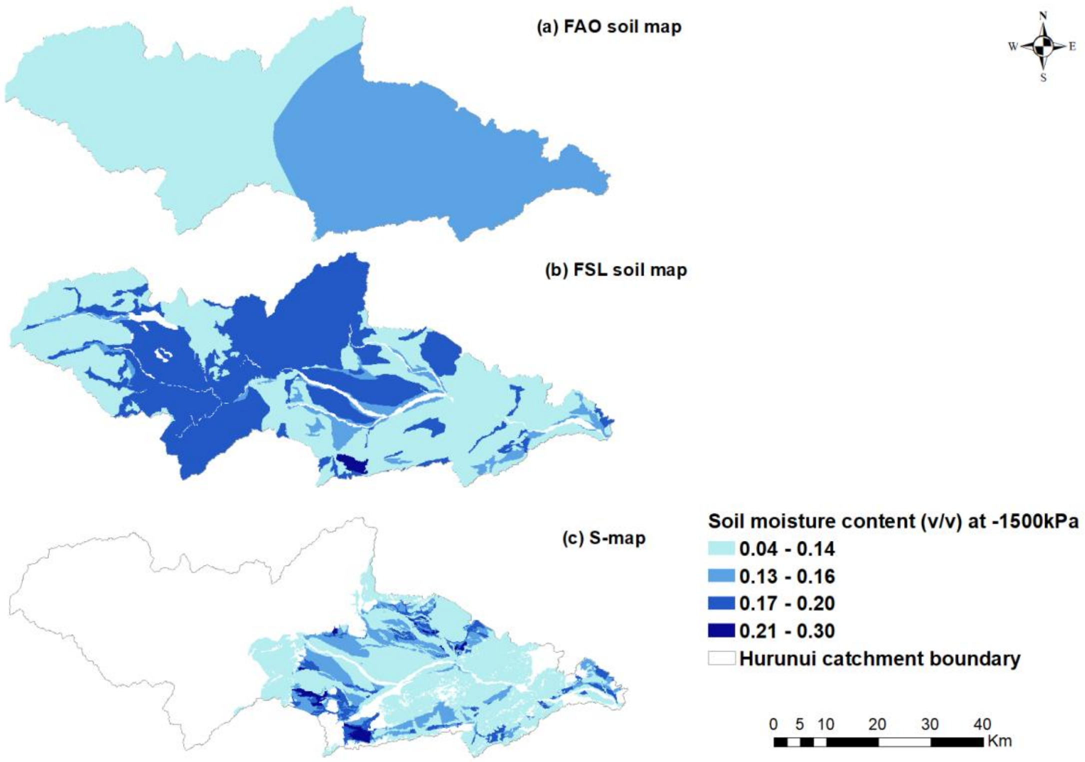


Figure 29 Soil moisture content at -1500 kPa using Saxton et al. (2006) PTF; (a) FAO soil map, (b) FSL soil map, (c) S-map

Figure 30 presents maps of K_{sat} obtained using the three data sets and Saxton and Rawls (2006) PTF. 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}).

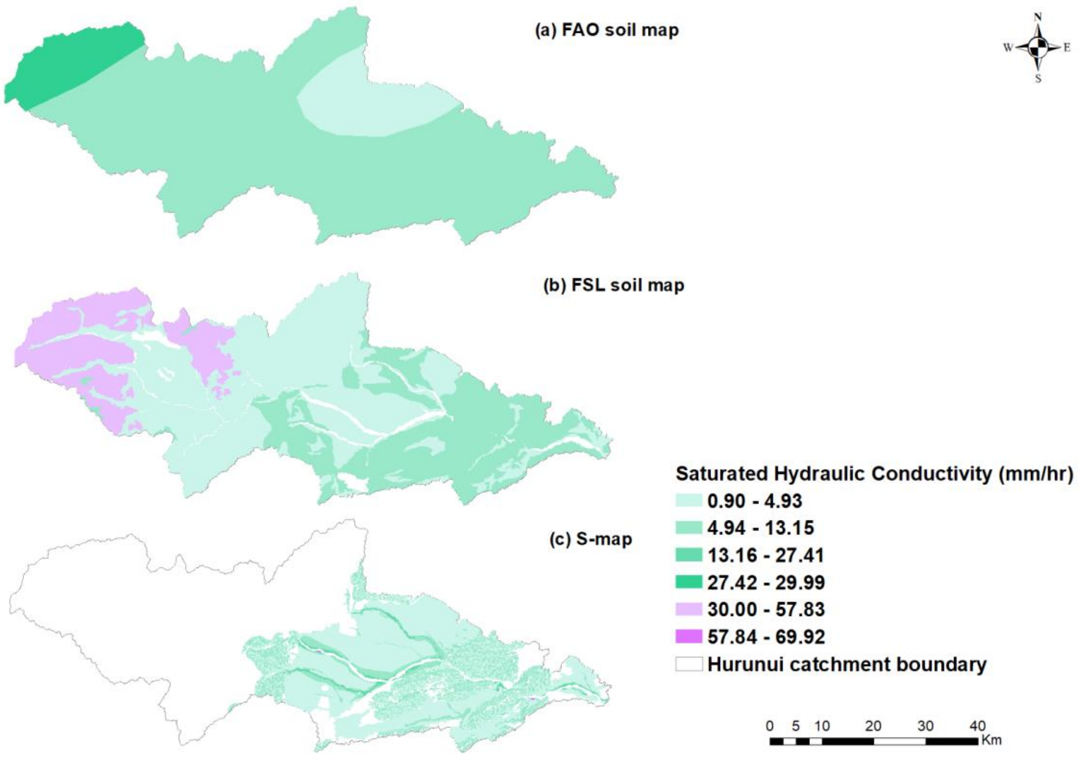


Figure 30 Maps of saturated hydraulic conductivity using Saxton et al. (2006); (a) FAO soil map, (b) FSL soil map, (c) S-map

The three datasets were also tested with the Mualem van Genuchten PTF by Wösten et al. (1999a). The K_{sat} maps are presented in Figure 31. A similar pattern can be seen between the resulting maps of FSL and S-map data (Figure 31b and Figure 31c). Value range of K_{sat} obtained using FAO data (Figure 31a) is much higher than the range obtained using FSL and S-map. Examples of van Genuchten SMRC and Mualem van Genuchten HCC using FSL map together with WISE soil database are in Figure 32.

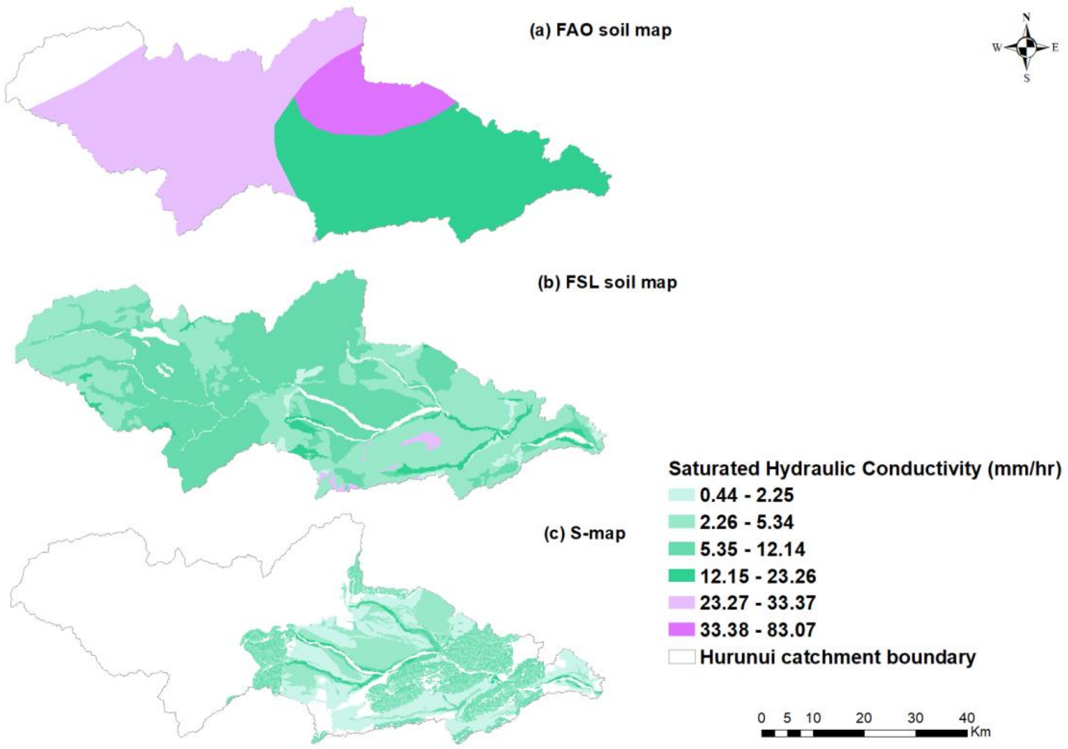


Figure 31 Maps of saturated hydraulic conductivity using Wösten et al. (1999a); (a) FAO soil map, (b) FSL soil map, (c) S-map

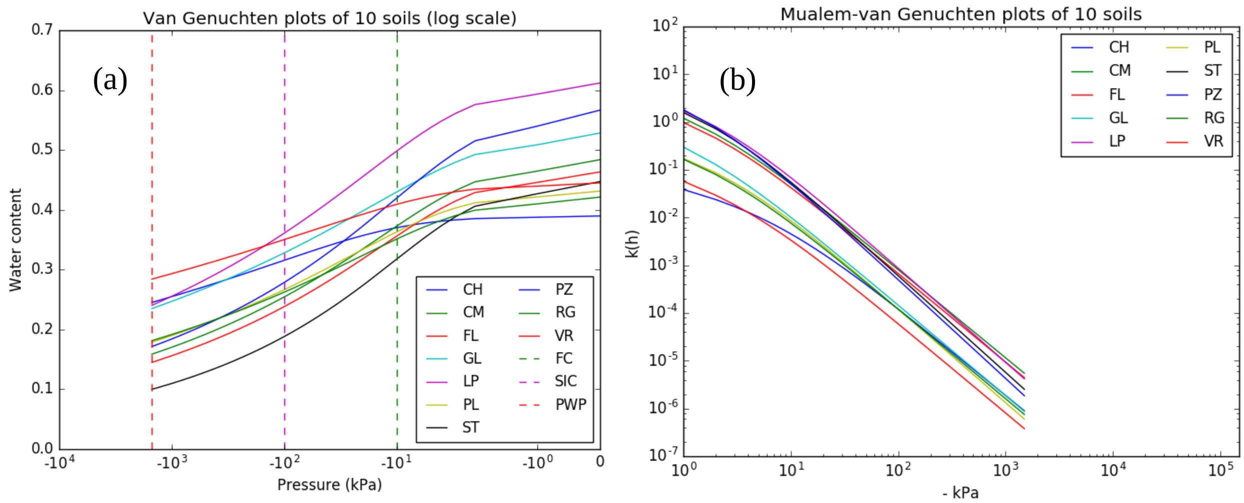


Figure 32 SMRCs (a) and HCCs (b) using FSL soil map and Wösten et al. (1999a) PTF

The soil moisture content results obtained from LUCI_PTFs tool were compared with soil moisture content information from the S-map data (Table 12 and Table 13). We see the moisture content results obtained using the PTF from Saxton et al. (2006) are closest to the S-map data at -1500 kPa. The PTFs from Weynants et al. (2009) and Wösten et al. (1999a) 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).

Table 12 Comparison of soil moisture generated via LUCI_PTFs toolbox using S-map vs weighted average of individual S-map sibling soil moisture

NZSC	WC sat (v/v) Saxton and Rawls (2006	WC sat (v/v) Wösten et al. (1999)	WC sat (v/v) Weynants et al. (2009)	WCsat (v/v) ***S-map data***	WC at -10kPa (v/v) Saxton and Rawls (2006)	WC at -10kPa (v/v) Wösten et al. (1999)	WC at -10kPa (v/v) Weynants et al. (2009)	WC at -10kPa (v/v) ***S-map data***	WC at -1500kPa (v/v) Saxton and Rawls (2006	WC at -1500kPa (v/v) Wösten et al. (1999)	WC at -1500kPa (v/v) Weynants et al. (2009)	WC at -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*
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 13 Comparison of soil moisture generated via LUCI_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)	WC sat (v/v) Wösten et al. (1999)	WC sat (v/v) Weynants et al. (2009)	WC sat (v/v) ***S-map data***	WC at -10kPa (v/v) Saxton and Rawls (2006)	WC at -10kPa (v/v) Wösten et al. (1999)	WC at -10kPa (v/v) Weynants et al. (2009))	WC at -10kPa (v/v) ***S-map data***	WC at -1500kPa (v/v) Saxton and Rawls (2006)	WC at -1500kPa (v/v) Wösten et al. (1999)	WC at -1500kPa (v/v) Weynants et al. (2009)	WC at -1500kPa (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*
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*

3.4 Conclusion

The guidelines and the associated LUCI_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'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 LUCI_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. 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 LUCI, 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 informed 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 LUCI_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.

4 Mapping multiple ecosystem services to support nature-based water resources management in the Vietnamese Mekong River Delta[9]

4.1 Introduction

Deltas, home to 4.5 % of the global population, are the most densely populated areas in the world with a general average of 478 people/km^2, eight times the lobal average (Edmonds et al., 2020). Deltas are also among the most productive and economically important global ecosystems (Day et al., 2016), providing a wide range of ecosystem services (ES). In these populated, flood-prone regions, trade-offs among agricultural production and reducing floods are at the forefront of resource management (Ikeuchi et al., 2015; van Staveren et al., 2018). Recognising the substantial ecological and socio-economic benefits of investment in natural capital, many deltas have incorporated nature-based solutions (Nbs) as part of flood risk management strategies instead of solely relying on hard infrastructures (Wesselink et al., 2015) e.g. the Mississippi delta (Day et al., 2005), the Dutch delta (van Staveren et al., 2014) and the Ganga–Brahmaputra–Meghna delta (Brammer, 2010; Rudra, 2018).

Ecosystem service assessments have been advocated as an important part of Nbs for natural flood resilience (Ronchi et al., 2019; UNDRR, 2020; Gupta et al., 2021). Among ES assessment tools, spatially explicit ES models have been demonstrated as particularly effective decision support tools (IPBES, 2016; Shoyama et al., 2017; Wood et al., 2018). Maps of multiple ES provide information on the existence and spatial heterogeneity of ES delivered by Nbs. Spatially explicit ES models, e.g. InVEST, ARIES, LUCI, possess tools/functions to facilitate ES spatial distribution mapping, scenario analysis and ES interactions analysis (trade-offs and synergies) (Sharps et al., 2017). These functions are not widely available or very accessible in discipline-specific models, such as hydrological models, ecological-environmental models, habitat distribution models, etc. In addition, ES models are often designed to be less data intensive and more accessible to non-disciplinary experts compared to discipline-specific models. However, deltas have unique biophysical characteristics that have been poorly accounted for in most ES models. Adaptions and enhancements of ES models for applications in deltas and floodplains are necessary if these models are to provide any significant value for these important parts of the world in the future.

In deltaic regions, Nbs often aim to preserve flood benefits while providing agriculture and aquaculture productivity. Suitable models for understanding these ES interactions should contain modelling tools for both flood benefits and agricultural/aquacultural productivity. Reviewing the functionality of ES models, the Land Utilisation and Capability Indicator (LUCI), rebranded as

[9] This chapter has been published as: Dang et al. (2021b)

Nature Braid – next-gen LUCI, has particular strengths in hydrology and agricultural productivity analysis (Emmett et al., 2017; La Notte et al., 2017). In LUCI, the concepts of spatial connectivity are well represented in all ES modelling algorithms which take into account the interacting effects of topography (hydrology routing), soil, water and biodiversity (Emmett et al., 2017; Trodahl et al., 2017). For example, the flood mitigation tool of LUCI performs spatially explicit topographical routing, considering the storage and permeability capacity of elements within the landscape from soil and land use data and honoring physical thresholds and mass balance constraints (Jackson et al., 2013; Jackson et al., 2016). LUCI's strengths in hydrology make it ideal for analyses of wetland ecosystem services and their interactions (Tomscha et al., 2021). To date, LUCI is the only ES model that can operate at both landscape and field/sub-field scale (5x5m grid cell) (Sharps et al., 2017; Trodahl et al., 2017), making it suitable for assisting field based flood management Nbs. Applications to date suggest that a 5x5 m DEM provides more than sufficient resolution for making decisions at the field scale (Jackson et al., 2013). LUCI has been widely used in England and Wales e.g. Jackson et al. (2013); Emmett et al. (2017); Sharps et al. (2017) and New Zealand e.g. Trodahl et al. (2017); Tomscha et al. (2019); Delpy et al. (2021); Nguyen et al. (2021); Tomscha et al. (2021). In the tropical Asia Pacific region, the model was applied to support ecosystem-based adaptation in Vanuatu (Pedersen Zari et al., 2020) and mapped multiple ES under land use change scenarios in the Cagayan de Oro catchment in the Philippines (Benavidez, 2018).

LUCI's algorithms were originally developed in temperate hill country regions. This is the first application of LUCI to a deltaic region. Located in the fluvial-to-marine transition zone, deltas have complex water flow with tidal influences and strong interactions with groundwater. Deltas also have cultivation activities adapted to seasonal flood conditions, e.g. aquaculture or mixed agriculture-aquaculture. The relationship between flooding and agriculture/aquaculture in deltas is temporally and spatially dynamic. These temporal and spatial configurations of agro-hydrological characteristics are important considerations for ES modelling in deltas. In addition, high-resolution spatially-explicit biophysical modelling for large deltaic regions remains computationally difficult (Ikeuchi et al., 2015). Exploring the application of LUCI in deltas was carried out in part to explore advantages and limitations of ES modelling in these regions, and to provide recommendations to extend the applicability of LUCI and ES modelling more generally for flat and low-lying regions.

The Vietnam Mekong Delta (VMD), the world's third largest delta, is a highly productive agricultural and aquacultural region of Vietnam (Coleman et al., 1989). Over recent decades, the VMD has witnessed extensive development of man-made water-control infrastructure, especially high dike systems in the upper part of the delta (Long Xuyen Quadrangle, Plain of Reeds and the areas between them, Figure 33) to fully protect rice fields from floods and enable intensive agriculture production (three rice crops per year) (Hung et al., 2014b). Details of the dike systems can be found in the *Study area* section. High dikes prevent flood water from connecting to the delta's floodplains. As such, traditional floodplain ecosystem services (ES) i.e., sediment trapping, water storage, water purification and provision, etc. are reduced (Hoa et al., 2008; Hung et al., 2014b; Manh et al., 2014).

Recognising the limitations of hard protection infrastructure, nature-based solutions for flood control are considered a key component of the Mekong Delta Plan (MDP, 2013). Efforts to reconnect the delta's floodplains with the Mekong River have been carried out in the upstream VMD, where significant flood mitigation features exist, including river-connected rice fields, swamps, and natural wetlands etc. (Tran et al., 2017; Tran et al., 2021). The first effective policy on Nbs in the VMD is the 8 crops in 3 years strategy (3-3-2 crop cycle) introduced by An Giang province in 2007 (Chapman et al., 2016; Tran et al., 2017). The 3-3-2 scheme means paddies in high dike systems are left fallow and fully flooded in the 9th crop cycle over three continuous years. However, the 3-3-2 scheme as well as some flood-based crop (lotus, water lilies, floating rice) demonstration projects have not succeeded to date, largely due to the lack of social and financial mechanisms to incentivise farmers' participation in Nbs (Tran et al., 2017; Tran et al., 2021). Obtaining financial and social support for Nbs in the region has been challenging, in part, because we lack the robust biophysical modelling needed to underpin the spatial planning for these efforts. Spatially explicit ES biophysical values can also facilitate spatially explicit economic value mapping (Pandeya et al., 2016). Information on ES economic value at farm scales can help farmer clearly see the benefit of flood control Nbs on their farms. Spatially explicit ES economic values are also useful for the design of financial mechanisms/instruments to encourage farmers to participate in Nbs (Barnett et al., 2016; Felardo et al., 2016).

Given the multi-pronged challenge of improving ES modelling and implementing practical solutions, the first objective of this study is to explore the use of the LUCI model to map the multiple ecosystem services (ES) as well as their synergies and trade-offs in the Vietnamese Mekong Delta (VMD). We focused on mapping flood mitigation, agriculture/aquaculture production, and climate regulation (carbon storage and sequestration) in two different years, 2010 and 2018. The year 2011 marked the completion of large-scale flood control infrastructure in the delta as well as changes in development strategies for the delta via the 'Guidelines for economic development in the VMD, 2011 - 2020' (Conclusion 28). In the process of trialling implementations of LUCI within the VMD's unique environmental conditions and data contexts in 2010 and 2018, we identify and suggest potential model enhancements to make the LUCI model more easily implementable for wider use in the VMD and/or areas with agriculture/aquaculture being an increasingly key global economic activity. The second objective is to at least somewhat account for the economic drivers which need to be considered alongside biophysical valuations for practical implementations of ES maps for Nbs in the upstream VMD by assigning economic values to different parcels using a benefits transfer approach. Nature-based solutions (Nbs) in this study are referred to as both the 3-3-2 scheme and flood-based crops. We hope the ES maps will facilitate the establishment of Nbs that ultimately contribute to the sustainable development of the VMD.

4.2 Study area

The Vietnamese Mekong Delta (VMD) is deposited from sediment transported down the Mekong river where the river meets the Vietnamese East Sea (MRC, 2016). It covers 39,000 km^2 of delta flats with an average elevation of 0.8 m and an elevation range of 0.5-5m above sea level (MDP, 2013; MRC, 2016). Before running through Vietnam, the Mekong river is divided into three branches near Phnom Penh, Cambodia: the Tonle River connected to Tonle Sap Lake (also called Great Lake with a storage capacity of 80 billion m^3, having a great influence on the hydrological regime of the whole Mekong river basin), and the Mekong and the Bassac rivers. The latter two branches then run into the VMD. The delta is affected by two tidal sources, regular semidiurnal tides (3.5.m) from the Vietnamese East Sea and irregular diurnal tides (0.8-1m) from the Gulf of Thailand (Le et al., 2007). The climate is tropical monsoonal with two seasons, the dry season from December to the end of April and the rainy season from May to November (Le et al., 2007; Hung et al., 2012). More than 90% of the rainfall generally falls in the rainy season (Tri, 2012), for example average annual rainfall during 1989 – 2017 in the VMD has been estimated as 1869 mm with only 107 mm on average falling during the dry season (Dang et al., 2020).

As with most other delta systems, the VMD possesses rich ecosystems which provide valuable goods and services. Wetlands of the Mekong Delta are among the richest ecosystems of the Mekong River basin with 1.9 million ha of freshwater river wetlands (tidal floodplains) and 1.05 million ha of saline estuarine wetlands (coastal marshes, peatland marsh, estuaries, etc.) (IUCN, 2005). The VMD also has other special types of wetlands including rice fields and aquacultural cultivation areas which deliver multiple benefits for local people, such as flood mitigation, sediment retention, carbon storage, food provision etc. (Burkhard et al., 2015; Chapman et al., 2016; Berg et al., 2017).

Due to its rich water and sediment resources, the VMD is an important agriculture and aquaculture region of Vietnam. It helps sustain the livelihoods and food security of 17 million inhabitants. Nationally, it contributes about 50% of Vietnam's rice production, 65% of aquaculture production and 70% of fruits annually (GSO, 2015). The importance of the VMD extends beyond Vietnam's boundary (Smajgl et al., 2015). VMD paddy rice area accounts for 2.5% of global paddy rice area (FAOstat, 2017b; GSO, 2017b) and total food production land in the VMD is about 0.27 % of the globe's food production land (FAOstat, 2017a; GSO, 2017a). Kondolf et al. (2018) estimated that the VMD produces around 2.4% of the global paddy rice harvest and 0.5% of the total global calorie supply.

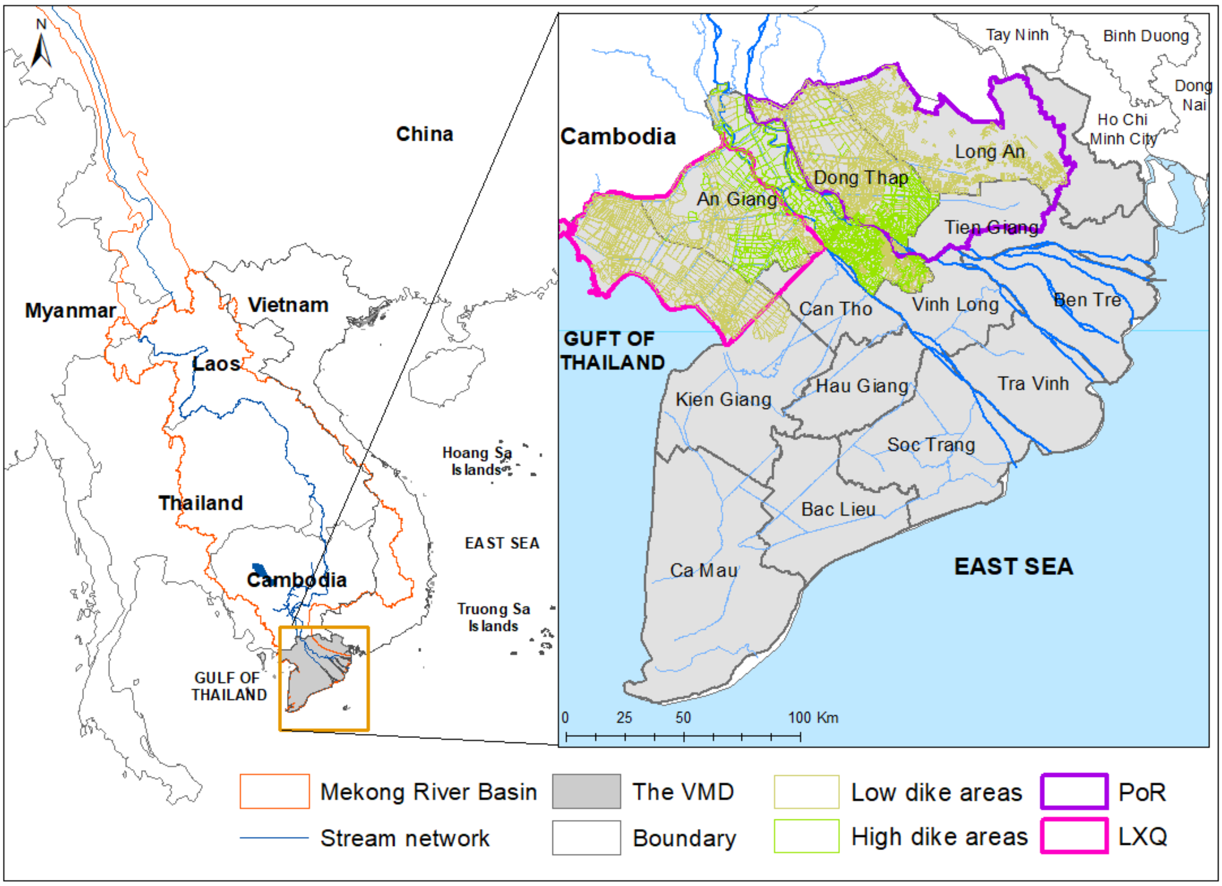


Figure 33 Location of the Vietnam Mekong Delta (VMD), Plain of Reeds (PoR) and Long Xuyen Quadrangle (LXQ)

Floods in the rainy season and salinity intrusion in the dry season are the two main challenges in the VMD (Le et al., 2009). During the rainy season (May to November), high rainfall in the Mekong river basin causes flooding in the mainstream of the Mekong river and the Mekong Delta. Inundation of one third of the delta can last up to 3 months (Hung et al., 2012). The population in the VMD has extensive experience in living with floods (Dung et al., 2011; Triet et al., 2017) and have generally adapted their lives to their presence (Le et al., 2009; Loc et al., 2016). In the dry season under the influence of tides, salinisation and the lack of fresh water in coastal areas are the problems to be addressed (Le et al., 2009). Located in the low-lying coastal zone, the tidal effects cause salinity intrusion to penetrate far inland, making salinisation intrusion worse during the dry season (Tri, 2012). Recently, effects of flood and salinity intrusion are getting worse due to upstream water usage by neighbouring countries, hydropower dam development in the upstream Mekong basin and a higher frequency of extreme weather events due to climate change. These impacts are expected to continue to increase in severity. Recent dam status updates indicate that 64 of the 187 existing and proposed hydropower dams are operating (Hecht et al., 2019). Out of these 64 dams, 18 dams are in China and the other 46 are in the Lower Mekong Basin tributaries (Hecht et al., 2019). Rising sea levels are also likely to infiltrate groundwater aquifers and increase salinity gradients in large parts of the Mekong Delta, particularly during the dry season (Smajgl et al., 2015). Within the delta, extensive groundwater extraction and sea-level rise have escalated land subsidence issues (Laura et al., 2014).

The VMD has a relatively dense and complex stream network, in part, due to its flat topography and the extent of human modification, with a huge system of navigation and irrigation channels and a sophisticated dike system. The dike system contains low dikes ("August" dikes) and high dikes. Low dikes were constructed to provide protection against flood peaks arriving around mid-July to mid-August, ensuring the farmers can double rice crop (i.e., grow two rice crops per year). Floodwater then inundates rice fields after harvesting when higher flood peaks are experienced. To maintain the country's position as one of the world's top rice exporters, the Vietnamese government instituted a policy (Resolution No. 63/NQ-CP) in 2009 to expand intensified rice farming and to purchase rice from farmers. Farmers were incentivised to increase production by shifting from two rice crops per year to three rice crops per year (Chapman et al., 2016; Tran et al., 2018). This led to the large expansion of high dike systems in the upper parts of the VMD's floodplains to facilitate the third rice crop during the flood season (Chapman et al., 2016; Tong, 2017; Tran et al., 2018). The total length of high dikes in the VMD is ~1,300 km, and the length of low dikes is ~13,300 km (Hung et al., 2014b). They are equipped with sluice gates and often additional pumping systems, which form the main linkage of floodplains with channels and main river.

4.3 Methodology

In this research, we used the LUCI model to map the spatial distribution of three ES delivered by flood management Nbs including flood mitigation, agriculture/aquaculture productivity, and climate regulation (carbon sequestration) services as well as their synergies and trade-offs across the VMD. Two approaches were used to parameterise soil and land cover information for LUCI. The first approach was coarse but enabled a rapid initial implementation, matching the VMD soils and land covers to their closest counterparts from other countries in datasets already supported by LUCI. The second approach is a user-defined parameterisation specific to the region and its available datasets, in which values for land and soil parameters were assigned based on local information and knowledge. As becomes clear later in the paper, when applying LUCI in a region where datasets have not been explicitly parameterised for use in the model, a first cut application can be made by matching regional datasets to already supported datasets. This is not recommended for final application of LUCI but can be a useful way of exploring model capacities and preliminary results for your region. Careful consideration should be given to whether the supported datasets span similar land use or soil types to those present in your region. Where they do not, direct user-specified parameterisation for at least those types dissimilar to any already supported should be immediately prioritised.

LUCI was run with these different parameterisation sets at two timeframes, 2010 and 2018. We then used the trade-offs map of flood mitigation and agriculture/aquaculture productivity to identify areas suitable for Nbs implementation. Next, we mapped ES value of Nbs by assigning economic values to the trade-offs map's parcels. Economic value was estimated using benefit transfer methods. The economic value of flood mitigation is the replacement cost of flood protection alternatives in the upstream VMD.

4.3.1 Land Utilisation and Capacity Indicator - LUCI model overview

The Land Utilisation and Capability Indicator model – LUCI is a second-generation extension and software implementation of the Polyscape framework. Descriptions of LUCI can be found in Jackson et al. (2013); Marapara (2016), Sharps et al. (2017) and Tomscha et al. (2021). LUCI is spatially explicit, respecting both the biophysical properties of individual landscape elements and their configuration when estimating ecosystem functions and services (Jackson et al., 2016). It explores the capability of a landscape to provide a variety of ES including flood mitigation, agricultural production, water quality (nitrogen and phosphorus), erosion risk and sediment delivery, carbon sequestration and habitat provision. LUCI compares the services provided by the current utilisation of the landscape to estimates of its potential capability. It then uses this information to identify areas where change might be beneficial, and where maintenance of the status might be desirable.

The flood mitigation tool takes into account spatially explicit topographical routing with connectivity and configuration details that have not previously featured in any ES services model (Jackson et al., 2013; Jackson et al., 2016; Marapara, 2016; Emmett et al., 2017; Sharps et al., 2017). LUCI uses GIS functions to calculate flow direction and flow accumulation, among other background information to support predictions. The tool then combines this information with storage and/or permeability capacity considerations based on soil and land use information to adapt mass (water, sediment, nutrients) accumulation using bespoke algorithms. Information on volumetric constraints on readily plant available water and plant available water, infiltration capacity, maximum drainage rate, and drainable water holding capacity is required (Marapara, 2016). These soil hydraulic properties are usually not readily available and costly to measure. To support LUCI users and broader hydrological applications, guidance, and an associated toolbox (LUCI_PTFs) to obtain required soil hydraulic properties in a cost-effective way were developed in Dang et al. (2022).

LUCI creates maps of ‘flood mitigating land’, which are areas with high storage and/or high permeability to mitigate floods. Flood mitigating land acts as a “sink” for fast moving overland flow and near-surface subsurface flow. Typical flood mitigating areas in the VMD are melaleuca forests, rice fields, aquaculture fields, mangroves, and other natural wetlands. In contrast, ‘mitigated land’ are the areas that receive mitigation, i.e. water originating in mitigated land later flow through mitigating areas before reaching a stream, lake or river. Finally, areas where a large amount of unmitigated flow routes directly to waterways are treated as priority areas for change, called “flood concentration” areas. The tool also calculates the average flow delivery to all points in the stream network to estimate water supply services. Parameters to define thresholds for the “corrected” flow accumulation values (soil and land use storage and/or permeability capacity) are used to categorise priority areas for targeting change (Jackson et al., 2013).

The spatially explicit hydrological routing algorithm of LUCI is valuable for the VMD. As the delta has a very dense stream network and wide floodplains, flood mitigation capacity of stream network and wide floodplains cannot be well recognised without considering spatially explicit hydrological routing. However, there are several characteristics of LUCI flood mitigation tool that do not correctly represent the flood mitigation capacity and flood regimes of the VMD. Firstly, for flood mitigation features, LUCI only focuses on the storage capacity of soil and considers waterlogged areas as not providing flood mitigation. But this is incorrect for the VMD, as the delta has large above ground flood water storage capacity in rice fields, which are frequently waterlogged. In addition, the flood tool evaluates flood mitigation potential based on physical principles of hillslope flow. The tool only considers flood water flow transfers from terrestrial environments (hillslopes, floodplains etc) to fluvial environments (streams, rivers, lakes etc). However, the VMD receives large upstream inflows annually (about 475 km^3/year for the whole Mekong Delta) (MRC, 2005), therefore the flood water flow from fluvial environments to terrestrial environments (e.g. overbank flow) is significantly important and needed to be considered in ES modelling process. It is noted that this study focused on adapting the most established parts of LUCI (ES tools) to a deltaic region. Although the LUCI framework has further relevant algorithms such as the flatwater inundation tool which accounts for overbank water flow (Ballinger et al., 2011; Benavidez, 2018), these algorithms have yet been well documented or widely applied. Implementing these algorithms for new sites and contexts requires significant developer input and time therefore overbank flows could not be included in ES modelling within the timeframe of this study.

The LUCI agricultural productivity tool evaluates potential agricultural productivity of land according to slope, fertility, aspect, and drainage. The model calculates predicted optimal agricultural utilisation based on soil type, using assigned values of fertility, waterlogging (permanent, seasonal, or negligible) and topographic data (aspect, slope and elevation). Weights can be applied to increase or decrease the importance of these parameters (Jackson et al., 2013; Emmett et al., 2017). Current agricultural utilisation is mapped according to the land cover data, ranking land use from highest productivity to lowest. Further agricultural productivity outputs consider differences between predicted productivity and "actual" productivity/land use.

Agricultural and aquacultural activities in the VMD are largely dependent on flood regimes. The LUCI agricultural productivity tool already considers the spatial interactions of hydrology routing with land and soil. These model features are key to representing the relationship between agriculture/aquaculture and floods in the VMD. However, the tool's algorithms/mechanisms related to waterlogging dependency were developed for farming systems in temperate regions, and it considers waterlogged areas as not suitable for agricultural production. However, this principle is not correct for the farming systems in the VMD as well as other deltas where important crops are mostly waterlogged crops that can provide high productivity, e.g. rice, aquaculture, lotus, etc. Therefore, to provide useful ES maps for the VMD, water-logging relevant parameters were taken outside of their physically realistic settings for hilly temperate regions to represent productivity as well as flood mitigation capacity of waterlogged crops.

The carbon sequestration tool of LUCI is based on Tier I and Tier II of the IPCC to calculate carbon levels at steady state. In this study, the Tier II approach was used. Values of carbon pools (above-ground carbon, below-ground carbon, deadwood carbon, litter carbon and organic carbon) were assigned based on land-use/land-cover and soil. The total values for biomass carbon and soil carbon were then fed into the model to identify areas with significant carbon stocks which should be protected, and areas where there is potential for sequestration. Carbon stock is estimated at pseudo steady state assuming that the land management regime is fully established, and soil and biomass carbon are no longer in flux. Carbon sequestration is estimated by comparing the potential/expected carbon stock at equilibrium and the current carbon storage. It is assumed that any change in carbon storage in soils follows land use change (Jackson et al., 2013).

LUCI has a unique built-in trade-off tool to identify locations where multiple services might benefit from interventions, or where there may be a trade-off with one service benefitting from interventions while another is reduced (Sharps et al., 2017). This study includes analysis of a trade-offs and synergies map of flood mitigation and agricultural/aquacultural productivity obtained from LUCI to examine areas where both flood mitigation potential and agricultural/aquacultural productivity potential exists. This information is then used to identify areas suitable for developing flood-based crops and prioritise Nbs implementation.

4.3.2 Data and materials

The input data for this study together with their sources are presented in Table 14. Data scarcity is a big obstacle of ES modelling, especially in Asia and Southeast Asia regions (Shoyama et al., 2017; Dang et al., 2021a). Besides the 5m DEM, the 30m SRTM DEM was used to investigate the capability of an open-access dataset with moderate resolution for ES modelling in the VMD, a data sparse region. The land use/land cover (LULC) map of 2010 and 2018 contained detailed LULC classes, e.g. rice fields with detailed crops rotation and aquacultural lands with specific crop types. Detailed land use/land cover classes are needed to represent the spatial heterogeneity of their multiple ES. A stream network was used to generate a hydrologically and topographically consistent DEM which is important to improve the accuracy of flow routing. Global gridded annual rainfall and potential evapotranspiration data were renormalised using hourly rainfall and potential evapotranspiration data obtained from ERA5 (at Tan Chau station location). Ideally, hourly climate data should be collected from local hydro-meteorological stations. However, local hydro-meteorological stations in the VMD only collect hourly rainfall data, not hourly potential evapotranspiration. In addition to the spatial data, information of soil and land evaluation are obtained from previous land and soil evaluation research conducted in the VMD (Tri et al., 2003; Vu et al., 2009; Vu et al., 2011; Khoa et al., 2013; Vu et al., 2013; Vu et al., 2014b; Vu et al., 2016; Vu et al., 2017; Du et al., 2018). This information is essential to understand soil and land characteristics in the VMD. Inundation maps obtained from the study on "Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta" by Le et al. (2018) and agriculture/aquaculture production statistics of the VMD were used to validate the results of flood mitigation and agriculture/aquaculture productivity maps.

Table 14 Data and data source

Required Data		**Data type**	**Data source**
DEM	5m DEM	Raster	The Ministry of Natural Resources and Environment, Vietnam
	30m SRTM DEM		United States Geological Survey (USGS)
Land-use/land-cover	LULC map 2010	Vector Polygon	Water Source University of Vietnam
	LULC map 2018		The National Institute of Agricultural Planning and Projection, Vietnam
Soil map		Vector Polygon	University of Dong Thap (WISDOM project)
Study area mask		Vector Polygon	Ministry of Natural Resources and Environment, Vietnam

Required Data	Data type	Data source
Stream network	Vector Polyline	Ministry of Natural Resources and Environment, Vietnam
Gridded annual rainfall (mm/year) 1km	Raster	Worldclim.org
Gridded annual potential evapotranspiration (mm/year) 1km	Raster	Worldclim.org
Hourly rainfall data of Tan Chau station	Tabulate	An Giang Hydro-Meteorological Station
Hourly rainfall data of Tan Chau station	Raster	ERA5 hourly data on single levels from 1979 to present
Hourly potential evapotranspiration of Tan Chau station	Raster	ERA5 hourly data on single levels from 1979 to present
Soil properties (sand, silt, clay, bulk density, organic carbon/organic matter, pH, CEC, ECE etc.)		WISE- the global soil properties databases
Inundation maps 2000 - 2013	Vector	Obtained from Le et al. (2018)
Agriculture and aquaculture production statistics 2010 - 2012 of the VMD's 13 provinces	Tabulate	General Statistics Office of Vietnam

4.3.3 Parameterising LUCI for mapping biophysical value of ES in the VMD

As discussed above, LUCI assumes some characteristics and mechanisms around flooding and soil waterlogging that are not directly applicable to the VMD. To obtain useful results for the VMD, we removed the water logging dependency and raised the productivity and flood mitigation values associated with waterlogged crops. We took two separate approaches to parameterising the soil and land cover information, in the first instance through matching VMD soils and land covers to their closest counterparts in already supported datasets from other countries, and through user-defined functions.

4.3.3.1 Matching VMD soil and LULC datasets to supported/already parameterised datasets

The aim of cross-referencing classes in new datasets to their closest matches in already-supported datasets provides a way to explore LUCI capacities and preliminary results for regions where limited information to support parameterisation is readily available. This step was done while collating information and data for establishing user-defined parameterisation for the VMD in the next section. As articulated in the first paragraph of section 4.3 and also in Dang et al. (2021b) "This is not recommended for final application of LUCI but can be a useful way of exploring model capacities and preliminary results for your region. Careful consideration should be given to whether the supported datasets span similar land use or soil types to those present in your region. Where they do not, direct user-specified parameterisation for at least those types dissimilar to any already supported should be immediately prioritised". Among available LULC and soil products, the New Zealand Land Cover Databasev2.0 (NZ LCDB2) land use data and NZ's Fundamental Soils Layer (FSL) soil data were selected to represent the VMD LULC classes and soil classes. The NZ LCDB 2 has more detailed LULC classes, especially with respect to wetlands, compared to other supported products. NZ's FSL soil data is also more readily available than other soil data. Detailed LULC and soil descriptions make it easier to match the VMD's LULC and soil classes to their closest counterparts from other countries. However, matching the VMD LULC classes with the available land databases is not very satisfactory in some VMD areas as none of the LULC datasets supported in LUCI to date have any classes similar to rice or agriculturally/aquaculturally productive wetlands in the VMD. Despite this shortcoming, details of the two preliminary crude matches (which we call link-code 1 and link-code 2) are presented in Table 15.

Table 15 Preliminary exploration of rice and aquacultural LULC classes using LCDB2 table

Land table	The VMD LULC classes	LCBD2
Link-code 1	"triple rice"	"short-rotation cropland"
	"double rice" and the "single rice"	"herbaceous freshwater vegetation"
	Aquacultural LULC classes (rice-shrimp, shrimp, mangrove-shrimp)	"pond and lake"
Link-code 1	"triple rice"	"short-rotation cropland"
	"double rice" and the "single rice"	"herbaceous freshwater vegetation"
	Aquacultural LULC classes (rice-shrimp, shrimp, mangrove-shrimp)	"herbaceous freshwater vegetation"

4.3.3.2 User-defined parameterisation

For the user-defined parameterisation, specific land and soil characteristics of the VMD can be brought into the modelling process. For the three selected ES, the required information for each of the LULC classes are: flood mitigating ability, agricultural/aquacultural productivity, and carbon pools' stock. Flood mitigating ability and agricultural/aquacultural productivity were defined based on the local knowledge of the study area and land evaluation research conducted in the VMD (Sys et al., 1991b, 1991a; van Mensvoort et al., 1993; Tri et al., 2003; Vu et al., 2009; Vu et al., 2011; Khoa et al., 2013; Vu et al., 2013; Vu et al., 2014b; Vu et al., 2016; Vu et al., 2017; Du et al., 2018). Given high productivity and flood mitigating capacity of the VMD's wetlands, the waterlogged dependency of LUCI's flood mitigation and agricultural productivity tools were altered to raise the flood mitigating and productivity values associated with waterlogged crops of the VMD, e.g. rice and aquaculture (rice-shrimp, shrimp, mangrove-shrimp classes). By doing this we partially take into account the flood mitigation capacity and agriculture/aquaculture productivity of wetlands and waterlogged crops in the VMD, however the flooding environment and processes, i.e. overbank floods, tides and groundwater influences, above-ground floodwater storage capacity, need further work to represent. Storage values of carbon pools were collected from carbon monitoring and estimation research conducted in the VMD. If the value could not be found in the VMD's studies, values of carbon pool of a similar LULC was collected from other studies in Vietnam or the guidance of global parameters from the IPCC (2006).

As for soil data, specific values of drainage ability, plant available water (PAW) and fertility were identified for the VMD soil classes. Information on organic carbon (OC)/organic matter (OM) was used to define soil fertility. For the VMD case study, we define soil with more than 4% of OC as the most fertile soil and the soil with less than 1% of OC as the least fertile soil. Drainage was represented by the soil's saturated hydraulic conductivity. Soil with higher saturated hydraulic conductivity had higher drainage. Information on soil hydraulic parameters were obtained using the guidance and an associated toolbox (LUCI_PTFs) provided by Dang et al. (2022) . We developed three sets (Set 1, Set 2 and Set 3) of land and soil tables to understand how different model parameterisations produced different outcomes. The details of each land and soil table are presented in Table 16. Details of the land and soil parameterisations are in Table 17 and Table 18 respectively.

Table 16 Three sets of soil and land tables for the user-defined parameterisation

Set	Description
Set 1	Both soil and land tables were set following the instruction of "LUCI Factors Help Documentation" (LUCI team, 2019). - Land table: aquacultural areas were assumed to have no productivity like other water classes. - Soil table: the waterlogged nature of the VMD soil classes was set but led to LUCI not recognising such soils can still have high agricultural value and flood mitigation capacity.
Set 2	Soil table was set following the instruction of "LUCI Factors Help Documentation" (LUCI team, 2019). However, in the land table, productivity of aquacultural areas did not follow the instructions. - Land table: aquacultural areas were assigned as high productivity areas - Soil table: the waterlogged nature of the VMD soil classes was set but led to LUCI not recognising such soils can still have high agricultural value and flood mitigation capacity.
Set 3	Altering the general parameterisation guidance for some parameters of both soil and land tables to help LUCI recognises flood mitigation capacity and productivity of waterlogged crops. - Land table: aquacultural areas were assigned as high productivity areas - Soil table: the flood mitigating, and productivity values associated with waterlogged crops were risen so LUCI can recognise agricultural/aquacultural value and flood mitigation capacity of soils in waterlogged conditions

Table 17 Land parameterisations for the Vietnamese Mekong Delta application

LULC Class	PFLOOD	PAGCLASS SET 1	PAGCLASS SET 2	PAGCLASS SET 3	CARBONABIO	CARBONBBIO	CARBONDEAD	CARBONLIT	SOILOC
Single Rice	2	2	2	2	4	1	0	0.6	20.05
Double Rice	2	1	1	1	6.67	1.1	0	0.6	20.05
Triple Rice	2	1	1	1	9.96	1.3	0	0.6	20.05
Rice-Shrimp	2	1	1	1	4	1	0	0.6	20.05
River	3	6	3	3	0	0	0	0	0
Melaleuca Forest	2	5	4	5	56.25	13.04	4	1.1	104.29
Orchard farm	2	2	2	1	39.78	2.68	0	0.6	64.2
Shrimp	2	6	1	1	0	0	0	0	0
Residential area	1	7	7	7	0	0	0	0	12.55
Ornamental plant garden	1	5	5	5	4	1	0	0.6	12.55
Sugarcane	2	2	2	2	4	1	0	0.6	12.55
Pineapple	2	2	2	2	4	1	0	0.6	12.55
Vegetable	2	2	2	2	4	1	0	0.6	12.55
Mangrove	2	5	3	3	125.8	32.92	3.4	0	691.35
Mangrove - Shrimp	2	5	2	2	125.8	32.92	3.4	0	691.35
Broad leaves forest	2	5	5	5	107.7	15.1	4	1.1	75.54
Salt	2	5	4	5	0	0	0	0	0
Rice-Vegetable	2	1	1	1	6.67	1.1	0	0.6	20.05
Lake and pond	3	6	3	3	0	0	0	0	0

PFLOOD: permeability/mitigating ability (value: 1-3); PAGCLASS: agricultural/aquacultural productivity (value: 1-7); CARBONBBIO (tonne/ha): Below-ground carbon; CARBONDEAD (tonne/ha): Deadwood carbon; CARBONLIT (tonne/ha): Litter carbon; SOILOC (tonne/ha): Soil carbon. Detailed instructions are in the "LUCI Factors Help Documentation" (LUCI team, 2019).

Table 18 Soil parameterisations for the Vietnamese Mekong Delta application

SOILTYPE	LUCI_WLOG SET 1	LUCI_WLOG SET 2	LUCI_WLOG SET 3	LUCI_FERT	PAW
Alluvial Soils with Yellow-red mottles	2	2	1	1	150.90
Deposited Alluvial Soils	2	2	1	1	144.85
Eroded Soils	2	2	2	4	11.85
Gleyic Alluvial Soils	2	2	1	2	119.34

SOILTYPE	LUCI_WLOG SET 1	LUCI_WLOG SET 2	LUCI_WLOG SET 3	LUCI_FERT	PAW
Grey Soils on acid-macmartic rock & sandy stones	1	1	1	4	163.17
Grey Soils on old Alluvium	2	2	1	3	169.01
Humic Grey Soils on old Alluvium	2	2	1	2	155.09
Undeposited Alluvial Soils	2	2	1	1	131.44
Saline Mangrove soils	3	3	1	3	134.40
Moderately Saline Soils	2	2	1	3	151.04
Peaty Acid Sulphate Soils	2	2	3	1	39.28
Saline - Acid Sulphate Soils - Sulfidic horizon: 0 - 50 cm	3	3	1	2	186.23
Saline - Potential Acid Sulphate Soils - Sulfidic material: 0 - 50 cm	3	3	1	2	186.23
Saline - Acid Sulphate Soils - Sulfidic horizon: > 50 cm	3	3	1	2	186.23
Saline - Potential Acid Sulphate Soils - Sulfidic material: > 50 cm	3	3	1	2	186.23
Raised ridges sandy soils	1	1	1	4	78.19
Actual Acid Sulphate Soils - Sulfidic horizon: 0 - 50 cm	2	2	1	2	186.23
Potential Acid Sulphate Mangrove Soils - Sulfidic material: 0 - 50 cm	3	3	1	2	186.23
Potential Acid Sulphate Soils - Sulfidic material: 0 - 50 cm	2	2	1	2	186.23
Strongly Saline Soils	2	2	1	4	134.40
Actual Acid Sulphate Soils - Sulfidic horizon: > 50 cm	2	2	1	2	37.60
Potential Acid Sulphate Mangrove Soils - Sulfidic material: > 50 cm	3	3	1	2	186.23
Potential Acid Sulphate Soils - Sulfidic material: > 50 cm	2	2	1	2	186.23
Slightly Saline Soils	2	2	2	3	134.40
Yellow-red Soils on acid macmartic rocks	1	1	1	4	167.12

LUCI_WLOG: Drainage ability (value: 1-3), - LUCI_FERT: soil fertility (value: 1-5); PAW: plant available water (mm). Detailed instructions are in the “LUCI Factors Help Documentation” (LUCI team, 2019).

4.3.4 Mapping economic values of flood-based crops in upper stream of the VMD

The first step in mapping the economic value of flood-based crops is identifying areas that are most suitable for flood-based crops. Trade-offs and synergies map of flood mitigation and agricultural/aquacultural productivity obtained from LUCI presents areas where both flood mitigation and agricultural/aquacultural productivity exist. These areas are mapped into two classes “excellent service provision” and “moderate service provision” in LUCI’s trade-offs and synergies map. Flood protection infrastructures are important to ensure the safety of crops and people when growing flood-based crops in flood season. Therefore, the most suitable areas to implement flood-based crops in the VMD should be the "excellent service provision" and "moderate service provision" locations within dike rings. Using ES modelling results to map ES economic values results in greater spatial heterogeneity and precision of ES economic value maps, than obtained from commonly used land use/land cover-based proxy methods.

After identifying the most suitable areas for flood-based crops, economic valuations were placed on these areas using simple benefit transfer methods, transferring the value estimated from previous research to our study. Replacement cost methods are widely used to estimate economic value of flood regulation service (IUCN, 1999). In this approach, the cost for planned flood control alternatives (low dike and high dike management cost) is assigned as the economic value of flood mitigation service. The management cost of low dike and high dike were estimated at USD 2,345.7/ha for high dikes and USD 118/ha for low dikes by Tran et al. (2019). We apply this value in our study as the economic value of flood mitigation service in the upstream VMD. We assume that the management cost is the minimum compensation that should be paid to farmers for implementing flood-based crops in the upstream of the VMD. These values were then placed on the flood mitigation and agriculture/aquaculture production trade-off and synergy map to produce an economic value map. Each cell then has the economic value based on its capacity to provide synergies of flood mitigation and agriculture/aquaculture productivity. We assume that the "moderate service provision" areas can provide 80% function of "excellent service provision" areas. The weight equal to 1 and 0.8 were applied when estimating economic value for the "excellent service provision" and the "moderate service provision" areas respectively. A map of the ES economic value based on only the dike system was also developed to compare with the map that was developed using ES modelling results. The comparison demonstrates how ES modelling can improve ES economic value mapping.

A proposed ecosystem service-based framework to support Nbs implementation in the VMD is presented in Figure 34. This framework was adapted from the framework of ecosystem services-based approach for decision making by Daily et al. (2009) and the circle for PES implementation by Marino and Pellegrino (2018). In this framework, ecosystem service modelling plays an important role in providing information of ecosystem service and support economic evaluation of ES. ES values are then used in payment for ecosystem services scheme which compensates farmers who implement nature-based alternatives by letting their rice fields flood during flood season.

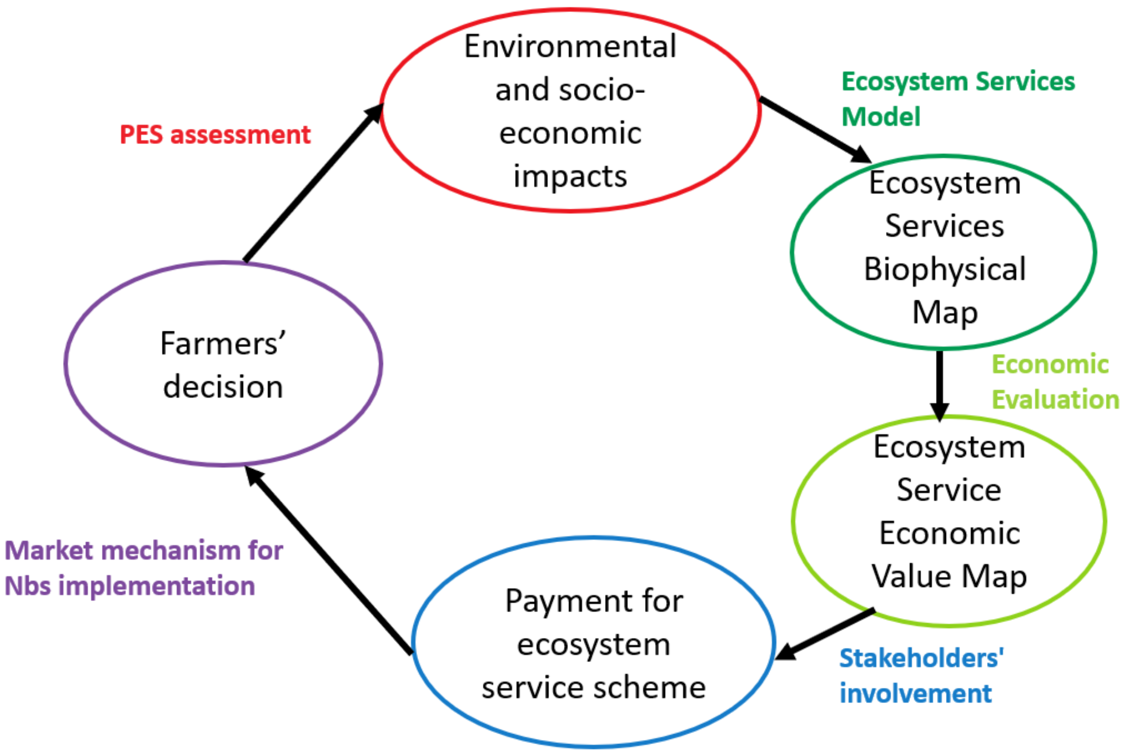


Figure 34 Ecosystem services-based framework to support floodplain restoration in VMD

Adapted from Daily et al. (2009) and Marino et al. (2018)

4.4 Results and Discussions

4.4.1 Ecosystem services biophysical mapping

LUCI was run with different input data combinations and model parameterisations to explore the applicability of the model to map flood mitigation, agriculture/aquaculture production, and carbon sequestration in the VMD. The modelling computation time for this study was accomplished in ~ 1,500 computer hours. For each ES of a single run, ~ 1500 million elements were computed. No such fine resolution ES modelling has been previously conducted in the VMD.

Maps of flood mitigation services, agriculture/aquaculture and carbon sequestration are presented in Figure 35, Figure 36, and Figure 37 respectively. LUCI delineates existing flood mitigation features of the VMD including rice fields, aquacultural areas, mangroves, and other wetlands. These areas are shown as flooding mitigation land in green colour (Figure 35). High flood concentration areas in red and moderate flood concentration areas in orange (Figure 35) are the areas with non-mitigated features. These areas could be modified to improve water holding capacity. Areas highlighted as having negligible flood concentration have local characteristics which promote flooding but have been protected by upstream and/or uphill mitigating soil and LULC combinations.

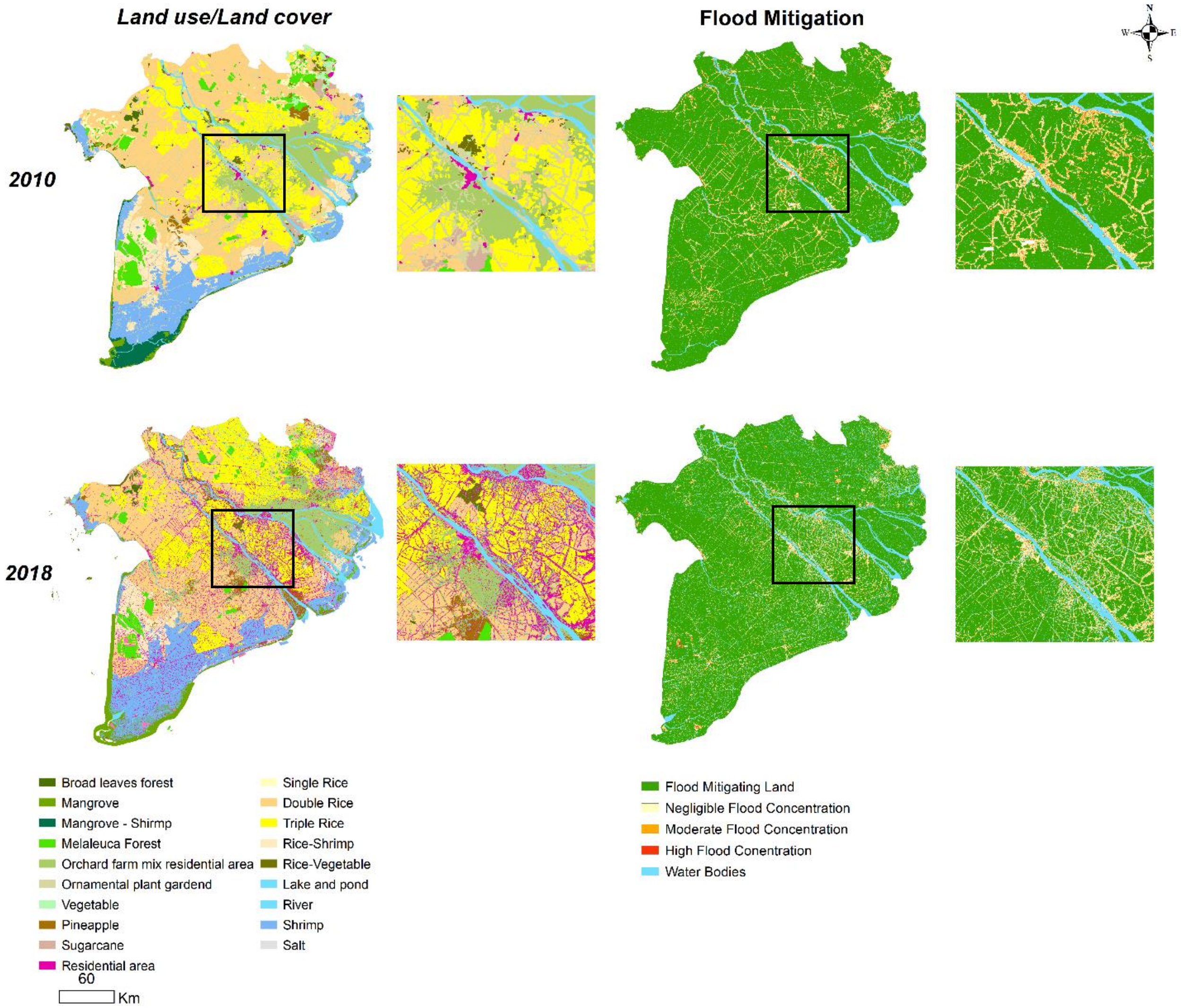


Figure 35 Flood mitigation service maps

Figure 36 presents agriculture/aquaculture productivity maps obtained using the three sets of land and soil tables described in the methodology. When using Set 1, productivity of aquacultural areas cannot be mapped properly. All aquacultural areas are shown in red (Figure 36, Agriculture Productivity – Set 1). Areas with high ES provision (optimum utilisation) are in dark green. Moderate ES provision areas including near optimum utilisation and non-optimum utilisation are in light green and orange respectively. Using Set 2 (productivity value of agricultural land was raised), productivity of aquacultural areas is better recognised than using Set 1 but not fully represented (Figure 36 Agriculture/Aquaculture Productivity – Set 2). In Set 3, the productivity value of agricultural land was also raised and additionally the waterlogging dependency in LUCI was taken out for ES modelling in the VMD. Using Set 3, productivity of typical agriculture/aquaculture lands of the VMD was much better represented compared to the previous sets (Agriculture/Aquaculture Productivity – Set 3).

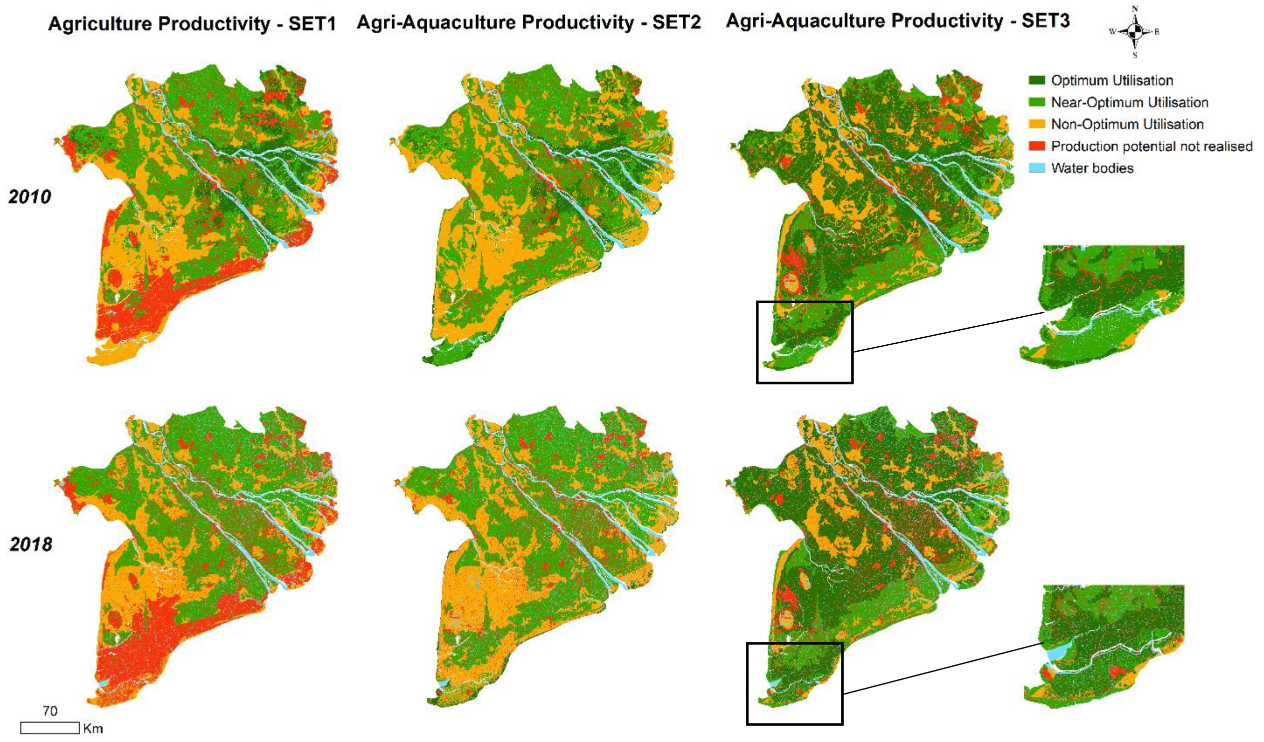


Figure 36 Agricultural and aquacultural productivity maps (Agri-aquaculture is referred to as agriculture and/or aquaculture)

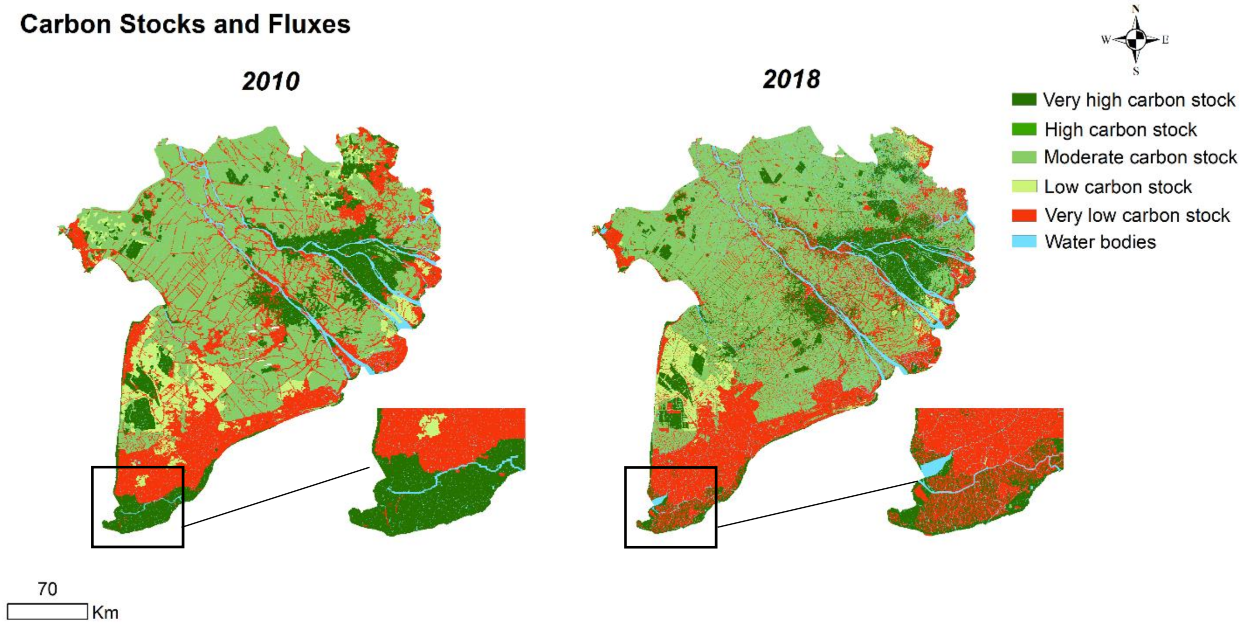


Figure 37 Carbon sequestration maps

In the carbon sequestration maps (Figure 37), the dark green areas have very high carbon stock (≥ 90 tonnes C/ha). These areas are broad leaves forest, melaleuca forest, mangrove forest and orchards. Areas with high carbon stock (50-90 tonnes C/ha) and moderate carbon stock (27-50 tonnes C/ha) are triple rice fields, double rice – vegetable, other crops and other wetlands. Rice-shrimp land has low carbon stock (21 – 217 tonnes C/ha) and aquacultural land has very low carbon stock.

Although “Shrimp” areas are waterlogged soils, their immediate potential carbon sequestration is low because topsoil to ~ 30-50 cm has been removed to build shrimp ponds (Järviö et al., 2018). In addition, plastic cover is usually placed over shrimp ponds (Do et al., 2022). As a result, carbon sequestration potential of shrimp pond is negligible.

Modelling carbon sequestration for the VMD is advantageous because there is a large amount of research on carbon stock measurements/estimations conducted in the VMD to date. These are the valuable sources of information to create carbon tables for mapping carbon sequestration service.

Figure 35, Figure 36, and Figure 37 also show the change in ES between 2010 and 2018. 2011 marks the completion of large-scale high dike systems and important water-control systems in the VMD, especially the Vam Nao project to connect Bassac River and Mekong River (Le et al., 2018). The year of 2011 also marks the change in economic development strategies of the delta. The Resolution 21 - policy guidelines for economic development in the VMD (2001 – 2010) is updated in 2011 by the Conclusion 28 - policy guidelines for economic development in the VMD (2011 – 2020) (Nguyen et al., 2020). ES maps of 2010 and 2018, therefore, can give the information on the influences of flood protection infrastructure and economic development policies on ES in the VMD. However, the comparison between ES maps between 2010 – 2018 only gives the relative trend of ES change during the study period, not the exact change in areas, as the LULC maps of 2010 and 2018 are different in source of origin and resolution.

A clear decrease in flood mitigation services can be seen in the riparian areas between the Mekong River and the Bassac River (area within black square, Figure 35). This reduction in mitigating land could be due to the development of dike system in the upstream and urban expansion in the riparian areas. Through 2010 – 2018, agriculture/aquaculture productivity for the VMD increased mostly in the southern part of the delta, Ca Mau province (area in black square, Figure 36). In the recent years, large areas of mangroves in the province have been converted to aquaculture. However, the development of aquaculture has led to reduction in carbon stocks in this area (Figure 37, Carbon stocks and flux).

The flood mitigation map produced by LUCI using the 2010 data was compared with an inundation map 2010 of the VMD. Similarly, the agriculture productivity map of 2010 was compared with the VMD agriculture/aquaculture production statistics at the district level (2010). The results demonstrate that LUCI provided reasonable information on spatial heterogeneity of flood mitigation and agriculture/aquaculture productivity in the VMD. As for carbon sequestration, all local carbon measurements/estimations available were used to develop the carbon table for the modelling process. There is no other source of information that can be used to compare with our carbon sequestration map. Field visits are ideal to validate the modelling results however we could not carry out field visits due to Covid-19 travel restrictions during the time conducting this study.

Maps of trade-offs and synergies between flood mitigation and agricultural/aquacultural productivity provide information on areas where both flood mitigation and agricultural/aquacultural productivity exist. Those areas that have excellent service provision and moderate service provision should be preserved to assure the co-existence of flood mitigation and agricultural/aqua cultural productivity in the VMD (Figure 38). The excellent service provision and moderate service provision within dike systems are the most and second most suitable areas to implement flood-based crops.

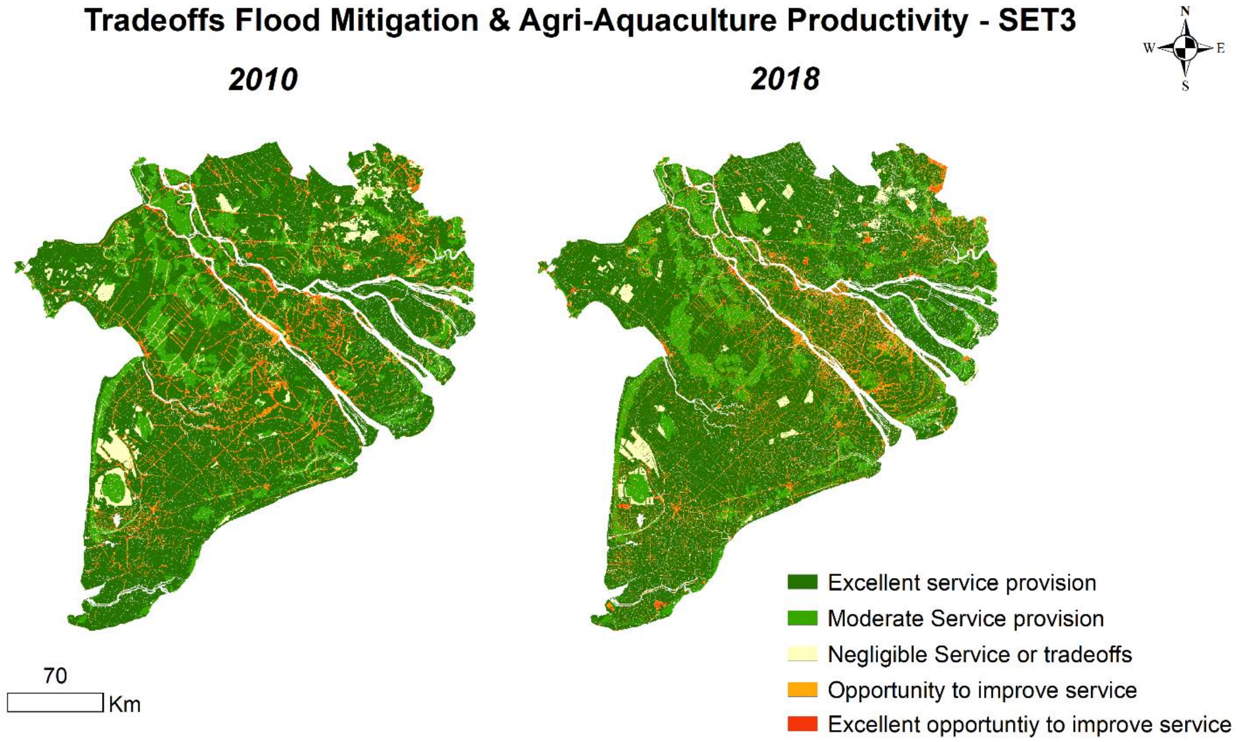


Figure 38 Trade-offs and synergies between flood mitigation and agricultural/aquacultural productivity

The preliminary exploration provided information on the suitability of the model in the VMD context. Flood mitigation services of “double rice” and “single rice” classes were partially acknowledged in the LUCI outputs (Figure 39). However, the coastal rice-shrimp areas and other aquacultural areas were considered to be water bodies, so LUCI did not identify any flood mitigation (or agriculture productivity) values in these places. Furthermore, the differing capabilities of alternate rice cropping systems to differently mitigate floods is not fully represented (Figure 39).

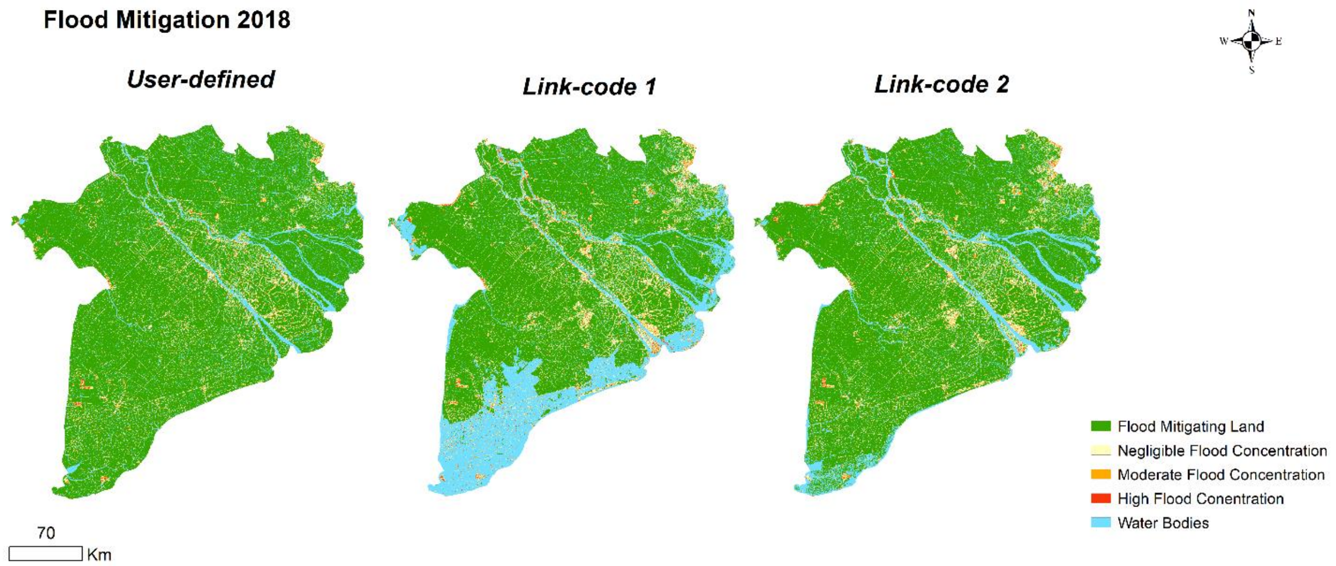


Figure 39 Maps of flood mitigation service using the crude matching

As Figure 40 shows, productivity of the VMD orchards is also not well recognised using either preliminary parameterisation due to the differences in fruit species as well as their annual growth cycles between Vietnam and NZ. Productivity of mangroves cannot be highlighted as well because NZ does not have integrated mangrove-aquaculture like the VMD. The differences in vegetation types and crops of Vietnam and New Zealand also led to poor carbon stock mapping using the crude matching. Carbon sequestration of rice fields, mangroves and other wetlands were mapped with very low carbon stock (Figure 41).

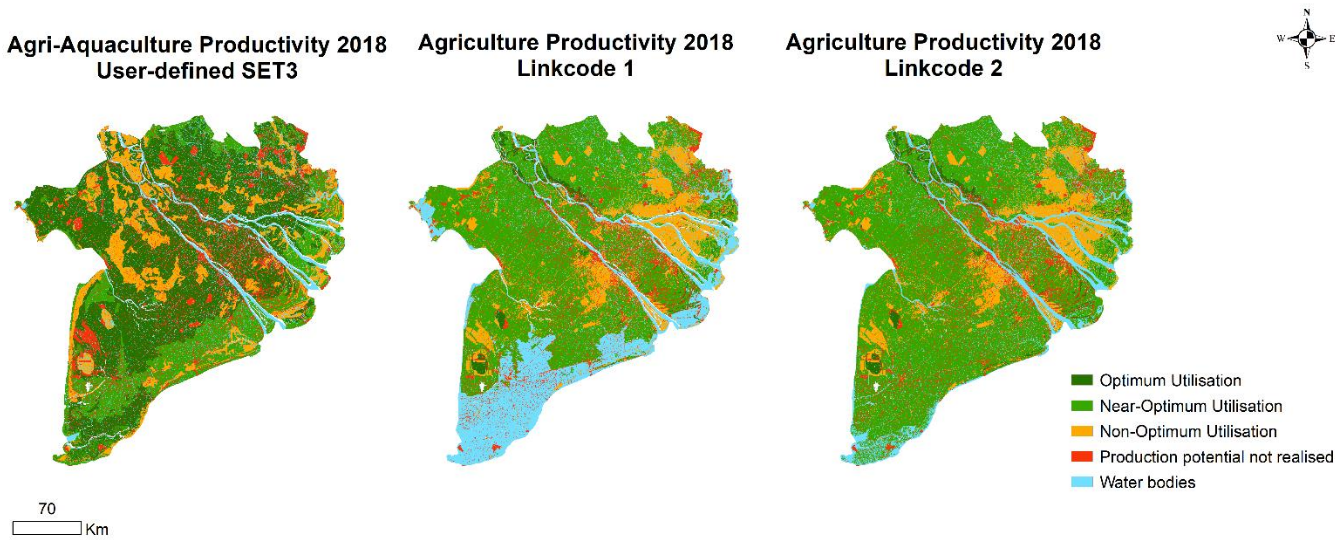


Figure 40 Maps of agricultural/aquacultural productivity using the crude matching

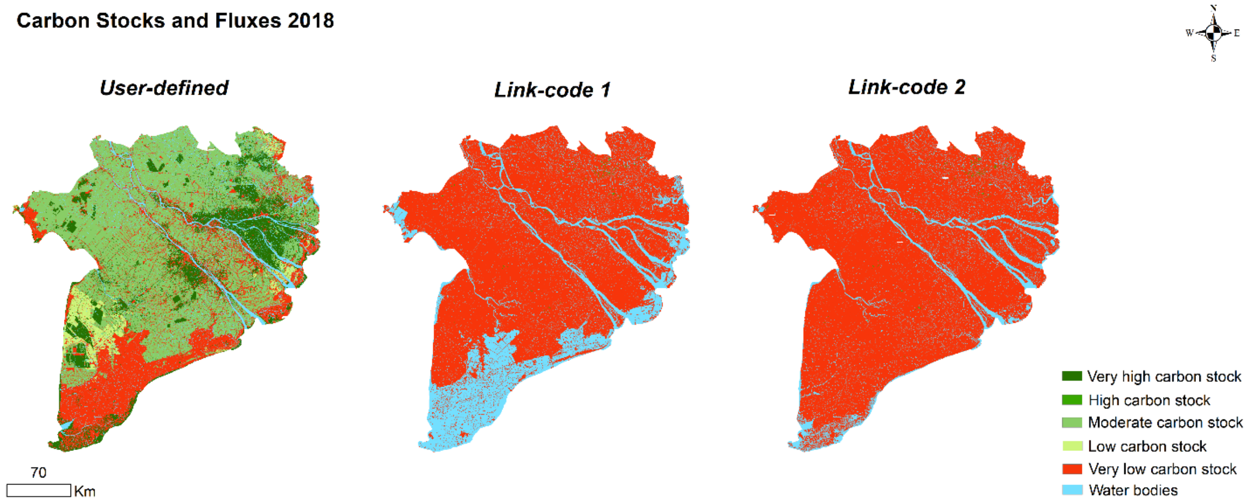


Figure 41 Maps of carbon stocks using crude matching

SRTM 30m DEM was also used to map multiple ES of the VMD to explore the applicability of global data in ES mapping in a data limitation context. Figure 42 shows maps of flood mitigation (Figure 42 (a)) and agriculture/aquaculture productivity (Figure 42 (b)) using SRTM 30m DEM compared with results from 5m DEM. The results show that at regional scale (the whole VMD), ecosystem service maps obtained using SRTM 30m DEM can provide comparable information with ecosystem service maps obtained from 5m DEM. However, SRTM 30m DEM cannot map ES properly at fine scale/local scale. Figure 42 (a) zooms in Can Tho city. SRTM 30m contains many artefacts and elevation errors. Therefore, using SRTM 30m can only provide reasonable ES maps for decision making at regional scale. ES maps obtained from SRTM 30m are rarely suitable for supporting decision making at local scales (e.g. small wetlands or farms). Therefore, deltaic regions should be prioritised for collection of high-resolution topographic information to improve representation of small-scale features that contribute to ES.

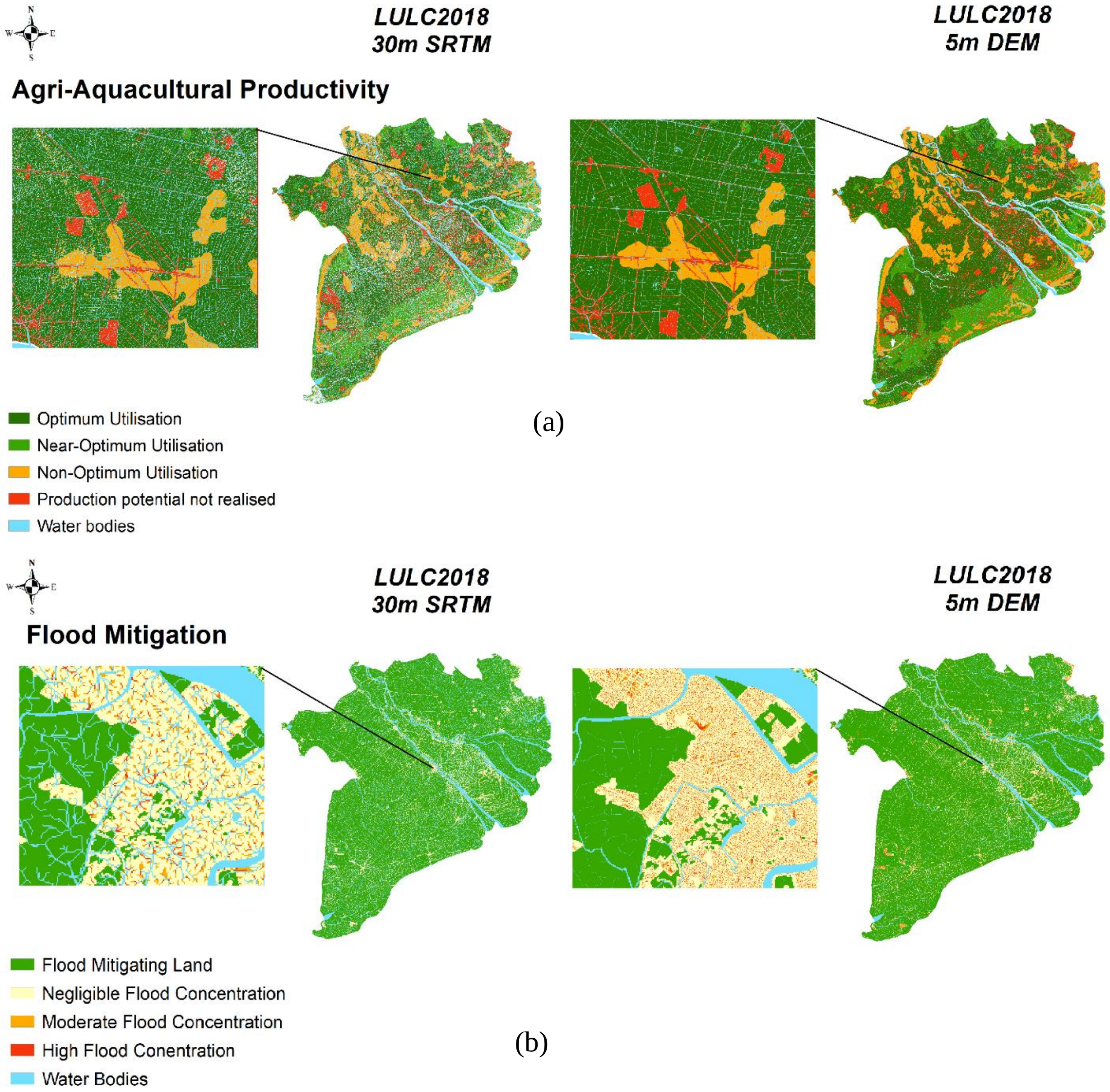
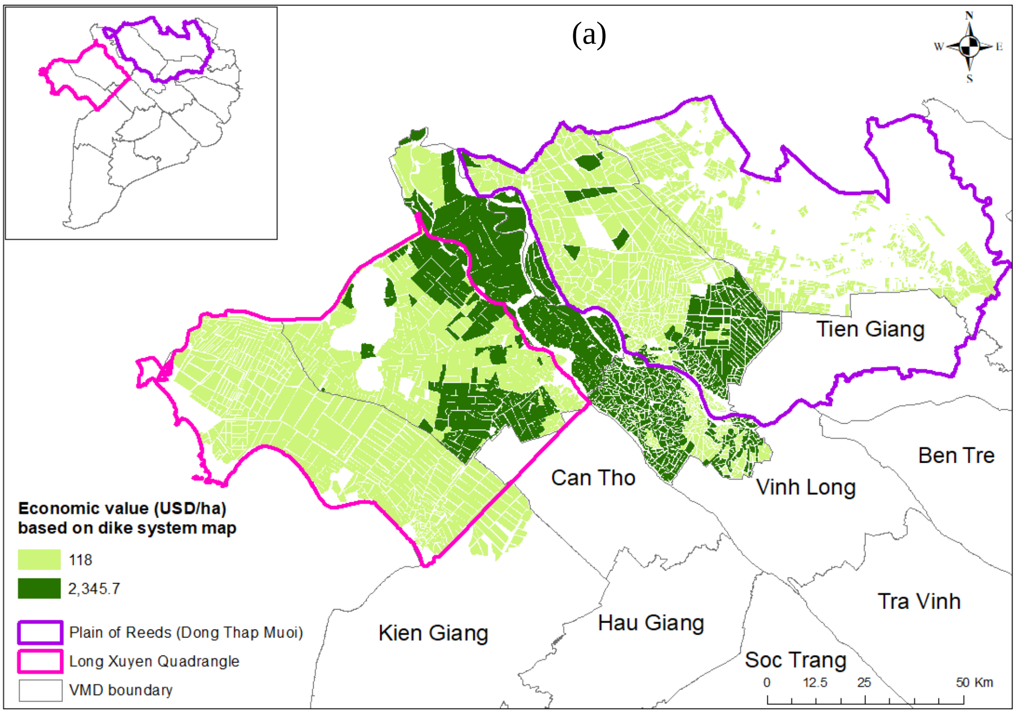


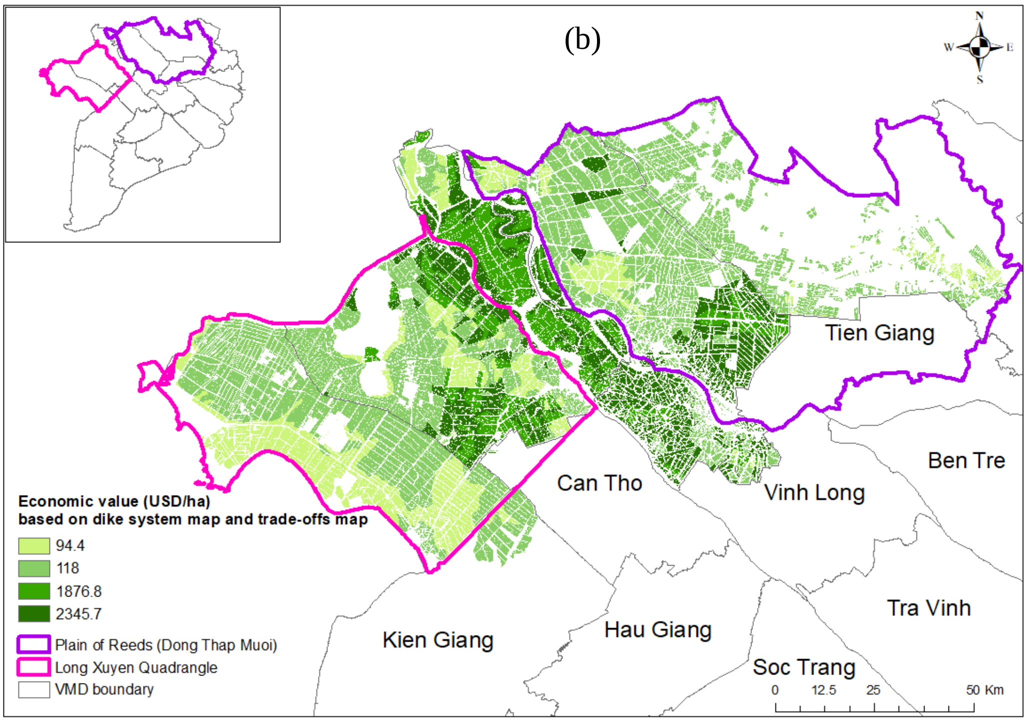
Figure 42 Maps of flood mitigation (a) and agriculture/aquaculture productivity (b) using SRTM 30m

4.4.2 Mapping ES values to support PES schemes in the upper part of the VMD

Maps of the economic value of flood-mitigation were developed based on the trade-offs and synergies mapping of flood mitigation and agricultural/aquaculture productivity, a dike system map and dike management (investment and maintenance) costs. Figure 43 (a) presents an ES economic value map using only dike system map information and Figure 43 (b) presents an ES economic map using both modelling result (synergies and trade-offs map) and the dike system map. It can be seen that Figure 43 (b) present more details and spatial heterogeneity of ES value compared with Figure 43 (a).

The most suitable areas to implement flood-based crops are in the two most flood-prone areas of the VMD; Dong Thap Muoi or "the Plain of Reeds" (within the purple boundary) and Long Xuyen Quadrangle (within the pink boundary); as well as in the areas between these two particularly flood prone regions. The areas with the highest value (2,345.6 USD/ha) are providing "excellent service provision" within high dikes. The areas with "moderate service provision" within high dikes have the second highest value (1,876.8 USD/ha). The areas within low dikes providing "excellent service provision" and "moderate service provision" are estimated to have a flood mitigation economic value of ~118 USD/ha and ~94.4 USD/ha respectively. The most cost-effective places to develop flood-based crops are the areas providing "excellent service provision" within low dikes. These areas can provide excellent service with less flood management cost. Figure 43 (c) presents ranking for Nbs implementation priority based on ES provision and flood management cost. Although the economic valuation methodology behind the map is simple, it can still provide useful guidance to spatially target payment amounts for farmers who implement flood-based crops. The maps of suitable areas for Nbs implementation can be used to support Nbs design and build future scenarios with stakeholder groups. We hope that this information can help to improve investment in low dike areas to encourage farmers not to increase the height of dikes in these areas. Investment in flood-based crops can help to improve the livelihoods of local people during flood season while preserving the natural floodplains.


(a)
Tien Giang
Ben Tre
Can Tho
Vinh Long
Tra Vinh
Kien Giang
Hau Giang
Soc Trang
Economic value (USD/ha)
based on dike system map
118
2,345.7
Plain of Reeds (Dong Thap Muoi)
Long Xuyen Quadrangle
VMD boundary
0 12.5 25 50 Km


(b)
Tien Giang
Ben Tre
Can Tho
Vinh Long
Tra Vinh
Kien Giang
Hau Giang
Soc Trang
Economic value (USD/ha)
based on dike system map and trade-offs map
94.4
118
1876.8
2345.7
Plain of Reeds (Dong Thap Muoi)
Long Xuyen Quadrangle
VMD boundary
0 12.5 25 50 Km

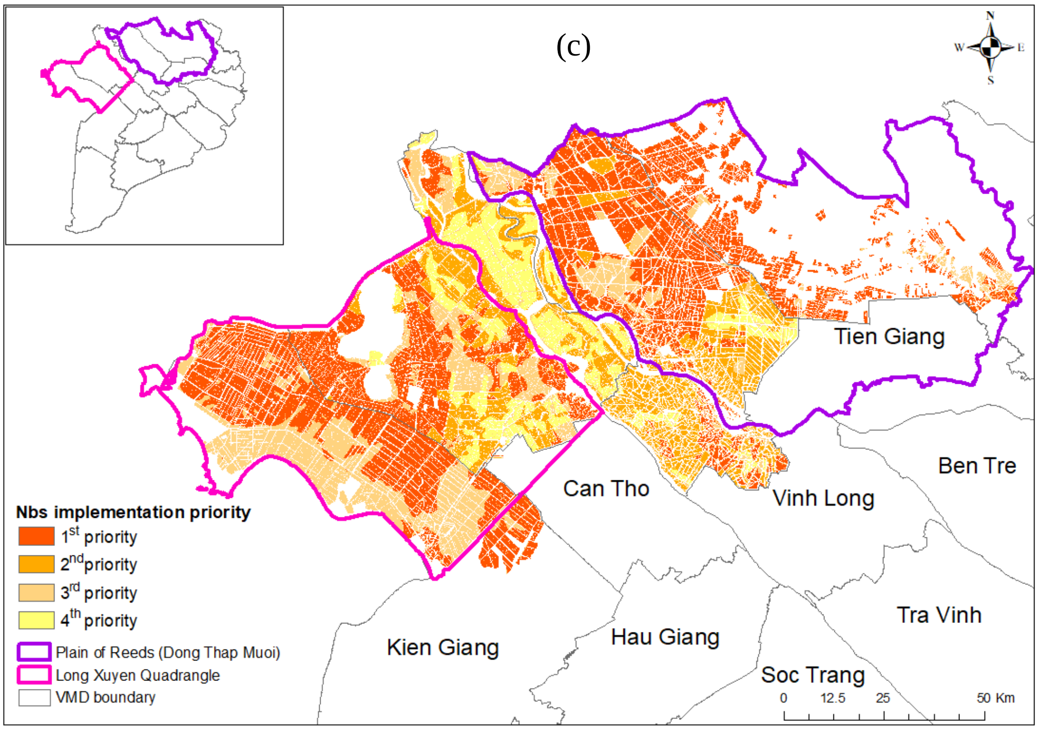


Figure 43 Ecosystem service value maps to support flood-based crops priority in the upper part of the VMD: (a) ES economic value map using only dike system map; (b) ES economic map using both modelling result (synergies and trade-offs map) and dike system map; (c) ranking for Nbs implementation priority

The implementation of flood-based crops, such as lotus, water lilies, floating rice, flood-based giant freshwater prawns or snake-head fish etc can improve the economic viability of flooding. In the upper VMD, these crops were recommended as the "no-regret" measure for flood control in the short and medium term (MDP, 2013). These no-regret measures are assessed as efficient and effective in all potential scenarios and flexibility can be kept for future developments (MDP, 2013). Development of flood-based crops aligns with Resolution 899 (2013) and Resolution 120 (2017) of the Vietnamese Government which resolved to carry out policy changes around the agriculture sector of the VMD to avoid the consequences of the current focus on maximising rice production and move instead towards development of more climate-resilient agriculture and food production in Vietnam.

A previous study advised that sustainable hydrological production in Mekong River basin should attain conservation goals (Arias et al., 2011). The ecosystem service - based framework, FOR-POWER framework, and PES for forest conservation was developed and applied to a proposed dam in Cambodia (Pursat 1) (Arias et al., 2011). We hope we have argued that PES schemes to protect wetlands in the downstream parts of the VMD will significantly augment the existing efforts to protect forests in upland areas.

4.4.3 Recommendations to improve LUCI to better adapt for the VMD, and delta and/or tropical geoclimatic regions more generally

Although reconceptualising some of LUCI's parameters and mechanisms can result in reasonable ES maps of flood mitigation and agriculture/aquaculture productivity for the VMD, the model can be further improved for deltaic regions, which would likely improve the applicability and utility of LUCI in the VMD. These improvements would not only be valuable for the VMD but also for broader coastal flat areas and other areas with waterlogging-tolerant and/or waterlogging-dependent crops.

The current hydrological routing of LUCI primarily considers flow directed from hills through to floodplains through to rivers. However, as a large receptor of the Mekong River, water flow exchanges back from the river to the floodplains (e.g., over-bank flow) is an important process in the VMD. Overbank flows are also the main sources of sediment in the floodplains of the VMD as well as other deltaic regions. While sediment retention is an important ES of flood control, sediment retention is not modelled in this study because the LUCI sediment retention tool was developed to predict terrestrial erosion and delivery to waterways and has not incorporated the sediment deposition processes from overbank flows coming from the river. In future developments, the hydrological routing algorithm of LUCI should include connections from rivers back to the floodplains. These improvements will enable LUCI to better represent the flood environment and sediment retention processes of the VMD and other deltaic regions. In addition, water flow in the VMD is greatly influenced by tidal regimes. Furthermore, the VMD also has huge areas of wetlands which have close interactions with groundwater movement. As earlier explained, some algorithms in the LUCI framework considering such processes do exist but are not yet mature enough to be easily implemented without significant developer input; our study highlights the need for prioritising effort to make these more widely applicable and user friendly to improve LUCI's applicability in wider environment and data contexts.

The agriculture productivity ES algorithms within LUCI should be adapted to recognise the potential food and fibre productivity of waterlogged areas for example, the rice field and aquaculturally utilised areas in the VMD

4.5 Conclusion

To date, this is the first fine scale multiple ecosystems services modelling study in the Vietnamese Mekong River Delta. With each modelling step processed at 5 by 5m for 39,000 km^2, the study deals with big data and high computational requirements. The Land Utilisation and Capability Indicator (LUCI) model was used to map flood mitigation, agriculture/aquaculture productivity, climate regulation (carbon sequestration) as well as their synergies and trade-offs in the VMD in two different years, 2010 and 2018. To obtain meaningful results for the VMD, the productivity and flood mitigation values associated with waterlogged crops were adapted to help LUCI recognise these ES provided by waterlogged crops. However, LUCI's parameters and algorithms could be further improved to better represent the often waterlogged environment and other unique processes within tropical delta regions.

The modelling results provide useful information on multiple ecosystem services and their distribution in the VMD, as well as their changes between 2010 - 2018. Comparing ES maps between these two timeframes reveals how flood control infrastructure accomplishment and regional development strategies updates in 2011 affect ES across the delta. There are decreases in flood mitigation in the lower stream of the VMD and increases in agriculture/aquaculture productivity in the southern parts of the delta. The increased agriculture/aquaculture production led to the reduction of carbon stock in the southern VMD. In addition, this study uses the biophysical ES modelling results combined with a benefits transfer approach to produce spatially explicit economic value mapping of flood mitigation benefits occurring in the upper part of the delta. The information on ES economic values shown at farm scale can help farmers see benefits of Nbs more clearly. The spatially explicit economic value map also shows where areas should be prioritised for Nbs implementation. Covid-19 has so far prevented us from carrying out planned participatory work with VMD farmers, other stakeholders and policymakers to evaluate their thoughts on LUCI predictions. We hope this information can be useful for informing designs of PES schemes for Nbs implementation which both preserve multiple ES relating to floods and sustains livelihoods of local people during flood season

5 Conclusion

The aim of this research was to enhance ecosystem services modelling by facilitating model parameterisation and adaptation, thereby reducing the intensive effort needed to produce ES assessments, especially in data-sparse regions and regions where ES models have not been well established. This chapter presents discussions, conclusions, and recommendations on the three main research chapters. Section 5.1 contains main findings regarding (1) current state, trends, and ways forward of ES assessments to support decision-making; (2) guidelines and a supporting toolbox for parameterising soil hydraulic properties required by ES models and broader integrated modelling and (3) applying LUCI in the VMD and exploring the use of the model results to support nature-based solutions. Section 5.2 gives recommendations to adapt and improve LUCI and other models for better meeting the needs of ES modelling in SEA, deltas, and data-sparse regions. Section 5.3 summarises the contributions of this thesis and section 5.4 presents limitations and recommendations for future work.

5.1 Main findings

5.1.1 Current state, trends, and ways forward of ES assessments to support decision-making

A review of literature on ES assessments with a focus on 118 case studies in Southeast Asia, which were identified from a stringent selection process, in Chapter 2 provided a big picture of achievements to date, key research gaps, and pathways for policy uptake of ES assessments in SEA, with a view to contributing to global needs. To date, ES assessment methods are diverse, varying from proxy-based mapping, modelling, economic valuation, and assessments of human perception to combinations among these assessment approaches. Over time, increasing attention has been paid to procuring spatially explicit ES assessments and also to better integrate stakeholders' perspectives into ES assessment. Among ES assessment tools, ES modelling has been demonstrated as an effective evidence-based assessment tool for decision-making in SEA. Some studies have aligned results with policy needs, but their tangible influence on policy still appears limited. Key gaps in current ES assessments in SEA are related to data constraints and limited ES mapping methodologies. To increase policy uptake of ES assessments, greater integration of different methodologies is needed. Furthermore, a regional strategy that facilitates cooperation among SEA countries through shared data accessibility, detailed guidance of ES assessment methods and capacity building will ensure greater reliability and policy uptake of future ES assessments.

5.1.2 Guidelines and an associated toolbox for soil hydraulic properties parameterisation

Soil plays an important role in the Earth’s water, geomorphic and chemical cycles. The importance of soil is increasingly recognised, and more complex representation of soils has been built into integrated environmental models. Users and developers often require sound hydraulic properties information while having limited access to specialist knowledge. Information on soil hydraulic properties is often not directly available as direct measurements are often costly and time-consuming. The guidelines and associated spatially referenced toolbox, LUCI_PTFS, developed in Chapter 4 addressed these issues. The guidelines and toolbox can speed the process of acquiring sensible key 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 (~150) of PTFs for different geoclimatic regions, not collated in anywhere else to date. LUCI_PTFs is an open-source ArcGIS toolbox which allows users to quickly get values, graphs, and spatial distributions of soil hydraulic properties across a range of different geoclimatic and data availability contexts. The soil hydraulic properties obtained using the guidelines and the toolbox could be used as inputs for various models among other purposes including ES, climate, hydrology, and crop models etc. The toolbox’s functionality was demonstrated in two contrasting case studies. The VMD case study represents a tropical, flat area with limitations of soil information, and the Hurunui catchment case study represents a temperate, hilly area with better available soil information. The results obtained from these two cases studies were compared with information of soil hydraulic properties from local soil samples and global soil samples. Through the case studies, the guidance and the associated toolbox LUCI_PTFs, demonstrated the potential capability to provide reasonable information on soil hydraulic properties in different data contexts and natural conditions in a short timeframe.

LUCI uses spatially explicit information on key soil moisture thresholds (saturated soil moisture content, field capacity, stomatal closure point, and permanent wilting point) and water held between these thresholds (drainable water, plant available water, readily plant available water, and hygroscopic water) for soil moisture accounting. The information is not readily available in data sparse regions. The guidance gives the definition of these parameters, information on secondary sources to obtain the parameters, and methods to parameterise the parameters from the available sources using pedotransfer functions which are suitable for different geo-climatic and data contexts. The LUCI_PTFs toolbox can help accelerate the soil parameterisation process to apply the LUCI model in data sparse regions.

5.1.3 Applying LUCI in the VMD to support nature-based solutions in the delta

The Land Utilisation and Capability Indicator – LUCI model was used to map three ES in the VMD, i.e. flood mitigation, agricultural productivity, and climate regulation (carbon storage and sequestration), as well as their trade-offs and synergies for different mix of land use/land cover in 2010 and 2018. To date, this is the first high-resolution (5 by 5 m) ES modelling study conducted for the whole VMD with ~ 1500 million elements per ES. This research deals with big data and large computation requirements. The modelling computation time for this study was completed in ~ 1500 hours.

Two parameterisation approaches used for ES modelling include matching the VMD soils and land covers to their closest counterparts in datasets already supported by LUCI and parameterising the VMD soils and land covers based on local knowledge for support in LUCI (user-defined parameterisation). In the first approach, the VMD soils and land covers were matched to their closest counterparts of the NZ LCDB2 land data and NZ FSL soil data which are already supported by LUCI. These datasets were selected because they are more detailed and readily available than other datasets within LUCI. Although matching the VMD LULC classes with the available land databases led to some incorrect representations of the selected ES in rice fields and aquacultural lands of the delta, this crude matching is a useful way of identifying important model parameters for LUCI application in the VMD as well as obtaining preliminary results for pre-assessments. In the user-defined parameterisation, land and soil parameters were assigned based on local information and knowledge. As LUCI was originally developed for temperate hill country landscapes, the model does not consider some of flood mitigation and productivity of waterlogged croplands. To obtain meaningful results for the VMD, we excluded the water logging dependency and raised the productivity and flood mitigation values associated with waterlogged crops. However, this cannot fully present flooding environment and process of deltaic areas. Therefore, the model mechanisms and algorithms also needed to be improved for better uptake in the VMD as well as other tropical flat areas. Detailed suggestions on the model improvements are presented in the next section.

The ES maps from this research can provide useful information on the spatial heterogeneity of ES across the VMD. From ES maps, better understandings of the existence of ES and their spatial distribution can be obtained. Comparing ES maps between 2010 - 2018 shows how infrastructure development and changes in development strategies affect ES across the delta. Due to the implementation of high dike systems in the upper stream VMD in 2011, urban and settlement areas have expanded in the lower stream VMD. This development led to the reduction of flood mitigation areas in the downstream VMD. Aquaculture development strategies focusing on the southern parts of the VMD were revealed through the increases in aquaculture productivity in these areas however the expansion of aquaculture led to the decreases in carbon stock. Trade-offs maps, flood mitigation, and agricultural productivity can help decision-makers find suitable places for flood-based crops. Flood-based crops in dike systems are considered as potential nature-based alternatives for the upstream VMD which will help preserve the benefits of natural floods and sustain the local people's livelihoods. ES maps obtained from LUCI are also useful to present spatially explicit ES values of flood mitigation. This spatially explicit economic value map can help farmers clearly see the monetary benefits of nature-based water resource management and inform the design of a Payment for Ecosystem Services scheme for incentivising Nbs implementation in the upstream delta.

5.2 Recommendations to adapt and improve LUCI and other models to better meet the needs of ES modelling in SEA, deltas, and data spare regions

LUCI has been widely applied in Wales, the United Kingdom, parts of continental Europe, and New Zealand. The first application of LUCI in Southeast Asia was in the Cagayan de Oro catchment, Philippines (Benavidez, 2018) which provided LUCI setting recommendations in a tropical hilly area dominated by forest and bushland. Our study added model settings and recommendations to adapt LUCI for a tropical deltaic area with agricultural and aquacultural lands as the key land uses. This section provides detailed enhancement suggestions for LUCI's algorithms and mechanisms to better uptake in the VMD as well as other deltaic regions. In addition, based on the review on ES assessments in SEA, ES modelling has been increasingly received the attention of researchers and decision-makers in the region, however, there has not been any study drawing out improvements needed for ES modelling to enter widespread use in SEA. Hence, this section also provides recommendations to improve the applicability of LUCI in SEA. The recommendations may also be useful for other ES models or other environmental models which would like to gain wider use in SEA.

5.2.1 Land and soil parameterisation

In LUCI, land and soil information play an important role in ES modelling. There are two approaches to parameterise land and soil inputs including matching new datasets to already supported datasets or user parameterising their dataset directly for support in LUCI (user-defined parameterisation). Using the former help to explore the model capacities and obtain preliminary results as well as reduce data preparation time however it will lead to uncertainties due to the mismatch between local LULC/soil classes and the LULC/soil classes available in LUCI's database. The user-defined parameterisation can bring specific characteristics of a study area into the modelling process.

The current supported/already parameterised datasets within LUCI only contain land and soil tables of the UK and NZ. LULC classes of the UK and NZ do not cover typical LULC classes/types of

SEA countries for example rice, aquaculture, agroforestry (oil palm, rubber, coffee, coconut). To improve the application of LUCI in SEA, LUCI should add more land and soil datasets which include specific LULC and soil types of SEA countries to the model's already supported datasets. It will help inexperienced users in SEA obtain reasonable ES maps from LUCI if they have either time or data limitations.

To improve the use of user-defined parameterisation in SEA as well as in many other parts of the world, detailed guidelines of required land and soil table's parameters/fields for each ES should be included in the LUCI manual. The guidelines for soil hydraulic properties parameterisation developed in this research can also be added to the LUCI manual. It will be useful for users when they would like to develop specific land and soil table for their study area or test different land and soil change scenarios. In addition, it can help reduce uncertainties caused by mistakes in the land and soil parameterisation process. To develop more already supported land and soil tables as well as detailed guidelines for land and soil user-defined parameterisation for SEA, more research is encouraged to be conducted in other parts of SEA.

5.2.2 Ecosystem service tools

SEA is rich in biodiversity and is a global priority for averting imminent species extinction (Duckworth et al., 2012). The region has a large number of species in the IUCN Red List including Southeast Asian Box Turtle (Mindanao, The Philippines), Sumatran orangutan (Indonesia), Javan rhino (Vietnam, Indonesia), Saola (Vietnam, Laos), Indochinese tiger (Myanmar, Thailand, Vietnam, Laos), Sumatran tiger (Indonesia) etc. Including SEA endangered species in LUCI's habitat tool will enable the applicability of LUCI to support biodiversity conservation in SEA.

The SEA is also rich in culture with many historic sites as well as beautiful attractions. For example, rice fields in many parts of the SEA region are included in UNESCO world heritage sites (Settele et al., 2018). Mapping cultural ES and trade-offs between cultural ES and providing, supporting and habitat services is essential to balance between development and preserve the existence of multiple services in SEA. Therefore, including a cultural ecosystem service assessment tool would be important to adapt LUCI for better supporting decision-making in the region.

5.2.3 Model algorithms and structures

To enhance the applicability of LUCI in the VMD as well as other deltaic regions, the most established parts of LUCI should upgrade their mechanisms and algorithms to specifically account for ES provided by water-tolerant crops (rice, lotus, water lily, aquaculture, etc.) and better present flooding environment/process in deltaic regions. The VMD is a large receptor of the Mekong River hence the overbank floodwater flows from the river to floodplains (overbank flow) contribute significantly to the inundation process of the delta. In addition, typical land uses in deltaic regions, i.e. rice fields and agricultural lands, have large above-ground floodwater storage capacity. However, the current hydrological routing of LUCI primarily considers flow directed from floodplains to rivers but not the flow from rivers to floodplains. In future development, LUCI should include connections from the river back to the terrestrial water storage to better present the flooding environment/process in the VMD and other deltaic regions. Additionally, important factors for aquacultural productivity should be considered including temperature, pH, dissolved oxygen, distance to river and geology.

In addition to the suggestions directly coming from this study, this study highlights the need to integrate some improvements which were already recognised by the LUCI development team but have not yet been fully implemented in the model. SEA, the VMD and other deltas have large coastal areas. Therefore, water flow in these regions is significantly influenced by tides and increasingly by sea-level rise. In addition, these regions have large areas of wetland therefore groundwater plays an important role in soil water budgets. Hence, tidal effects, sea-level rise and groundwater influences should be taken into account in ES modelling to represent hydrological regime of these regions. Although LUCI framework has some algorithms which account for overbank water flow, tidal effects and groundwater, these algorithms have yet to be well documented or made easily available to use without significant developer input. This study expresses the need to make these algorithms to be more easily accessible for LUCI users.

Previous studies by the LUCI team also noted limitations of the D8 algorithm to extract flow direction and flow accumulations in flat areas (Emmett & the GMEP team, 2017; Marapara, 2016). As D8 algorithm assigns flow leaving a given pixel into only one of the eight neighbour pixels (Tarboton, 1997), it will lead to coarse stream delineation and the absence of existing river segments and/or artificial parallel river segments, especially in flat areas (Mayorga et al., 2005; Lai et al., 2016). This application of LUCI in an enormous flat area, the VMD, highlights the importance of improving the LUCI flow direction algorithm to better present flows in deltaic regions, perhaps through moving to the D-infinity or Multiple Flow Direction algorithms. The multiple flow direction algorithms allow for continuous flow angles, therefore it can help to overcome the limitations of the D8 method (Tarboton, 1997; Zhao et al., 2009).

LUCI was designed from the beginning to be computationally efficient and its implementation over ~ 2012-2016 over all of Wales as part of the Glastir Monitoring and Evaluation Project (GMEP) (Emmett & the GMEP team, 2017) led to the model becoming particularly efficient for large data problems. However, some changes implemented as the number of contributing programmers grew over a time that LUCI was mostly applied at smaller scales led to some accidental removal of this big data application efficiency. This work is the first application on a similarly large scale to the GMEP in a few years. This work among others highlighted the need to restore LUCI's original efficiencies for big data applications.

The LUCI development team has also recognised the limitation of LUCI when the model is based on proprietary GIS software (e.g. ArcGIS). It is difficult to transfer the mapping process developed in this study to decision-makers in the VMD if they do not have access to proprietary GIS software. Moving LUCI to an open-source platform will improve the capacity of the model to support researchers and decision-makers in the VMD and developing countries broadly. Training and workshops in LUCI are also necessary to introduce the model to users in the region and provide technical supports to solve users' queries. Information collected from users are valuable to develop LUCI to better meet the need of users in these regions.

5.3 Summary of contributions

This thesis provided original contributions that are important for ES modelling and ES assessment in the Vietnamese Mekong Delta and Southeast Asia as well as deltaic regions and data sparse regions broadly. These includes:

- The thesis presented the first systematic review of ES assessment in SEA which will help to improve understandings of current states, trends, and ways forward for ES modelling and assessments to better support policymakers and future research in ES assessment in SEA and beyond.
- The thesis developed comprehensive guidance to parameterise soil hydraulic properties which are important for ES modelling as well as other models. The guideline and associated toolbox, LUCI_PTFs, help users quickly select an appropriate PTF for their study area, turning a task that would otherwise take many days to weeks into a shorter time instead.
- This research provided meaningful high resolution (5x5 m) ES biophysical and economic value maps for the Vietnamese Mekong Delta. The ES maps can be used to support nature-based solutions in the upstream delta which both preserve multiple ES relating to floods and sustains livelihoods of local people during flood season.
- This research contributed to an emerging literature that attempts to adapt ES models for mapping multiple ecosystem services in deltaic regions. Recommendations were suggested to adapt LUCI and other models to improve their applicability in the Vietnamese Mekong Delta, Southeast Asia as well as other data-sparse regions in the world.
- This work has attracted the attention of scientists in the Vietnamese Mekong Delta (VMD) and Southeast Asia (SEA). Building on the knowledge provided by this thesis, and in

particular the improved ability to find important parameters for ES modelling, in the VMD, a project is being conducted by Dong Thap University to obtain supporting soil organic carbon data in the upper stream of the VMD. Outputs from this thesis will also be used for the project "Assessment and projection of land use/land cover changes and their impacts on ecosystem services in Long Xuyen Quadrangle, Vietnamese Mekong Delta" conducted by Dong Thap and Can Tho Universities. The use of LUCI is also integral to a proposal submitted to the Asia-Pacific Network for Global Change Research, "Safeguarding the Regional Food Security under Climate Change impacts via mainstreaming Nature-based Solutions-centered adaptation strategies in the Lower Mekong Basin", led by the Asian Institute of Technology. The information on suitable areas for Nbs implementation also has potential to support the "Flood-based-livelihoods" programme in the VMD of the International Union for Conservation of Nature (IUCN).

- The greatest impact of my work for stakeholders in the VMD and SEA is paving the way for future meaningful research on ES modelling in these regions. My work helps to connect researchers and scientists from the VMD, SEA, and New Zealand. The suitable locations for flood management Nbs identified from this thesis can support future Nbs development which will bring benefits to nature and the people of the VMD.
- Although the thesis focuses on Southeast Asia and a tropical delta region, the outputs can contribute to ES and broader integrated modelling in New Zealand and beyond. Although data for ES modelling are more available in New Zealand compared to SEA or the VMD, the readily accessible soil data of New Zealand, FSL, does not contain detailed soil hydraulic properties information that is required by various models. The guideline and the associated toolbox can help obtain required soil hydraulic properties quickly with a reasonable level of accuracy. The LUCI model development for specific land use parameterisation will benefit the application of LUCI in New Zealand and any other study areas when granular data is available. The specific land use parameterisation has recently been used in two applications of LUCI (Nature Braid – next-gen LUCI) in the Greater Wellington Region and the Canterbury Region of New Zealand. The suggested improvement to better map aquacultural productivity is also meaningful for New Zealand. In spite of the importance of aquaculture in New Zealand, there is very limited research that includes ES assessment around aquaculture production for the country.

5.4 Limitations and recommendations for future work

Due to time limitations and travel restriction during the Covid-19 pandemic, this thesis still has some limitations that can be addressed in future work:

- The ES assessment review in the SEA region only contains self-identified ES studies which clearly stated they focus on "ecosystem services". This search strategy may omit important studies which directly assess a service without mentioning the term "ecosystem service". Therefore, future work should include each single service in search strategy to avoid missing important and relevant studies.

- The *"Guidelines for parameterising soil hydraulic properties version 1.0"* and *"LUCI_PTFs toolbox version 1.0"* were tested with the two case studies in the VMD and the NZ Hurunui catchment. In future, the guidelines and associate toolbox should be tested in other areas which have different climate and topography other than the two case studies. This testing will help explore the limitations of the guidelines and associated toolbox for future development. In addition, more PTFs should be added to the LUCI_PTFs toolbox to provide more options for users.

- In chapter 3, the weighted average approach based on siblings' proportion was used to estimate S-map soil properties. A future study might test the use of dominant sibling and random sibling selection approach to obtain soil hydraulic properties and compare them with the weighted average approach.

- In this study, LUCI was used to model flood mitigation, agricultural productivity and carbon sequestration services and their trade-offs and synergies in the VMD. As agriculture and aquaculture are the important economic activities in the region, other water services including water quality and sediment retention are also important in the area. Future studies should apply LUCI water quality and sediment retention tools in the VMD to explore the model capacity and draw out model improvements to better represent these two services in deltaic conditions.

- In this study, we applied LUCI for the VMD because it is challenging to obtain high-resolution DEM and updated LULC map and soil map for the whole Mekong River Basin. However, the use of the VMD boundary limits the consideration of the upstream contributions to water flows in this study. LUCI has algorithms to add/feed the upstream contribution to downstream flow. Further study can seek the integration of LUCI and dynamic hydrological model, i.e. MIKE DHI, to bring in the upstream contribution to the water flow in the VMD using this function of LUCI.

- It is also important to communicate ES maps obtained from this study with farmers, stakeholders, and policymakers in the VMD validate our modelling results and receive their feedback. Due to travel restrictions during the time conducting this thesis, the planned field visit and interviews with local people could not be conducted. In future studies, field visits and semi-structured interviews with farmers should be conducted to obtain ground-truthed data. Workshops with farmers, stakeholders and policymakers should be organised to understand whether the map visualisation and scale of information are able to accelerate the design of Nbs or not; and to obtain opinions on what other information is required to support their decision-making as well as other issues that should be considered in future modelling practices.

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Appendix A1

SEA ES assessment studies from reference list of important reviews

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		22. Felardo, J., Lippitt, C.D., 2015. Spatial forest valuation: the role of location in determining attitudes toward payment for ecosystem services policies. For. Policy Econ. 62, 158–167 (Thailand)

No	Review paper	ES studies in Southeast Asia
4	Turner, K. G., Anderson, S., Gonzales-Chang, M., Costanza, R., Courville, S., Dalgaard, T., Dominati, E., Kubiszewski, I., Ogilvy, S., Porfirio, L., Ratna, N., Sandhu, H., Sutton, P. C., Svenning, J.-C., Turner, G. M., Varennes, Y.-D., Voinov, A., & Wratten, S. (2016). A review of methods, data, and models to assess changes in the value of ecosystem services from land degradation and restoration. Ecological Modelling, 319, 190-207.	No reference
5	Andrew, M. E., Wulder, M. A., Nelson, T. A., & Coops, N. C. (2015). Spatial data, analysis approaches, and information needs for spatial ecosystem service assessments: A review. GIScience and Remote Sensing, 52(3), 344-373.	No reference
6	Brown, G., & Fagerholm, N. (2015). Empirical PPGIS/PGIS mapping of ecosystem services: A review and evaluation. Ecosystem Services, 13, 119-133.	No reference
7	Bunse, L., Rendon, O., & Luque, S. (2015). What can deliberative approaches bring to the monetary valuation of ecosystem services? A literature review. Ecosystem Services, 14, 88-97.	No reference
8	de Araujo Barbosa, C. C., Atkinson, P. M., & Dearing, J. A. (2015). Remote sensing of ecosystem services: A systematic review. Ecological Indicators, 52, 430-443.	1.Castella, J.C., Lestrelin, G., Hett, C., Bourgoin,J.,Fitriana,Y.R.,Heinimann,A., P fund, J.L., 2013.Effects of landscape segregation on livelihood vulnerability: moving from extensive shifting cultivation to rotational agriculture and natural forests in northern Laos.Hum.Ecol.41,63–76. 2.Estoque,R.C.,Murayama,Y.,2013.Landscape pattern and ecosystem service value changes: implications for environmental sustainability planning for the rapidly urbanizing summer capital of the Philippines.Landsc.UrbanPlann.116,60–72. 3.Jepsen, M.R., Leisz, S., Rasmussen, K., Jakobsen, J., Moller-Jensen, L., Christiansen, L., 2006. Agent-based modelling of shifting cultivation field patterns, Vietnam. Int. J. Geogr. Infor. Sci. 20, 1067–1085. 4.Marghany, M., Hashim, M., 2010. MODIS satellite data for modeling chlorophyll-a concentrations in Malaysian coastal waters. Int. J. Phys. Sci. 5, 1489–1495. 5.Schmitt, K., Albers, T., Pham, T.T., Dinh, S.C., 2013. Site-specific and integrated adaptation to climate change in the coastal mangrove zone of Soc Trang Province, Viet Nam. J. Coast. Conserv. 17, 545–558.

No	Review paper	ES studies in Southeast Asia
		6.Stolle, F., Dennis, R.A., Kurniwan, I., Lambin, E.F., 2004. Evaluation of remote sensing- based active fire datasets in Indonesia. Int. J. Remote Sens. 25, 471–479.
		7.Wada, Y., Rajan, K.S., Shibasaki, R., 2007. Modelling the spatial distribution of shifting cultivation in Luangprabang, Lao PDR. Environ. Plann. B-Plann. Des. 34, 261–278.
9	Malinga, R., Gordon, L. J., Jewitt, G., & Lindborg, R. (2015). Mapping ecosystem services across scales and continents – A review. Ecosystem Services, 13, 57-63.	No reference
10	Suich, H., Howe, C., & Mace, G. (2015). Ecosystem services and poverty alleviation: A review of the empirical links. Ecosystem Services, 12, 137-147.	1.Brooks,S.E.,Reynolds,J.D.,Allison,E.H.,2008.Sustainedbysnakes?Seasonal livelihood strategies and resource conservation by Tonle Sap fishers in Cambodia. Hum.Ecol.36,835–851.
		2.Triet T, Caines R. 2007. Towards sustainable rural development: combining biodiversity conservation with poverty alleviation – a case study in Phu My village, Kien Giang Province, Vietnam. In: Morioka T, Hakuri K, Yabar H, editors. Transition to a resource-circulating society: strategies and initiatives in Asia. Osaka (Japan): Osaka University Press. p. 181–190.
11	Wolff, S., Schulp, C. J. E., & Verburg, P. H. (2015). Mapping ecosystem services demand: A review of current research and future perspectives. Ecological Indicators, 55, 159-171.	No reference
12	A blueprint for mapping and modelling ecosystem services (Crossman et al., 2013)	No reference
13	Mapping ecosystem services' values: Current practice and future prospects (Schägner et al., 2013)	1. Vollmer, D., Grêt-Regamey, A., 2013. Rivers as municipal infrastructure: demand for environmental services in informal settlements along an Indonesian river. Global Environ. Change 23, 1542–1555, http://dx.doi.org/10.1016/j.gloenvcha.2013.10.001
14	Barbier, E. B. (2012). A spatial model of coastal ecosystem services. Ecological Economics, 78, 70-79.	1. Othman, J., Bennett, J., Blamey, R., 2004. Environmental management and resource management options: a choice modelling experience in Malaysia. Environment and Development Economics 9, 803–824.
		2. Barbier, E.B., 2003. Habitat–fishery linkages and mangrove loss in Thailand. Contemporary Economic Policy 21, 59–77.
		3. Barbier, E.B., 2007. Valuing ecosystems as productive inputs. Economic Policy 22,177–229.
		4. Barbier, E.B., Koch, E.W., Silliman, B.R., Hacker, S.D., Wolanski, E., Primavera, J.H., Granek, E.F., Polasky, S., Aswani, S., Cramer, L.A., Stoms, D.M., Kennedy, C.J., Bael, D., Kappel, C.V., Perillo, G.M., Reed, D.J., 2008. Coastal ecosystem-based management with nonlinear ecological functions and values. Science 319, 321–323.

No	Review paper	ES studies in Southeast Asia
15	Egoh, B., Drakou, E. G., Dunbar, M. B., Maes, J., & Willemen, L. (2012). Indicators for mapping ecosystem services: a review. Retrieved from Publications Office of the European Union, Luxembourg. (Report EUR 25456 EN).	No reference
16	Martínez-Harms, M. J., & Balvanera, P. (2012). Methods for mapping ecosystem service supply: a review. International Journal of Biodiversity Science, Ecosystem Services & Management, 8(1-2), 17-25.	No reference
17	Seppelt, R., Dormann, C. F., Eppink, F. V., Lautenbach, S., & Schmidt, S. (2011). A quantitative review of ecosystem service studies: approaches, shortcomings and the road ahead. Journal of Applied Ecology, 48(3), 630-636.	No reference
18	de Groot, R. S., Alkemade, R., Braat, L., Hein, L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity, 7(3), 260-272.	1.Van Beukering, P.J.H., Cesara, H.S.J., Janssen, M.A., 2003. Economic valuation of the Leuser National Park on Sumatra, Indonesia. Ecol. Econ. 44, 43–62.

Appendix A2

List of selected publications

No.	Country	Code	Research
1	Thailand	TL1	Arunyawat, S., & Shrestha, R. P. (2016). Assessing Land Use Change and Its Impact on Ecosystem Services in Northern Thailand. Sustainability, 8(8), 22.
2	Thailand	TL2	Cao, V., Margni, M., Favis, B. D., & Deschenes, L. (2015). Aggregated indicator to assess land use impacts in life cycle assessment (LCA) based on the economic value of ecosystem services. Journal of Cleaner Production, 94, 56-66
3	Thailand	TL3	Asafu-Adjaye, J., & Tapsuwan, S. (2008). A contingent valuation study of scuba diving benefits: Case study in Mu Ko Similan Marine National Park, Thailand. Tourism Management, 29(6), 1122-1130.
4	Thailand	TL4	Felardo, J., & Lippitt, C. D. (2016). Spatial forest valuation: The role of location in determining attitudes toward payment for ecosystem services policies. Forest Policy and Economics, 62(Supplement C), 158-167.
5	Thailand	TL5	Ferraro, P. J., Hanauer, M. M., Miteva, D. A., Nelson, J. L., Pattanayak, S. K., Nolte, C., & Sims, K. R. E. (2015). Estimating the impacts of conservation on ecosystem services and poverty by integrating modeling and evaluation. Proceedings of the National Academy of Sciences, 112(24), 7420-7425.
6	Thailand	TL6	Kaiser, G., Burkhard, B., Romer, H., Sangkaew, S., Graterol, R., Haitook, T., . . . Sakuna-Schwartz, D. (2013). Mapping tsunami impacts on land cover and related ecosystem service supply in Phang Nga, Thailand. Natural Hazards and Earth System Sciences, 13(12), 3095-3111
7	Thailand	TL7	Seenprachawong, U. (2016). An Economic Valuation of Coastal Ecosystems in Phang Nga Bay, Thailand. In N. Olewiler, H. A. Francisco, & A. J. G. Ferrer (Eds.), Marine and Coastal Ecosystem Valuation, Institutions, and Policy in Southeast Asia (pp. 71-91). Singapore: Springer Singapore.
8	Thaiand	TL8	Narjes, M. E., & Lippert, C. (2016). Longan fruit farmers' demand for policies aimed at conserving native pollinating bees in Northern Thailand. Ecosystem Services, 18(Supplement C), 58-67.
9	Thailand	TL9	Sathirathai, S., & Barbier, E. B. (2001). Valuing mangrove conservation in southern Thailand. Contemporary Economic Policy, 19(2), 109-122.
10	Thailand	TL10	Trisurat, Y., Eawpanich, P., & Kalliola, R. (2016). Integrating land use and climate change scenarios and models into assessment of forested watershed services in Southern Thailand. Environmental Research, 147, 611-620.
11	Thailand	TL11	Janekarnkij, P. (2014). Payment For Ecosystem Services (Pes) As Tool For Mae Lao Watershed Conservation. Agricultural and Resource Economics (ARE) Working Paper.
12	Thailand	TL13	Jourdain, D., & Vivithkeyoonvong, S. (2017). Valuation of ecosystem services provided by irrigated rice agriculture in Thailand: a choice experiment considering attribute nonattendance. Agricultural Economics, 48(5), 655-667.

13	Thaiand	TL14	Arunyawat, S., & Shrestha, R. P. (2018). Simulating future land use and ecosystem services in Northern Thailand. Journal of Land Use Science, 13(1-2), 146-165.
14	Thailand	TL15	Monprapussorn, S. (2018). Impact of climate and land use change on ecosystem services: A case study of Samutsakorn province, Thailand. Ecological Informatics, 47, 45-49.
15	Indonesia	IN1	Ferraro, P. J., Hanauer, M. M., Miteva, D. A., Nelson, J. L., Pattanayak, S. K., Nolte, C., & Sims, K. R. E. (2015). Estimating the impacts of conservation on ecosystem services and poverty by integrating modeling and evaluation. Proceedings of the National Academy of Sciences, 112(24), 7420-7425.
16	Indonesia	IN2	Sumarga, E., Hein, L., Edens, B., & Suwarno, A. (2015). Mapping monetary values of ecosystem services in support of developing ecosystem accounts. Ecosystem Services, 12(Supplement C), 71-83.
17	Indonesia	IN3	van Beukering, P. J. H., Cesar, H. S. J., & Janssen, M. A. (2003). Economic valuation of the Leuser National Park on Sumatra, Indonesia. Ecological Economics, 44(1), 43-62.
18	Indonesia	IN4	van Beukering, P. J. H., Kenneth Grogan, Sofie Louise Hansfort, and Daniel Seager. (2009). An Economic Valuation of Aceh's Forests: The Road Towards Sustainable Development.
19	Indonesia	IN5	Naidoo, R., Malcolm, T., & Tomasek, A. (2009). Economic benefits of standing forests in highland areas of Borneo: quantification and policy impacts. Conservation Letters, 2(1), 35-44.
20	Indonesia	IN6	Barkmann, J., Glenk, K., Keil, A., Leemhuis, C., Dietrich, N., Gerold, G., & Marggraf, R. (2008). Confronting unfamiliarity with ecosystem functions: The case for an ecosystem service approach to environmental valuation with stated preference methods. Ecological Economics, 65(1), 48-62.
21	Indonesia	IN7	Olschewski, R., Tscharntke, T., Benitez, P. C., Schwarze, S., & Klein, A. M. (2006). Economic evaluation of pollination services comparing coffee landscapes in Ecuador and Indonesia. Ecology and Society, 11(1), 14.
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23	Indonesia	IN9	Pattanayak, S. K. (2004). Valuing watershed services: concepts and empirics from southeast Asia. Agriculture Ecosystems & Environment, 104(1), 171-184.
24	Indonesia	IN10	Abram, N. K., Meijaard, E., Ancrenaz, M., Runting, R. K., Wells, J. A., Gaveau, D., . . . Mengersen, K. (2014). Spatially explicit perceptions of ecosystem services and land cover change in forested regions of Borneo. Ecosystem Services, 7(Supplement C), 116-127.
25	Indonesia	IN11	Arif Rahman Hakim, S. S., Mangara Tambunan. (2011). Economic Valuation of Nature-Based Tourism Object in Rawapening, Indonesia: An Application of Travel Cost and Contingent Valuation Method. Journal of Sustainable Development.
26	Indonesia	IN12	Bhagabati, N. K., Ricketts, T., Sulistyawan, T. B. S., Conte, M., Ennaanay, D., Hadian, O., . . . Wolny, S. (2014). Ecosystem services reinforce Sumatran tiger conservation in land use plans. Biological Conservation, 169, 147-156.

27	Indonesia	IN13	Glenk, K., Barkmann, J., Schwarze, S., Zeller, M. Marggraf, R. (2006). Differential Influence of Relative Poverty on Preferences for Ecosystem Services: Evidence from Rural Indonesia.
28	Indonesia	IN14	Law, E. A., Bryan, B. A., Meijaard, E., Mallawaarachchi, T., Struebig, M., & Wilson, K. A. (2015a). Ecosystem services from a degraded peatland of Central Kalimantan: implications for policy, planning, and management. Ecological Applications, 25(1), 70-87.
29	Indonesia	IN15	Law, E. A., Bryan, B. A., Torabi, N., Bekessy, S. A., McAlpine, C. A., & Wilson, K. A. (2015b). Measurement matters in managing landscape carbon. Ecosystem Services, 13(Supplement C), 6-15.
30	Indonesia	IN16	Malik, A., Fensholt, R., & Mertz, O. (2015). Economic Valuation of Mangroves for Comparison with Commercial Aquaculture in South Sulawesi, Indonesia. Forests, 6(9), 3028-3044.
31	Indonesia	IN17	Mathe, S., & Rey-Valette, H. (2015). Local Knowledge of Pond Fish-Farming Ecosystem Services: Management Implications of Stakeholders' Perceptions in Three Different Contexts (Brazil, France and Indonesia). Sustainability, 7(6), 7644-7666.
32	Indonesia	IN18	Mintje Wawo, L. A., Dietriech G. Bengen and Yusli Wardiatno. (2014). Valuation of Seagrass Ecosystem Services in Kotania Bay Marine Nature Tourism Park, Western Seram, Indonesia. Asian Journal of Scientific Research, 7(591-600).
33	Indonesia	IN19	Muhamad, D., Okubo, S., Harashina, K., Parikesit, Gunawan, B., & Takeuchi, K. (2014). Living close to forests enhances people′s perception of ecosystem services in a forest–agricultural landscape of West Java, Indonesia. Ecosystem Services, 8(Supplement C), 197-206.
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35	Indonesia	IN21	Pattanayak, S. K., & Wendland, K. J. (2007). Nature’s care: diarrhea, watershed protection, and biodiversity conservation in Flores, Indonesia. Biodiversity and Conservation, 16(10), 2801-2819.
36	Indonesia	IN22	Pfund, J. L., Watts, J. D., Boissiere, M., Boucard, A., Bullock, R. M., Ekadinata, A., . . . Urech, Z. L. (2011). Understanding and Integrating Local Perceptions of Trees and Forests into Incentives for Sustainable Landscape Management. Environmental Management, 48(2), 334-349.
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38	Indonesia	IN24	Sumarga, E., Hein, L., Edens, B., & Suwarno, A. (2015). Mapping monetary values of ecosystem services in support of developing ecosystem accounts. Ecosystem Services, 12(Supplement C), 71-83.
39	Indonesia	IN25	van Oudenhoven, A. P. E., Siahainenia, A. J., Sualia, I., Tonneijck, F. H., van der Ploeg, S., de Groot, R. S., . . . Leemans, R. (2015). Effects of different management regimes on mangrove ecosystem services in Java, Indonesia. Ocean & Coastal Management, 116, 353-367.
40	Indonesia	IN26	Villamor, G. B., & Noordwijk, M. (2016). Gender specific land-use decisions and implications for ecosystem services in semi-matrilineal Sumatra. Global Environmental Change-Human and Policy Dimensions, 39, 69-80.
41	Indonesia	IN27	Maresfin Rusin, N. (2007). Willingness to pay toward the conservation of ecotourism resources at Gunung Gede Pangrango National Park, West Java, Indonesia. (Masters thesis, Universiti Putra Malaysia.)

42	Indonesia	IN28	Estoque, R. C., & Murayama, Y. (2016). Quantifying landscape pattern and ecosystem service value changes in four rapidly urbanizing hill stations of Southeast Asia. Landscape Ecology, 31(7), 1481-1507.
43	Indonesia	IN29	Afentina, A., McShane, P., Plahe, J., & Wright, W. (2017). Cultural Ecosystem Services of Rattan Garden: The Hidden Values. European Journal of Sustainable Development, 6(3), 360-372.
44	Indonesia	IN30	Susilo, H., Takahashi, Y., & Yabe, M. (2017). The Opportunity Cost of Labor for Valuing Mangrove Restoration in Mahakam Delta, Indonesia. Sustainability, 9(12), 13.
45	Indonesia	IN31	Bateman, L., Yi, D., Cacho, O. J., & Stringer, R. (2018). Payments for environmental services to strengthen ecosystem connectivity in an agricultural landscape. Environment and Development Economics, 23(6), 635-654.
46	Indonesia	IN32	Fedele, G., Locatelli, B., Djoudi, H., & Colloff, M. J. (2018). Reducing risks by transforming landscapes: Cross-scale effects of land-use changes on ecosystem services. PLOS ONE, 13(4), 21.
47	Indonesia	IN33	Jaung, W., Bull, G. Q., Sumaila, U. R., Markum, & Putzel, L. (2018). Estimating water user demand for certification of forest watershed services. Journal of Environmental Management, 212, 469-478.
48	Indonesia	IN34	Kim, Y. S., Latifah, S., Afifi, M., Mulligan, M., Burke, S., Fisher, L., Siwicka, E., Remoundou, K., Christie, M., Lopez, S. M., & Jenness, J. (2018). Managing forests for global and local ecosystem services: A case study of carbon, water and livelihoods from eastern Indonesia. Ecosystem Services, 31, 153-168.
49	Indonesia	IN35	Suwarno, A., van Noordwijk, M., Weikard, H. P., & Suyamto, D. (2018). Indonesia's forest conversion moratorium assessed with an agent-based model of Land-Use Change and Ecosystem Services (LUCES). Mitigation and Adaptation Strategies for Global Change, 23(2), 211-229.
50	Indonesia	IN36	Damastuti, E., & de Groot, R. (2019). Participatory ecosystem service mapping to enhance community-based mangrove rehabilitation and management in Demak, Indonesia. Regional Environmental Change, 19(1), 65-78
51	Malaysia	MA1	Abram, N. K., Meijaard, E., Ancrenaz, M., Runting, R. K., Wells, J. A., Gaveau, D., . . . Mengersen, K. (2014). Spatially explicit perceptions of ecosystem services and land cover change in forested regions of Borneo. Ecosystem Services, 7(Supplement C), 116-127.
52	Malaysia	MA2	Abdullah, M., Mamat, M. P., Yaacob, M. R., Radam, A., & Fui, L. H. (2015). Estimate the Conservation Value of Biodiversity in National Heritage Site: A Case of Forest Research Institute Malaysia. Procedia Environmental Sciences, 30(Supplement C), 180-185.
53	Malaysia	MA3	Abd. Ghani, A. N., Othman, M. S., Yacob, M. R., Mohamed, S., & Hussin, M. Z. (1999). Economic Valuation of Forest Goods and Services of Ayer Hitam Forest, Puchong, Selangor. Pertanika Journal of Tropical Agricultural Science, 22 (2), 147-160.
54	Malaysia	MA4	Bann, C. (1999). A Contingent Valuation of the Mangroves of Benut, Johor State, Malaysia
55	Malaysia	MA5	Barau, A. S. (2015). Perceptions and contributions of households towards sustainable urban green infrastructure in Malaysia. Habitat International, 47(Supplement C), 285-297.
56	Malaysia	MA6	Ibrahim, F. H., Simin, M., & Abd. Ghani, A. N. (1999). Tree species diversity and economic value of a watershed forest in Ulu Muda Forest Reserve, Kedah. Pertanika Journal of Tropical Agricultural Science, 22 (1)(63-68).

57	Malaysia	MA7	Mohd, R. Y., Alias, R., & Ahmad, S. (2009). A Contingent Valuation Study of Marine Parks Ecotourism: The Case of Pulau Payar and Pulau Redang in Malaysia
58	Malaysia	MA8	Puan Chong Leong, M. Z., Awang Noor Abd. Ghani and Abdullah Mohd (2005). Contingent Valuation of a Malaysian Highland Forest: Non-market Benefits Accrued to Local Residents. Journal of Applied Sciences, 5(916-919).
59	Malaysia	MA9	Samdin, Z. (2008). Willingness to pay in Taman Negara: a contingent valuation method. International Journal of Economics and Management, 2 (1), 81-94
60	Malaysia	MA10	Vincent, J. R., Ahmad, I., Adnan, N., Burwell, W. B., Pattanayak, S. K., Tan-Soo, J.-S., & Thomas, K. (2016). Valuing Water Purification by Forests: An Analysis of Malaysian Panel Data. Environmental and Resource Economics, 64(1), 59-80.
61	Malaysia	MA11	Yacob, M. R., Radam, A., & Rawi, S. B. (2009). Valuing Ecotourism and Conservation Benefits in Marine Parks: The Case of Redang Island, Malaysia
62	Malaysia	MA12	Yacob, M. R., Radam, A., & Samdin, Z. (2011). Willingness to pay for domestic water service improvements in Selangor, Malaysia : a choice modeling approach. International Business and Management, 2 (2), 30-39.
63	Malaysia	MA13	Kitayama, K., Fujiki, S., Aoyagi, R., Imai, N., Sugau, J., Titin, J., Nilus, R., Lagan, P., Sawada, Y., Ong, R., Kugan, F., & Mannan, S. (2018). Biodiversity Observation for Land and Ecosystem Health (BOLEH): A Robust Method to Evaluate the Management Impacts on the Bundle of Carbon and Biodiversity Ecosystem Services in Tropical Production Forests. Sustainability, 10(11), 15.
64	Philippines	PH1	Garcia, J. N. M., Aguilar, E. A., Sangalang, J. B., Alcantara, A. J., Habito, R. C. E., Medina, C. P., & Malayang, B. (2009). Valuation of Ecosystem Services of Coconut Types: Framework and Methodology Development. Journal of Environmental Science and Management, 12(1), 68-81.
65	Philippines	PH2	Arin, T., & Kramer, R. A. (2002). Divers' willingness to pay to visit marine sanctuaries: an exploratory study. Ocean & Coastal Management, 45(2), 171-183.
66	Philippines	PH3	Samonte-Tan, G. P. B., White, A. T., Tercero, M. A., Diviva, J., Tabara, E., & Caballes, C. (2007). Economic Valuation of Coastal and Marine Resources: Bohol Marine Triangle, Philippines. Coastal Management, 35(2-3), 319-338.
67	Philippines	PH4	Vista, A. B., & Rosenberger, R. S. (2015). Estimating the Recreational Value of Taal Volcano Protected Landscape, Philippines Using Benefit Transfer. Journal of Environmental Science and Management.
68	Philippines	PH5	Estoque, R. C., & Murayama, Y. (2012). Examining the potential impact of land use/cover changes on the ecosystem services of Baguio city, the Philippines: A scenario-based analysis. Applied Geography, 35(1), 316-326.
69	Philippines	PH6	Estoque, R. C., & Murayama, Y. (2013). Landscape pattern and ecosystem service value changes: Implications for environmental sustainability planning for the rapidly urbanizing summer capital of the Philippines. Landscape and Urban Planning, 116(Supplement C), 60-72.
70	Philippines	PH7	Diamante-Camacho, L., Camacho, S. C., & Yeo-Chang, Y. (2009). Values of forest products in the makiling forest reserve (MFR), Philippines. Forest Science and Technology, 5(2), 35-44.
71	Philippines	PH8	Ahmed, M., Umali, G. M., Chong, C. K., Rull, M. F., & Garcia, M. C. (2007). Valuing recreational and conservation benefits of coral reefs—The case of Bolinao, Philippines. Ocean & Coastal Management, 50(1), 103-118.

72	Philippines	PH9	Tekken, V., Spangenberg, J. H., Burkhard, B., Escalada, M., Stoll-Kleemann, S., Truong, D. T., & Settele, J. (2017). “Things are different now”: Farmer perceptions of cultural ecosystem services of traditional rice landscapes in Vietnam and the Philippines. Ecosystem Services, 25(Supplement C), 153-166.
73	Philippines	PH10	Burkhard, B., Müller, A., Müller, F., Grescho, V., Anh, Q., Arida, G., Bustamante, J. V., Van Chien, H., Heong, K. L., Escalada, M., Marquez, L., Thanh Truong, D., Villareal, S., & Settele, J. (2015). Land cover-based ecosystem service assessment of irrigated rice cropping systems in southeast Asia—An explorative study. Ecosystem Services, 14(Supplement C), 76-87.
74	Philippines	PH11	Estoque, R. C., & Murayama, Y. (2016). Quantifying landscape pattern and ecosystem service value changes in four rapidly urbanizing hill stations of Southeast Asia. Landscape Ecology, 31(7), 1481-1507.
75	Philippines	PH12	Langerwisch, F., Vaclavik, T., von Bloh, W., Vetter, T., & Thonicke, K. (2018). Combined effects of climate and land-use change on the provision of ecosystem services in rice agro-ecosystems. Environmental Research Letters, 13(1), 12.
76	Philippines	PH13	Tamayo, N. C. A., Anticamara, J. A., & Acosta-Michlik, L. (2018). National Estimates of Values of Philippine Reefs' Ecosystem Services. Ecological Economics, 146, 633-644.
77	Vietnam	VN1	Tekken, V., Spangenberg, J. H., Burkhard, B., Escalada, M., Stoll-Kleemann, S., Truong, D. T., & Settele, J. (2017). “Things are different now”: Farmer perceptions of cultural ecosystem services of traditional rice landscapes in Vietnam and the Philippines. Ecosystem Services, 25(Supplement C), 153-166.
78	Vietnam	VN2	Burkhard, B., Müller, A., Müller, F., Grescho, V., Anh, Q., Arida, G., Bustamante, J. V., Van Chien, H., Heong, K. L., Escalada, M., Marquez, L., Thanh Truong, D., Villareal, S., & Settele, J. (2015). Land cover-based ecosystem service assessment of irrigated rice cropping systems in southeast Asia—An explorative study. Ecosystem Services, 14(Supplement C), 76-87.
79	Vietnam	VN3	Quyen, N. T. K., Berg, H., Gallardo, W., & Da, C. T. (2017). Stakeholders’ perceptions of ecosystem services and Pangasius catfish farming development along the Hau River in the Mekong Delta, Vietnam. Ecosystem Services, 25, 2-14.
80	Vietnam	VN4	Loc, H. H., Thi Hong Diep, N., Can, N. T., Irvine, K. N., & Shimizu, Y. (2016). Integrated evaluation of Ecosystem Services in Prawn-Rice rotational crops, Vietnam. Ecosystem Services.
81	Vietnam	VN5	Zavalloni, M., Groeneveld, R. A., & van Zwieten, P. A. M. (2014). The role of spatial information in the preservation of the shrimp nursery function of mangroves: A spatially explicit bio-economic model for the assessment of land use trade-offs. Journal of Environmental Management, 143, 17-25.
82	Vietnam	VN6	McDonough, S., Gallardo, W., Berg, H., Trai, N. V., & Yen, N. Q. (2014). Wetland ecosystem service values and shrimp aquaculture relationships in Can Gio, Vietnam. Ecological Indicators, 46, 201-213.
83	Vietnam	VN7	Berg, H., Söderholm, A. E., Söderström, A.-S., & Tam, N. T. (2017). Recognizing wetland ecosystem services for sustainable rice farming in the Mekong Delta, Vietnam. Sustainability Science, 12(1), 137-154.
84	Vietnam	VN8	Pham, L. T. H., & Brabyn, L. (2017). Monitoring mangrove biomass change in Vietnam using SPOT images and an object-based approach combined with machine learning algorithms. Isprs Journal of Photogrammetry and Remote Sensing, 128, 86-97.

85	Vietnam	VN9	Nam, P. K., Son, T. V .H., Cesar, H., Pollnac, R . (2005). Financial sustainability of the Hon Mun Marine Protected Area: Lessons for other marine parks in Vietnam.
86	Vietnam	VN10	Quoc Vo, T., Kuenzer, C., & Oppelt, N. (2015). How remote sensing supports mangrove ecosystem service valuation: A case study in Ca Mau province, Vietnam. Ecosystem Services, 14(Supplement C), 67-75.
87	Vietnam	VN11	Kuenzer, C., & Tuan, V. Q. (2013). Assessing the ecosystem services value of Can Gio Mangrove Biosphere Reserve: Combining earth-observation- and household-survey-based analyses. Applied Geography, 45, 167-184.
88	Vietnam	VN12	Do, T. N., & Bennett, J. (2009). Estimating wetland biodiversity values: a choice modelling application in Vietnam's Mekong River Delta. Environment and Development Economics, 14(2), 163-186.
89	Vietnam	VN13	Hall, J. M., Van Holt, T., Daniels, A. E., Balthazar, V., & Lambin, E. F. (2012). Trade-offs between tree cover, carbon storage and floristic biodiversity in reforesting landscapes. Landscape Ecology, 27(8), 1135-1147.
90	Vietnam	VN14	Tuan, T. H., Van Xuan, M., Nam, D., & Navrud, S. (2009). Valuing direct use values of wetlands: A case study of Tam Giang–Cau Hai lagoon wetland in Vietnam. Ocean & Coastal Management, 52(2), 102-112.
91	Vietnam	VN15	Nguyen, T. T., Pham, V. D., & Tenhunen, J. (2013). Linking regional land use and payments for forest hydrological services: A case study of Hoa Binh Reservoir in Vietnam. Land Use Policy, 33(Supplement C), 130-140.
92	Vietnam	VN16	Orchard, S. E., Stringer, L. C., & Quinn, C. H. (2016). Mangrove system dynamics in Southeast Asia: linking livelihoods and ecosystem services in Vietnam. Regional Environmental Change, 16(3), 865-879.
93	Vietnam	VN17	Estoque, R. C., & Murayama, Y. (2016). Quantifying landscape pattern and ecosystem service value changes in four rapidly urbanizing hill stations of Southeast Asia. Landscape Ecology, 31(7), 1481-1507.
94	Vietnam	VN18	UNEP. (2015). Success Stories in Mainstreaming Ecosystem Services into Macro-economic Policy and Land Use Planning: Evidence from Chile, Trinidad and Tobago, South Africa and Viet Nam
95	Vietnam	VN19	Dang, K. B., Burkhard, B., Muller, F., & Dang, V. B. (2018). Modelling and mapping natural hazard regulating ecosystem services in Sapa, Lao Cai province, Vietnam. Paddy and Water Environment, 16(4), 767-781.
96	Vietnam	VN20	Dang, K. B., Windhorst, W., Burkhard, B., & Müller, F. (2019). A Bayesian Belief Network – Based approach to link ecosystem functions with rice provisioning ecosystem services. Ecological Indicators, 100, 30-44.
97	Vietnam	VN21	An, L. T., Markowski, J., Bartos, M., Thoai, T. Q., Tuan, T. H., & Rzenca, A. (2018). Tourist and Local Resident Preferences for the Northern Yellow-Cheeked Gibbon (Nomascus annamensis) Conservation Program in the Bach Ma National Park, Central Vietnam. Tropical Conservation Science, 11, 16.
98	Vietnam	VN22	Langerwisch, F., Vaclavik, T., von Bloh, W., Vetter, T., & Thonicke, K. (2018). Combined effects of climate and land-use change on the provision of ecosystem services in rice agro-ecosystems. Environmental Research Letters, 13(1), 12.
99	Vietnam	VN23	Loc, H. H., Ballatore, T. J., Irvine, K. N., Diep, N. T. H., Tien, T. T. C., & Shimizu, Y. (2018a). Socio-geographic indicators to evaluate landscape Cultural Ecosystem Services: A case of Mekong Delta, Vietnam. Ecosystem Services, 31, 527-542.

100	Vietnam	VN24	Loc, H. H., Diep, N. T. H., Tuan, V. T., & Shimizu, Y. (2018b). An analytical approach in accounting for social values of ecosystem services in a Ramsar site: A case study in the Mekong Delta, Vietnam. Ecological Indicators, 89, 118-129.
101	Vietnam	VN25	Ngoc, Q. T. K. (2019). Assessing the value of coral reefs in the face of climate change: The evidence from Nha Trang Bay, Vietnam. Ecosystem Services, 35, 99-108.
102	Cambodia	CBD1	Kibria, A. S. M. G., Behie, A., Costanza, R., Groves, C., & Farrell, T. (2017). The value of ecosystem services obtained from the protected forest of Cambodia: The case of Veun Sai-Siem Pang National Park. Ecosystem Services, 26(Part A), 27-36.
103	Cambodia	CBD2	Watkins, K., Sovann, C., Brander, L., Neth, B., Chou, P., Spoann, V., Hoy, S., Choeun, K., & Aing, C. (2016). Mapping and Valuing Ecosystem Services in Mondulkiri: Outcomes and Recommendations for Sustainable and Inclusive Land Use Planning in Cambodia.
104	Cambodia	CBD3	Arias, M. E., Cochrane, T. A., Lawrence, K. S., Killeen, T. J., & Farrell, T. A. (2011). Paying the forest for electricity: a modelling framework to market forest conservation as payment for ecosystem services benefiting hydropower generation. Environmental Conservation, 38(4), 473-484.
105	Laos	LA1	Pfund, J. L., Watts, J. D., Boissiere, M., Boucard, A., Bullock, R. M., Ekadinata, A., . . . Urech, Z. L. (2011). Understanding and Integrating Local Perceptions of Trees and Forests into Incentives for Sustainable Landscape Management. Environmental Management, 48(2), 334-349.
106	Laos	LA2	Jensen, A. (2009). Valuation of non-timber forest products value chains. Forest Policy and Economics, 11(1), 34-41.
107	Laos	LA3	Rasmussen, L. V., Mertz, O., Christensen, A. E., Danielsen, F., Dawson, N., & Xaydongvanh, P. (2016). A combination of methods needed to assess the actual use of provisioning ecosystem services. Ecosystem Services, 17, 75-86.
108	Laos	LA4	Yoshida, A., Chanhda, H., Ye, Y.-M., & Liang, Y.-R. (2010). Ecosystem service values and land use change in the opium poppy cultivation region in Northern Part of Lao PDR. Acta Ecologica Sinica, 30(2), 56-61.
109	Singapore	SIN1	Thiagarajah, J., Wong, S. K. M., Richards, D. R., & Friess, D. A. (2015). Historical and contemporary cultural ecosystem service values in the rapidly urbanizing city state of Singapore. Ambio, 44(7), 666-677.
110	Singapore	SIN2	Richards, D. R., & Tunçer, B. (2017). Using image recognition to automate assessment of cultural ecosystem services from social media photographs. Ecosystem Services.
111	Myanmar	MY1	Estoque, R. C., & Murayama, Y. (2016). Quantifying landscape pattern and ecosystem service value changes in four rapidly urbanizing hill stations of Southeast Asia. Landscape Ecology, 31(7), 1481-1507.
112	Myanmar	MY2	Mandle, L., Wolny, S., Bhagabati, N., Helsingen, H., Hamel, P., Bartlett, R., Dixon, A., Horton, R., Lesk, C., Manley, D., De Mel, M., Bader, D., Myint, S. N. W., Myint, W., & Mon, M. S. (2017). Assessing ecosystem service provision under climate change to support conservation and development planning in Myanmar. PLOS ONE, 12(9), 23.
113	Myanmar	MY3	Estoque, R. C., Myint, S. W., Wang, C. Y., Ishtiaque, A., Aung, T. T., Emerton, L., Ooba, M., Hijioka, Y., Mon, M. S., Wang, Z., & Fan, C. (2018). Assessing environmental impacts and change in Myanmar's mangrove ecosystem service value due to deforestation (2000-2014). Global Change Biology, 24(11), 5391-5410.

114	Myanmar	MY4	Feurer, M., Heinimann, A., Schneider, F., Jurt, C., Myint, W., & Zaehringer, J. G. (2019). Local Perspectives on Ecosystem Service Trade-Offs in a Forest Frontier Landscape in Myanmar. Land, 8(3), 19.
115	SEA	SEA1	TEEB. (2012). The Economics of Ecosystems and Biodiversity for Southeast Asia (ASEAN TEEB). Coral reef ecosystem service values.
116	SEA	SEA2	TEEB. (2012). The Economics of Ecosystems and Biodiversity for Southeast Asia (ASEAN TEEB). Mangrove ecosystem service values
117	SEA	SEA3	M. Brander, L., J. Wagtendonk, A., S. Hussain, S., McVittie, A., Verburg, P. H., de Groot, R. S., & van der Ploeg, S. (2012). Ecosystem service values for mangroves in Southeast Asia: A meta-analysis and value transfer application. Ecosystem Services, 1(1), 62-69.
118	Lower MK (Thailand 12, Vietnam 18, Lao 5, Cambodia 4)	LMK	Trisurat, Y., Aekakkararungroj, A., Ma, H. O., & Johnston, J. M. (2018). Basin-wide impacts of climate change on ecosystem services in the Lower Mekong Basin. Ecological Research, 33(1), 73-86.

Appendix A3

Review database's structure

A3.1 Author and project

Total research No	Country No	Country	Year	First author based in home country (1: Yes, 0:No)	First author based in Other country	Type	Project	Funded/award	Funding organization/project name	Fund by home country	Other
1	1	Thailand	2016								
2	2	Thailand	2015								
3	3	Thailand	2008								
…	…	…	…								
117	3	SEA	2012								
118	4	Lower MK	2017								

A3.2 Spatial and time scale

Total research No	Country No	Country	Year	Location	Scale					Time scale				Resolution					
					Local-Patch/village level or small scale (< 100 km2)	Regional-sub provincial-provincial/state or sub-national (100 - 10^5 km2	National (10^5 - 10^6 km2)	Multi-national (>10^6 km2	Multi-scale	Historical change over time	Single point in time	Future outcome short term (Scenario)	Future outcome medium term or long term (Scenario)	< 10 m	10 - 50	50 - 200	200 - 1000	>1000	Un-known
1	1	Thailand	2016																
2	2	Thailand	2015																
3	3	Thailand	2008																
4	4	Thailand	2016																
5	5	Thailand	2015																

A3.3 Ecosystem

Total research No	Country No	Country	Year	Forest	Wetland	Agro-forest	Agriculture	Marine ecosystem	Urban	Fresh water	Mixed
1	1	Thailand	2016								
2	2	Thailand	2015								
3	3	Thailand	2008								
4	4	Thailand	2016								

A3.4 ES type

Country No	Country	Year	Provisioning						Regulating									Cultural& Amenity					Supporting/Habitat	
			Medicine	Water	Food	Raw materials	Genetic resource	Ornamental resources	Erosion prevention	Climate regulation	Biological control	Pollination	Air quality regulation	Maintenance of soil fertility	Regulation of water flows	Moderation of extreme events	Waste treatment	Aesthetic information	Recreation and tourism	Inspiration for culture, art, design	Spiritual experience	Information for cognitive development	Maintenance of life cyles	Maintenance of Genetic Diversity
1	Thailand	2016																						
2	Thailand	2015																						
3	Thailand	2008																						
4	Thailand	2016																						

A3.5 Method and data

Country No	Country	Year	Economic valuation	Mapping	Perception assessment	Other quantitative assessment	Economic valuation and Mapping	Economic valuation and Other quantitative assessment	Perception assessment and Mapping	Economic evaluation										Mapping				Perception			Other quantitative assessment approach
										Contingent valuation	Travel cost	Market price	Choice experiment	Replacement cost	Damage cost	Benefit transfer	Net present value	Resource Rent	Other economic valuation	Ecosystem service model	Other modelling approach	Proxy	Other mapping methods	Questionnaire survey	Interview	Focus group	
1	Thailand	2016																									
2	Thailand	2015																									
3	Thailand	2008																									

Country No	Country	Year	Secondary data														Primary data			
			Land-use/land-cover map	DEM	Soil map	Topographic map	Hydrological map	Road map	Evapotranspiration data	Precipitation data	Temperature	Population density	Soil properties	Statistical data	Result of previous studies	*Remote sensing data*	Questionnaire, Interview, Focus group	Field data collection	*Sampling method*	*No of samples*
1	Thailand	2016																		
2	Thailand	2015																		
3	Thailand	2008																		

A3.6 Result validation

Total research No	Country No	Country	Year	Accuracy assessment of ES assessment	
				Mention	Detail
1	1	Thailand	2016		
2	2	Thailand	2015		
3	3	Thailand	2008		
4	4	Thailand	2016		

A3.7 Policy

Total research No	Country No	Country	Year	Land use policy/planning	Waste managemt	Conservation strategy	Risk management	Climate change mitigation	Sustainable management
1	1	Thailand	2016						
2	2	Thailand	2015						
3	3	Thailand	2008						
4	4	Thailand	2016						
5	5	Thailand	2015						
6	6	Thailand	2013						
7	7	Thailand	2016						

Appendix B1

Contents

Table B1.1 Symbols and definitions of frequently used parameters in the guidelines for parameterising soil hydraulic properties and LUCI_PTFs tool

Symbol	Parameter	Unit*	Definition
Greek symbols			
α_{vG}	Parameter of the van Genuchten (1980) equation	cm^{-1}	The parameter corresponds approximately to the inverse of the air-entry value (USDA, 2010)
θ	Volumetric soil moisture content	cm^3cm^{-3}	The ratio of water volume to soil volume.
θ_i	Volumetric initial soil moisture content	cm^3cm^{-3}	The soil moisture content at the onset of a rain event
θ_r	Volumetric residual soil moisture content	cm^3cm^{-3}	Here we introduce several widely known definitions: - Lebedeff (1927) defined residual moisture content as the maximum molecular moisture holding capacity when an increase in suction had little effect on the soil moisture content. - Brooks and Corey (1964) defined residual moisture content as the moisture content at which soil suction reach infinity. - Van Genuchten (1980) defined the residual moisture content as the moisture content for which the gradient d θ/dh becomes zero. From a practical point of view it seems sufficient to define θ_r as the moisture content at some large negative value of the pressure head, e.g., at the permanent wilting point (h = -15,000 cm or ψ = -1500 kPa). - Van Genuchten et al. (1991) defined the residual moisture content as the moisture content at which the slope of the soil moisture retention curve and coefficient of permeability go to zero when soil suction becomes large. - Nitao and Bear (1996) suggested that the residual moisture content is related to the lowest measured moisture content (more a maximum suction measurable by instrument than an actual physical constant). - Jackson (2007) the residual moisture content represents the moisture content beyond which unfeasible amounts of pressure potential are required to extract water from the soil pores. The soil moisture characteristic curve is a continuous function and there is no specific point that can be called the residual moisture content. Currently, most investigators treat residual moisture content as a fitting parameter with no real physical significance (Vanapalli et al., 1998).
θ_s	Volumetric soil moisture content at saturation	cm^3cm^{-3}	Saturated moisture content is the moisture content at saturation when all soil pores are filled with water. It presents the maximum amount of water a soil can store. It is closely related to the total soil porosity.
$\theta(h)$	Volumetric soil moisture content-pressure head curve or soil moisture retention curve		The relationship between soil moisture and pressure head.

Symbol	Parameter	Unit*	Definition
λ_{BC}	Brooks-Corey pore size distribution index	dimensionless	Fitting parameter of the Brooks-Corey equation
ϕ	Porosity	cm^3cm^{-3}	The amount of pore spaces between soil particles. The larger the amount, the more water the soil can hold and transport.
ϕ_e	Effective porosity	cm^3cm^{-3}	Effective porosity is approximately equalling to porosity minus volumetric soil moisture content at field capacity
φ	Water pressure	kPa	Water pressure can be expressed kPa when potential energy is expressed per unit volume (J m-3 = N m m-3=N m-2= Pa).
Roman alphabet			
BD	Bulk density	$g\ cm^{-3}$	The dry weight of a soil sample per unit volume, thereby representing the percentage of pore spaces and level of compaction. The close association between bulk density and organic matter content, infiltration rate, hydraulic conductivity, biological activity makes it a crucial index for soil functioning
CEC	Cation exchange capacity	$cmol_c\ kg^{-1}$	Represents the quantity of negative charge available to attract cations
Cl	Clay	%	Clay content in soil texture, particles size < 0.002 mm
DW	Drainable water	cm^3cm^{-3}	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)
FC	Field capacity	cm^3cm^{-3}	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) - Gijsman et al. (2007): "FC is the drained upper limit." (p.93) - 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 purpose, 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).

Symbol	Parameter	Unit*	Definition
			Some examples of different pressures used to define FC are: FSL New Zealand soil map and Hihydro soil data use -10kPa to define FC, SoilGrids map defines FC at several pressure potentials, at -10 kPa (pF 2.0), -20 kPa (pF2.3) and -33 kPa (pF2.5); -33 kPa was used to define FC for the soil in Mekong Delta, Vietnam (Nguyen et al., 2015) and the study by Sommer et al. (2008) defined FC at -6 kPa (60 cm or pF1.8).
h	Soil water pressure	cm	The height of water column in a soil expressed relative to atmospheric pressure (gauge pressure). Potential energy is expressed per unit weight ($J\ N^{-1} = m$).
h_b	Brooks-Cory air entry pressure or bubbling pressure	cm	The air-entry value is identified as the point at the largest pores which air can enter into the soil.
HG	Hydroscopic water		HG is water held below wilting point
K	Soil hydraulic conductivity	$mm\ hr^{-1}$	The ease with which pores of a saturated soil permit water movement (USDA).
K(h)	Hydraulic conductivity curve		The relationship between hydraulic conductivity and pressure head.
K(θ)	Hydraulic conductivity curve		The relationship between hydraulic conductivity and moisture content.
K_{sat}	Saturated hydraulic conductivity	$mm\ hr^{-1}$	Saturated hydraulic conductivity is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient. It can be thought of as the ease with which pores of a saturated soil permit water movement (USDA). K_{sat} differed with vegetation type and soil depth, and the impact of vegetation type on K_{sat} was dependent on soil depth. K_{sat} did not differ among vegetation types at soil depths of 0–10 and 20–30 cm, but was significantly lower in managed forest types (mixed evergreen broad-leaved and coniferous forests, bamboo forests, and tea gardens) than native evergreen broadleaf forests at a depth of 10–20 cm.
l_{MvG}	A lumped parameter that accounts for pore tortuosity and pore connectivity	Dimensionless	Fitting parameter of Mualem van Genuchten equation.
m_{vG}	Exponent parameter in the van Genuchten (1980) equation	dimensionless	Fitting parameter of van Genuchten equation.
n_{vG}	Curve shape parameter in the van Gencuhten (1980) equation	dimensionless	Fitting parameter of van Genuchten equation.
NRAW	Not readily available water	$cm^3 cm^{-3}$	NAW is water held between stomata closure point and permanent wilting point:

Symbol	Parameter	Unit*	Definition
			NAW = Stomata closure point (WSC)- Permanent wilting point (PWP).
OC	Organic carbon	%	Organic carbon content in soil.
OM	Organic matter	%	Organic matter content in soil.
PAW	Total plant available water	%	Plant available water is water held from field capacity (an upper limit 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 can be extracted by plants PAW = Field capacity (FC) – PWP (Permanent wilting point)
pH			The acidity or basicity of soil.
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 moisture potential of pF 4.2, pF = log10 (-cm pressure head) (Gijsman et al., 2007).
RAW	Readily plant available water	%	Portion of the available water holding capacity is 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 LUCI_PTFs toolbox, the fraction default value is 0.5 but users can define the fraction themselves.
Sa	Sand	%	Sand content in soil texture, particle size 0.05 - 2 mm (USDA); 0.063 – 2 mm (FAO); 0.06 - 2.0 mm (NZ)
SAT	Saturated point		SAT present the maximum amount of water can be hold 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”; hence in practice SAT is often estimated as 0.95 of total measured porosity.
Se		mm hr^{-1}	Relative saturation
Si	Silt	%	Silt content in soil texture, particle size 0.002 - 0.05 mm (USDA); 0.002 - 0.063 mm (FAO); 0.002 – 0.06 mm (NZ)
TWC	Total water content	%	TWC = Moisture content at saturation - Moisture content at wilting point at wilting point.
w	Gravimetric water content at a specific matric potential	kg kg^{-1}	The ratio between mass of water to that of soil (solid).
WSC	Water at plants’ stomata close point	cm^3cm^{-3}	WSC is the point at which plants’ stomata close due to water stress. WSC is also called critical point or refill point in some literatures (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

Symbol	Parameter	Unit*	Definition
			hardy crops (cotton, sorghum etc.) at -100 kPa (WADAF, 2019). Other example, Hihydro soil data uses pF 3.0 (1,000 cm or -100 kPa) to define stomata closure point

(*): The unit is used in the guideline and LUCI_PTFs tool

Table B1.2 Soil properties information available in global and regional databases

Database	Type of data	Soil moisture content and hydraulic conductivity	Other soil properties	Description formation	Availability	Coverage
The World Soil Information Service (WoSIS) Soil Profile Database Year update: 2019	Tabulate data and point data	W_{-6kPa}; W_{-10kPa}; W_{-33kPa}; $W_{-100kPa}$; $W_{-200kPa}$; $W_{-500kPa}$; $W_{-1500kPa}$ θ_{-6kPa}; θ_{-10kPa}; θ_{-33kPa}; $\theta_{-100kPa}$; $\theta_{-200kPa}$; $\theta_{-500kPa}$; $\theta_{-1500kPa}$	Physical properties: soil texture (Sa, Si, Cl); BD; coarse fragments Chemical properties: OC; TOTC (total carbon); TOTN (total nitrogen); TOTP (total phosphorus), pH, CEC (Cation exchange capacity), ECE (Electrical conductivity)	- Each profile was provided with the original soil classification (FAO, WRB, USDA). - Comprised of 196,498 geo-referenced profiles originating from 173 countries. - Information contains depth of soil samples, both topsoil and subsoil.	Free	Global
WISE - Global Soil Profile Data, version 3.1 Year update: 2009	Tabulate data	θ_{-10kPa}; θ_{-33kPa}; $\theta_{-1500kPa}$	Physical properties: soil texture (Sa, Si, Cl, gravel); BD Chemical properties: OC; $CaCO_3$; $CASO_4$; pH; CEC; ECE	- All profiles have been harmonized with respect to the original Legend (1974) and Revised Legend (1988) of FAO-Unesco. - 10,250 soil profiles, with some 47,800 horizons, from 149 countries, including many tropical soils samples. - Information of sequential horizon number, numbered from the top down	Free	Global
The UNsaturated SOil hydraulic DAtabase (UNSODA 2.0) Year update: 2020	Tabulate data	θ_s, $\theta(h)$ K_{sat}, $K(h)$	Physical properties: soil texture (Sa, Si, Cl); BD; PD (particle density); SAR (Sodium Adsorption Ratio), ESP (Exchangeable Sodium Percentage) Chemical properties: OM; pH, CEC, ECE, Fe and Al Oxide	- USDA-SCS soil textural classes - 790 soil samples from around the world - Were the first truly international soil hydraulic databases - Information contain depth of soil samples, both topsoil and subsoil - Very few tropical soils	Free	Global
The Grenoble soil catalogue GRIZZLY (the original link cannot be found) Year update: 1996	Tabulate data	θ_s, $\theta(h)$ K_{sat} (some), $K(h)$ (some)	Physical properties: soil texture (Sa, Si, Cl); BD	- 660 soil water retention from different countries - Very few tropical soils	Free, request needed	Mostly Europe, USA

Database	Type of data	Soil moisture content and hydraulic conductivity	Other soil properties	Description formation	Availability	Coverage
Information collected from (Nemes, 2011)		Brook-Corey equation parameters: h_b, λ_{BC} and van Genuchten equation parameters: αV_G, n_{VG}, m_{VG}				
Hydraulic Properties of European Soils (HYPRES) Year update: 1998	Tabulate data Information integrated in the 1: 1 000 000 scale soil map of Europe	θ_s; θ_r, θ_{FC}, θ_{PWP}, α_{MvG}, n_{MvG}, m_{MvG}, l_{MvG} K_{sat}, K(h): K_{0kPa}, K_{-1kPa}, K_{-2kPa}, K_{-5kPa}, K_{-10kPa}, K_{-20kPa}, K_{-25kPa}, K_{-50kPa}, $K_{-100kPa}$, $K_{-200kPa}$, $K_{-1000kPa}$, $K_{-1500kPa}$, $K_{-1600kPa}$	Physical properties: soil texture (Sa, Si, Cl); BD; PD Chemical properties: OM	- FAO soil legend - has approximately 4900 soil horizons - Information of topsoil and subsoil	Limited by license agreements or the need for an agreement with the author(s) or owners	Europe
National Cooperative Soil Survey – soil Characterisation Data (NCSS) Year update: 2014	Tabulate data and point data	θ_{-6kPa}; θ_{-10kPa}; θ_{-33kPa}; $\theta_{-100kPa}$; $\theta_{-200kPa}$; $\theta_{-500kPa}$; $\theta_{-1500kPa}$	Physical properties: soil texture (Sa, Si, Cl); BD Chemical properties: OC; TOTC; TOTN; TOTS; CEC; ECE; pH; Fe Oxide; Al Oxide; Gypsum etc.	- USDA soil textural classes - More than 100,000 samples - Information of sequential horizon number, numbered from the top down - The data can be read using soilDB package (CRAN R-project)	Free	USA
IGBP-DIS database Year update: 2014	Tabulate data and gridded map	θ_s, θ_r, θ_{FC}, θ_{PWP}, α_{vG}, n_{vG}, m_{vG}, l_{MvG} $\theta_{pF0.0}$; $\theta_{pF1.0}$; $\theta_{pF1.5}$; $\theta_{pF1.7}$; $\theta_{pF2.0}$; $\theta_{pF2.3}$; $\theta_{pF2.5}$; $\theta_{pF2.7}$; $\theta_{pF3.4}$; $\theta_{pF3.7}$; $\theta_{pF4.2}$ Available Water Capacity K_{sat}; K(h)	Physical properties: soil texture (Sa, Si, Cl); Gravel; BD Chemical properties: OC; TOTN; Extractable phosphorus; $CaCO_3$; CEC; ECE; pH; Gypsum; Soil carbon density; Exchangeable sodium; Exchangeable potassium; Exchangeable aluminium	- 131,472 soil samples, originating from 20,920 profiles, includes much of NRCS-NSSC samples, contains tropical and subtropical samples	Free	Global
SoilGrids 250m & 1km Year update: 2017	Grided map	θ_{FC} (pF2.0, pF2.3 and pF 2.5); θ_{PWP}	Physical properties: soil texture (Sa, Si, Cl); Coarse fragments; BD Chemical properties: OC; CEC; N (Nitrogen); pH	- SoilGrids prediction models are fitted using over 230 000 soil profile observations from the WoSIS database and a series of environmental covariates - World Reference Base soil groups, and USDA Soil Taxonomy suborders	Free	Global

Database	Type of data	Soil moisture content and hydraulic conductivity	Other soil properties	Description formation	Availability	Coverage
				- Global soil property maps at six standard depth intervals (0-5; 5-15; 15-30; 30-60; 60-100; 100-200)		
Hihydro soil data 1km Year update: 2016	Grided map	θ_s; θ_r; θ_{FC} (θ_{pF2}); θ_{WSC} (θ_{pF3}); θ_{PWP} ($\theta_{pF4.2}$); α_{vG}, n_{vG} K_{sat} USDA hydrologic soil group	Physical properties: soil texture (Sa, Si, Cl) Chemical properties: OM	- Based on SoilGrid 1km - Every variable is given for six different (standard) depths (0-5; 5-15; 15-30; 30-60; 60-100; 100-200)	Free	Global
Soil Water Infiltration Global (SWIG) database	Tabulate data	θ_s; θ_r; θ_i; θ_{FC}; θ_{PWP} K_{sat}	Physical properties: soil texture (Sa, Si, Cl); gravel; BD; PD; dg (geometric mean diameter); Sg (standard deviation of soil particle sizes) Chemical properties: OC; EC; pH; Gypsum; CCE; CEC; Soil sodium adsorption ratio (SAR)	- 5023 soil water infiltration measurements derived from 54 countries - The World Reference Base (WRB) and USDA soil taxonomy systems based on the SoilGrids	Free	Global – 54 countries
Global Soil Dataset for use in Earth System Models (GSDE), 1km and 10km Year update: 2019	Map	θ_{-10kPa}; θ_{-33kPa}; $\theta_{-1500kPa}$	Physical properties: soil texture (Sa, Si, Cl); BD Chemical properties: OC	- Based on the 1:5 million scale Digital Soil Map of the World (DSMW) and various regional and national soil databases (WISE 3.1, NCSS 2011)	Free, registration required	Global
The SoilKsatDB Year update: 2020	Tabulate data and point data; 1km resolution gridded map	θ_s, θ_{FC}, θ_{PWP} K_{sat}	Physical properties: soil texture, BD Chemical properties: OC	- 1,910 sites with 13,267 K_{sat} measurements were assembled from published literature and other sources, standardized, and quality-checked in order to provide a global database of soil saturated hydraulic conductivity - The SoilKsatDB covers most global regions, with the highest data density from the USA, followed by Europe, Asia, South America, Africa, and Australia	Free	Global
A High-Resolution Global Map of Soil Hydraulic Properties 1km Year update: 2018	Gridded map, GeoTIFF format	Mean and standard deviation of Kosugi model's parameters ($\log_{10}$(hm), $\log_{10}$(K_{sat}), θ_s; θ_r) Mean and standard deviation of θ_{FC}; K_{sat} Mean plant available water (PAW)		- Based on SoilGrids 1km	Free	Global

Database	Type of data	Soil moisture content and hydraulic conductivity	Other soil properties	Description formation	Availability	Coverage
Global soil hydraulic properties map Year update: 2017	Gridded map	θ_s; θ_r; α_{vG}, n_{vG} K_{sat}		- Based on SoilGrids 1km	Free	Global
Europe Year update: 2016	Gridded map, GeoTIFF format	Topsoil's hydraulic parameters: θ_s, θ_{FC}, θ_{PWP} K_{sat}		- Used the European Soil Database - FAO texture class - Equation of Toth et al., (2014)	Free, request needed	Global
China Dataset of Soil Hydraulic Parameter by Dai et. al (2013) Year Update: 2013	Gridded map 1km (30 arc seconds)	Mualem van Genuchten parameters (θ_s; θ_r, α_{vG}, n_{vG}, m_{vG} K_{sat}), Clapp and Hornberger parameters (θ_s, h_s, λ_{CH}, K_{sat}), θ_{-33kPa}; $\theta_{-1500kPa}$ for seven soil layers to depth of 1.38m		- The Chinese soil characteristics dataset was derived by using the 1:1 000 000 Soil Map of China and 8595 representative soil profiles - 5 PTFs to derive the parameters in the Clapp and Hornberger functions and the van Genuchten and Mualem functions and 10 PTFs for soil water contents at capillary pressures of 33 and 1500 kPa. - The inputs into the PTFs include soil particle size distribution, bulk density, and soil organic matter.	Free	China
South America (15 arcsec resolution, approximately 450m) Year update: 2014	Gridded map, GeoTIFF and NetCDF format	Hydraulic parameter values for the Brooks and Corey, Campbell, van Genuchten–Mualem and van Genuchten–Burdine soil hydraulic models		- Used update PTFs derived for South American soils - Soil profile of water movement to 30cm depth	Free	Tropical South America
Hydrophysical Database for Brazilian Soils (HYBRAS) Year update: 2018	Tabulate data	θ_{0kPa}; θ_{-10kPa}; θ_{-6kPa}; θ_{-33kPa}; $\theta_{-1500kPa}$ θ_s; θ_r, α_{vG}, n_{vG}, m_{vG} K_{sat}	Physical properties: soil texture (Sa, Si, Cl); BD Chemical properties: OM	- The database structure was based mainly on HYPRES and partially on UNSODA	Free	Brazil
Soil property maps of Africa at 250 m resolution Year update: 2015	Gridded map		Physical properties: soil texture (Sa, Si, Cl); BD; depth to bed rock Chemical properties: OC; CEC; TOTN; exchangeable acidity; exchangeable bases (Ca, Mg, K, Na); exchangeable aluminium; pH	- Fit using the Africa Soil Profiles (legacy) database and the Africa Soil Information Service (AfSIS) Sentinel Site database. These data sets contain over 28 thousand sampling locations - USDA Soil Taxonomy - Every variable is given for six different (standard) depths (0-5; 5-15; 15-30; 30-60; 60-100; 100-200)	Free	Africa

Database	Type of data	Soil moisture content and hydraulic conductivity	Other soil properties	Description formation	Availability	Coverage
Harmonised World Soil Database (HWSD) 1 km v1.2 Year update: 2014	Gridded map	Available water storage capacity, value is in category classification: 1 = 150mm water per m of the soil unit, 2 = 125 mm, 3 = 100 mm, 4 = 75 mm, 5 = 50 mm, 6 = 15 mm, 7 = 0 mm	Physical properties: soil texture (Sa, Si, Cl); gravel; BD; soil depth Chemical properties: OC; CEC; TOTC; total exchangeable nutrients; lime and gypsum contents; sodium exchange percentage; salinity; pH Soil depth, depth of obstacles to roots	- Over 16,000 different soil mapping units - The component soil types are typified by the soil classification units of either the 1974 Legend of the FAO Soil Map of the World or of the 1990 Revised Legend of the Soil Map of the World - Information of topsoil (0-30 cm) and subsoil (30-100 cm)	Free	Global
FAO Digital Soil Map of the World (DSMW) scale 1: 5 million Year update: 2007	Tabulate data and map, GIS polygon format		Physical properties: soil texture (Sa, Si, Cl); BD; soil depth Chemical properties: OC; CEC; pH; base saturation; C/N ratio; $CaCO_3$	- 4931 mapping units - FAO-UNESCO Legend	Free	Global
The digital Soil and Terrain (SOTER) databases scale 1: 1million Year update: 2013	Map, GIS polygon format		Physical properties: soil texture (Sa, Si, Cl); BD Chemical properties: OC; TOTN; CEC; pH; base saturation; C/N ratio; $CaCO_3$; gypsum content; exchangeable sodium; ECE electric conductivity		Free	30 countries

Note: Before using the soil hydraulic properties from global database, user should check how the parameters were developed, whether the values were estimated for the soil material rather than the whole soil which includes stones (coarse fragments). If there are stones, then a whole soil θ_h needs to be corrected for stones

Table B1.3 Examples of simple look-up tables for soil hydraulic properties

Table

Parameters of TESSEL Land surface model, the European Land Data Assimilation System (ELDAS) project (Teuling et al., 2009)

Soil texture	θ_s	θ_{FC}	θ_{WSC}	θ_{PWP}	θ_r	$\theta_{WSC} - \theta_{PWP}$	K_{sat} (mm day^{-1})
Coarse	0.403	0.244	0.244	0.059	0.025	0.185	600
Medium,	0.439	0.347	0.347	0.151	0.010	0.196	100
Medium - TESSEL	0.472	0.323	0.323	0.171	0.171	0.152	395
Medium fine	0.430	0.383	0.383	0.133	0.010	0.250	22
Fine	0.520	0.448	0.448	0.279	0.010	0.169	248
Very fine	0.614	0.541	0.541	0.335	0.010	0.206	150
Organic	0.766	0.663	0.663	0.267	N/A	0.396	80

Table

Parameters of ISBA Land surface model (Centre National de Recherches Meteorologiques, France), the European Land Data Assimilation System (ELDAS) project (Teuling et al., 2009)

Soil texture	θ_s	θ_{FC}	θ_{WSC}	θ_{PWP}	θ_r	θ_{WSC} - θ_{PWP}	K_{sat} (mm day^{-1})
Sand	0.397	0.156	0.156	0.083	0.083	0.073	497
Sandy loam	0.430	0.199	0.199	0.117	0.117	0.082	241
Loam	0.451	0.254	0.254	0.166	0.166	0.088	117
Loamy clay	0.462	0.309	0.309	0.220	0.220	0.089	65
Clay	0.473	0.373	0.373	0.288	0.288	0.085	37

Parameters of TERRA Land surface model, German Weather Services; the European Land Data Assimilation System (ELDAS) project (Teuling et al., 2009)

Soil texture	θ_s	θ_{FC}	θ_{WSC}	θ_{PWP}	θ_r	θ_{WSC} - θ_{PWP}	K_{sat} (mm day^{-1})
Sand	0.364	0.196	0.167	0.042	0.012	0.125	4138
Sandy loam	0.445	0.260	0.230	0.100	0.030	0.130	815
Loam	0.455	0.340	0.293	0.110	0.035	0.186	459
Loamy clay	0.475	0.370	0.335	0.185	0.060	0.150	66
Clay	0.507	0.463	0.424	0.257	0.065	0.167	1
Peat	0.863	0.763	0.668	0.265	0.098	0.403	5

The mean values for the 11 USDA soil texture classes for Brooks and Corey parameters, the total porosity and the water content at -33kPa and -1500kPa and the geometric values for the Brooks and Corey bubbling pressure and pore size distribution, Rawls et al. (1982)

Soil texture	θ_s/ϕ (Total porosity) $cm^3\ cm^{-3}$	θ_r $cm^3\ cm^{-3}$	ϕ_e (Effective porosity) $cm^3\ cm^{-3}$	h_b (Bubbling pressure)		Pore size distribution		θ_{-33kPa} $cm^3\ cm^{-3}$	$\theta_{-1500kPa}$ $cm^3\ cm^{-3}$	K_{sat} (cm hr^{-1})
				Arithmetic, cm	Geometric, cm	Arithmetic	Geometric			
Sand	0.437	0.020	0.417	15.98	7.26	0.694	0.592	0.091	0.033	21
Loamy sand	0.437	0.035	0.401	20.58	8.69	0.553	0.474	0.125	0.055	6.11
Sandy loam	0.453	0.041	0.412	30.20	14.66	0.378	0.322	0.207	0.095	2.59
Loam	0.463	0.027	0.434	40.12	11.15	0.252	0.220	0.270	0.117	1.32
Silt loam	0.501	0.015	0.486	50.87	20.76	0.234	0.211	0.330	0.133	0.68
Sandy clay loam	0.398	0.068	0.330	59.41	28.08	0.319	0.250	0.255	0.148	0.43
Clay loam	0.464	0.075	0.390	56.43	25.89	0.242	0.194	0.318	0.197	0.23
Silty clay loam	0.471	0.040	0.432	70.33	32.56	0.177	0.151	0.366	0.208	0.15
Sandy clay	0.430	0.109	0.321	79.48	29.17	0.223	0.168	0.339	0.239	0.12
Silty clay	0.479	0.056	0.423	76.54	34.19	0.150	0.127	0.387	0.250	0.09
Clay	0.475	0.090	0.385	85.60	37.30	0.165	0.131	0.396	0.272	0.06

Table

Mean values of some hydraulic parameters (Cosby et al., 1984)

Soil texture	Definition	θ_s (%)	Log K_{sat} (cm hr^{-1})
Sandy loam		43.4	-0.13
Sand	Sand: 92%; Silt: 5%; Clay: 3%	33.9	0.82
Loamy sand	Sand: 82%; Silt: 12%; Clay: 6%	42.1	0.30
Loam		43.9	-0.32
Silty loam		47.6	-0.40
Sandy clay loam	Sand: 58%; Silt: 15%; Clay: 27%	40.4	-0.20
Clay loam	Sand: 32%; Silt: 34%; Clay: 34%	46.5	-0.46
Silty clay loam	Sand: 10%; Silt: 56%; Clay: 34%	46.4	-0.54
Sandy clay	Sand: 52%; Silt: 6%; Clay: 42%	40.6	0.01
Silty clay	Sand: 6%; Silt: 47%; Clay: 47%	46.8	-0.72
Light clay		46.8	-0.86
All classes		45.7	-0.42

Mean values of Mualem-van Genuchten parameters, USDA Soil Texture Classes, (Carsel & Parrish, 1988)

Soil texture	Definition	θ_s	θ_r	α_{vG}	n_{vG}	K_{sat} (cm hr^{-1})
Clay	Mean sand: 14.9%, Mean clay: 55.2%	0.38	0.068	0.008	1.09	0.20
Clay loam	Mean sand: 29.8%, Mean clay: 32.6%	0.41	0.095	0.019	1.31	0.26
Loam	Mean sand: 40.0%, Mean clay: 19.7%	0.43	0.078	0.036	1.56	1.04
Loamy sand	Mean sand: 80.9%, Mean clay: 6.4%	0.41	0.057	0.124	2.28	14.59
Silt	Mean sand: 5.8%, Mean clay: 9.5%	0.46	0.034	0.016	1.37	0.25
Silt loam	Mean sand: 16.6%, Mean clay: 18.5%	0.45	0.067	0.020	1.41	0.45
Silt clay	Mean sand: 6.1%, Mean clay: 46.3%	0.36	0.070	0.005	1.09	0.02
Silt clay loam	Mean sand: 7.6%, Mean clay: 33.2%	0.43	0.089	0.010	1.23	0.07
Sand	Mean sand: 92.7%, Mean clay: 2.9%	0.43	0.045	0.145	2.68	29.70
Sandy clay	Mean sand: 47.5%, Mean clay: 41.0%	0.38	0.100	0.027	1.23	0.12
Sandy clay loam	Mean sand: 54.3%, Mean clay: 27.4%	0.39	0.100	0.059	1.48	1.31
Sandy loam	Mean sand: 63.4%, Meand clay: 11.1%	0.41	0.065	0.075	1.89	4.42

Mualem-van Genuchten parameters, European soils, Wösten et al. (1999)

Table

Soil texture	Definition	θ_s	θ_r	α_{vG}	n_{vG}	m_{vG}	l_{MvG}	K_{sat} (cm day^{-1})
Top-soils								
Coarse	Clay < 18% and sand > 65%	0.403	0.025	0.0383	1.3774	0.2740	1.2500	60.000
Medium	18% < clay < 35% and 15% < sand or clay < 18% and 15% < sand < 65%	0.439	0.010	0.0314	1.1804	0.1528	-2.3421	12.061
Medium fine	Clay < 35% and sand < 15%	0.430	0.010	0.0083	1.2539	0.2025	-0.5884	2.272
Fine	35% < clay < 60%	0.520	0.010	0.0367	1.1012	0.0919	-1.9772	24.800
Very fine	60% < clay	0.614	0.010	0.0265	1.1033	0.0936	2.5000	15.000
Sub-soils								
Coarse	Clay < 18% and sand > 65%	0.366	0.025	0.0430	1.5206	0.3424	1.2500	70.000
Medium	18% < clay < 35% and 15% < sand or clay < 18% and 15% < sand < 65%	0.392	0.010	0.0249	1.1689	0.1445	-0.7437	10.755
Medium fine	Clay < 35% and sand < 15%	0.412	0.010	0.0082	1.2179	0.1789	0.5000	4.000
Fine	35% < clay < 60%	0.481	0.010	0.0198	1.0861	0.0793	-3.7124	8.500
Very fine	60% < clay	0.538	0.010	0.0168	1.0730	0.0680	0.0001	8.235
Organic*		0.766	0.010	0.0130	1.2039	0.1694	0.4000	8.000

*within the organic soils no distinction is made in topsoils and subsoils

Rosetta Lite program (Schaap et al., 2001)

Soil texture	θ_s	θ_r	α_{vG}	n_{vG}	K_{sat} (cm day^{-1})
Sand	0.375	0.053	0.035	31.8	643
Loamy sand	0.39	0.049	0.035	1.75	105
Sandy loam	0.387	0.039	0.027	1.45	38.2
Loam	0.399	0.061	0.011	1.47	12.0
Silt	0.489	0.050	0.007	1.68	43.7
Silty loam	0.439	0.065	0.005	1.66	18.3
Sandy clay loam	0.384	0.063	0.021	1.33	13.2
Clay loam	0.442	0.079	0.016	1.41	8.18
Silty clay loam	0.482	0.090	0.008	1.52	11.1
Sandy clay	0.385	0.117	0.033	1.21	11.4
Silty clay	0.481	0.111	0.016	1.32	9.61
Clay	0.459	0.098	0.015	1.25	14.8

Mualem van Genuchten parameters, (Tóth et al., 2015)

Modified FAO texture classes	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α_{vG} (cm^{-1})	n_{vG} (-)	m_{vG} (-)	K_{sat} (cm day^{-1})	l_{MvG} (-)

Table

Top-soils							
Coarse	0.045	0.438	0.0478	1.3447	0.2563	17.30	-2.5587
Medium	0.000	0.459	0.0309	1.1920	0.1611	12.49	-3.8570
Medium fine	0.000	0.432	0.0094	1.2119	0.1749	1.68	-4.4460
Fne	0.000	0.478	0.0403	1.1176	0.1053	40.19	-4.7040
Very fine	0.000	0.522	0.0112	1.1433	0.1253	2.69	-5.0000
Organic	0.111	0.697	0.0069	1.4688	0.3192	1.42	0.3284
Sub-soils							
Coarse	0.057	0.404	0.0426	1.5349	0.3485	9.68	-1.8191
Medium	0.000	0.428	0.0347	1.1725	0.1471	11.78	-4.9869
Medium fine	0.000	0.418	0.0066	1.2173	0.1785	1.87	-3.3761
Fine	0.000	0.430	0.0011	1.2290	0.1863	0.07	-1.8486
Very fine	0.000	0.511	0.0002	1.4048	0.2882	0.02	5.0000
Organic	0.000	0.835	0.0113	1.2256	0.1841	10.81	2.7337

USDA texture classes	θ_r ($cm^3\ cm^{-3}$)	θ_s ($cm^3\ cm^{-3}$)	α_{vG} (cm^{-1})	n_{vG} (-)	m_{vG} (-)	K_{sat} (cm day^{-1})	l_{MvG} (-)
Top-soils							
Sand	0.061	0.411	0.0258	1.8005	0.4446	8.33	-0.7306
Loamy sand	0.052	0.475	0.0341	1.4846	0.3264	8.95	-1.8749
Sandy loam	0.000	0.441	0.0750	1.1904	0.1599	44.88	-4.3523
Loam	0.000	0.491	0.0347	1.1931	0.1618	14.17	-4.3000
Silt loam	0.000	0.424	0.0074	1.2545	0.2029	1.17	-3.5496
Silt	0.009	0.465	0.0042	1.4853	0.3267	1.38	-2.6418
Sandy clay loam	0.000	0.409	0.0700	1.1335	0.1178	43.63	-5.0000
Clay loam	0.000	0.465	0.1284	1.1160	0.1040	195.15	-5.0000
Silty clay loam	0.000	0.463	0.0107	1.1892	0.1591	1.38	-2.6418
Sandy clay	0.192	0.523	0.0351	1.4455	0.3082	43.80	-1.6202
Silty clay	0.000	0.455	0.0309	1.1110	0.0999	0.01	5.0000
Clay	0.000	0.499	0.0234	1.1200	0.1072	17.07	-5.0000
Organic	0.111	0.697	0.0069	1.4688	0.3192	1.42	0.3284
Sub-soils							
Sand	0.034	0.368	0.0356	1.7767	0.4372	5.97	-1.4096
Loamy sand	0.037	0.423	0.0419	1.4222	0.2968	14.84	-1.9583
Sandy loam	0.000	0.437	0.0681	1.1966	0.1643	53.50	-3.7279
Loam	0.000	0.432	0.0336	1.1701	0.1454	8.58	-5.0000
Silt loam	0.000	0.422	0.0077	1.2483	0.1989	1.76	-3.3247
Silt	0.009	0.465	0.0042	1.4853	0.3267	0.45	-5.0000
Sandy clay loam	0.000	0.384	0.0717	1.1206	0.1076	37.09	-5.0000

Table							
Clay loam	0.000	0.413	0.0227	1.1191	0.1064	12.35	-5.0000
Silty clay loam	0.000	0.408	0.0032	1.1993	0.1662	0.45	-5.0000
Sandy clay	0.000	0.365	0.0016	1.1812	0.1534	43.80	-1.6202
Silty clay	0.000	0.442	0.0003	1.3861	0.2786	0.01	5.0000
Slay	0.000	0.461	0.0004	1.3027	0.2323	0.04	1.1840
Organic	0.000	0.835	0.0113	1.2256	0.1841	10.81	2.7337

Table B1.4 Estimation of Soil moisture retention curve (SMRC) and hydraulic conductivity curve (HCC)

Model name	Model	Parameter	Reference
Soil moisture characteristics			
Gardner (1958)	$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{1 + \alpha_{GN}\psi^{n_{GN}}}$$	α_{GN}: fitting parameter which is a function of air-entry value of the soil n_{GN}: fitting parameter related to the pore size distribution, fitting parameter which is a function of rate of water extraction from soil once air-entry value of soil has been exceeded Pressure unit in the original paper: bar	Matlan et al. (2014) and Fredlund (2006), chapter 5
Brooks and Corey (1964)	$$S_e = \frac{\theta(h) - \theta_r}{\phi - \theta_r} = \begin{cases} 1, & h \le h_b \\ \left(\frac{h_b}{h}\right)^{\lambda_{BC}}, & h > h_b \end{cases}$$ Or: $$\theta(h) \begin{cases} \phi, & h \le h_b \\ \theta_r + \frac{(\phi - \theta_r){h_b}^{\lambda_{BC}}}{h^{\lambda_{BC}}}, & h > h_b \end{cases}$$ The equation has been also written as (Beven, 2012; Pan et al., 2019): $$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \begin{cases} 1, & h \le h_b \\ \left(\frac{h_b}{h}\right)^{\lambda_{BC}}, & h > h_b \end{cases}$$	λ_{BC}: pore size distribution index h_b: air-entry pressure Pressure unit in the original paper: cm	(USDA, 2010))

Model name	Model	Parameter	Reference
	Or: $$\theta(h)\begin{cases}\theta_s\,, & h \le h_b\\ \theta_r + \dfrac{(\theta_s-\theta_r){h_b}^{\lambda_{BC}}}{h^{\lambda_{BC}}}\,, & h > h_b\end{cases}$$ in which θ_s *is assumed to be equal to* ϕ		
Visser (1966)	$$\psi = \alpha_{VS}\frac{(\phi - \psi)^{\beta_{VS}}}{\psi^{\gamma_{VS}}}$$	α_{VS}, β_{VS}, γ_{VS}: constant, equation parameters; Visser found that β_{VS} varied from 0-10, α_V from 0-3 ϕ (fraction): porosity, 0.4-0.6 Pressure unit in the Hillel (2004): bar	The function is found in Hillel (2004). The function is suitable for only some soils within limited suction ranges (Hillel, 2004).
Brutsaert (1967)	$$S_e = \frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r} = \frac{1}{1+\left(\frac{\psi}{\alpha_{BS}}\right)^{n_{BS}}}$$ Or $$\theta(\psi) = \theta_r + \frac{(\theta_s-\theta_r)}{1+\left(\frac{\psi}{\alpha_B}\right)^{n_B}}$$	α_{BS}: fitting parameter which is a function of air-entry value of the soil n_{BS}: fitting parameter which is a function of rate of water extraction from soil once air-entry value has been exceeded Pressure unit in the Fredlund (2006): kPa	(Fredlund, 2006), chapter 5
Laliberte (1969)	$$S_e = \frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r} = \frac{1}{2}erfc\left[\alpha_{LB} - \frac{\beta_{LB}}{\gamma_{LB}+\psi/h_b}\right]$$	h_b : air entry pressure α_{LB}, β_{LB}, γ_{LB}: parameters assumed to be unique functions of pore size distribution index Pressure unit in the Fredlund (2006): kPa	(Fredlund, 2006), chapter 5
Gardner (1970)	$$\theta(\mathrm{h}) = \alpha_{GN} * \frac{1}{\mathrm{h}^{\beta_G}}$$	α_{GN} and β_{GN}: fitting parameters Pressure unit in the Pan et al. (2019): cm	(Pan et al., 2019)
Farrel and Larson, (1972)	$$\theta(\psi)\begin{cases}\theta_s\,, & \psi < \psi_{crit}\\ \theta_r + (\theta_s-\theta_r)\left[1-\frac{1}{\alpha_{FL}}ln\frac{\psi}{\psi_{crit}}\right], & \psi \ge \psi_{crit}\end{cases}$$	α_{FL}: equation parameter which is a function of air-entry value of soil	(Dourado-Neto et al., 2000)
Campbell (1974)	$$\theta(\psi) = \begin{cases}\theta_s\left(\frac{\psi_b}{\psi}\right)^{\lambda_{CB}}, & \psi > \psi_b\\ \theta_s, & \psi \le \psi_b\end{cases}$$	λ_{CB}: pore size distribution index, dimensionless fitting parameter h_b: air-entry pressure Pressure unit in the original paper: bar	(Dourado-Neto et al., 2000)

Model name	Model	Parameter	Reference
Clapp and Hornberger (1978)	$\theta(h) = \theta_s \left(\frac{h}{h_s}\right)^{\lambda_{CH}}$, $h < h_i$	h_s: saturation suction λ_{HC}: pore size distribution index, dimensionless fitting parameter h_i: an inflection point near the saturation range Pressure unit in the original paper: cm	
Simmons et al. (1979)	$\theta(\psi) = \Phi_S + \frac{1}{\beta_S} ln\left(\frac{\psi}{\alpha_S} + 1\right)$	ϕ_S, α_S and β_S: fitting parameters Pressure unit in the original paper: cm	(Dourado-Neto et al., 2000)
Libardi et al. (1979)	$\theta(\psi) = \theta_s + \frac{1}{\beta_L} ln\left(\frac{\psi}{\alpha_L} + 1\right)$	α_L and β_L: fitting parameters	(Dourado-Neto et al., 2000)
Van Genuchten (1980)	$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha_{VG} h)^{n_{VG}}]^{m_{VG}}}$ Other form: $\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha_{VG} h)^{n_{VG}}]^{m_{VG}}}$	α_{VG} (cm^{-1}): equation parameter which is a function of air-entry value of soil m_{VG}, n_{VG} (dimessionless): equation parameter Mualem (1976) m = 1 – 1/n Burdine (1953) m = 1 – 2/n Pressure unit in the original paper: cm	
Tani (1982)	$\theta(h) = \theta_r + (\theta_s - \theta_r)\left(1 + \frac{h}{h_{ip}}\right) \exp\left(\frac{h}{h_{ip}}\right)$	Ψ_{ip}: soil moisture at the inflection point Pressure unit in the original paper: cm	
MacKee and Bumb (1984)	$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)(\alpha_{MB1} - \psi)}{n_{MB1}}$	α_{MB1}: curve-fitting parameter n_{MB1}: curve-fitting equation parameter Pressure unit in the Fredlund (2006): kPa	(Fredlund, 2006), chapter 5
Exponential (Bruce & Luxmore, 1986)	$\theta(\psi) = -\frac{1}{\beta_{Exp}} \ln\left(\frac{\psi}{\alpha_{Exp}}\right)$	α_{Exp} and β_{Exp}: fitting parameters Pressure unit in the Ferreira B et al. (2012): kPa	(Ferreira B et al., 2012)
Driessen (1986)	$\theta(\psi) = \theta_s \psi^{-\gamma_D \ln(\psi)}$	γ_D: fitting parameter Pressure unit in the Ferreira B et al. (2012): kPa	(Dourado-Neto et al., 2000); (Ferreira B et al., 2012)
MacKee and Bumb (1987)	$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{1 + \exp(\psi - \alpha_{MB2})/\alpha_{MB2}}$	α_{MB2}: curve-fitting parameter n_{MB2}: curve-fitting parameter Pressure unit in the Fredlund (2006): kPa	(Fredlund, 2006), chapter 5

Model name	Model	Parameter	Reference
Ross and Smettem (1993)	$S_e = \frac{\theta(\mathrm{h}) - \theta_r}{\theta_s - \theta_r} = W_{RS1}\,(1 + \alpha_{RS1}\mathrm{h})e^{(-\alpha_{RS1}\mathrm{h})} + W_{RS2}\,\frac{1}{[1 + (\alpha_{RS2}\mathrm{h})^{n_{RS}}]^{m_{RS}}}$ $W_{RS1} + W_{RS2} = 1$	W_{RS1} and W_{RS2}: the weights of the total pore space fraction to be attributed to each sub-curve and α_{RS}, n_{RS}, m_{RS} are the fitting parameters Pressure unit in the original paper: m	
Fredlund and Xing (1994)	$\theta(\psi) = C(\psi)\frac{\theta_s}{\left[ln\left[e + (\frac{\psi}{\alpha_{FX}})^{n_{FX}}\right]\right]^{m_{FX}}}$ $C(\psi) = 1 - \frac{\ln(1 + \frac{\psi}{\psi_r})}{\ln(1 + \frac{10^6}{\psi_r})}$	α_{FX}: fitting parameter which is primarily a function of air-entry value of soil n_{FX}: fitting parameter which is primarily a function of rate of water extraction from soil once air-entry value has been exceeded m_{FX}: fitting parameter which is primarily a function of residual moisture content $C(\psi)$: correction factor which is primarily a function of suction corresponding to residual moisture content Pressure unit in the original paper: kPa	(Fredlund, 2006), chapter 5
Durner (1994)	$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = W_{D1}\,\frac{1}{[1 + (\alpha_{D1}h)^{n_{D1}}]^{m_{D1}}} + W_2\,\frac{1}{[1 + (\alpha_{D2}h)^{n_{D2}}]^{m_{D2}}}$ $m_i = 1 - 1/n_i$ $W_{D1} + W_{D2} = 1$	W_{D1} and W_{D2}: relative weights of the inter and intra aggregate pore population α_{D1}, α_{D1}(cm $^{-1}$): equation parameter which is primarily a function of air-entry value of soil n_{D1}, m_{D1}, n_{D2}, m_{D2} (dimensionless): equation parameters Pressure unit in the original paper: cm	SWRC Fit tool
Kosugi (1996), Lognormal distribution model	$\theta(h) = \theta_r + \frac{1}{2}(\theta_s - \theta_r)erfc\left[\frac{\ln(\frac{h}{h_m})}{\sigma_{KS}\sqrt{2}}\right]$	σ_{KS} is a dimensionless parameter to characterize the width of the pore-size distribution, fitting parameter h_m: a capillary pressure head, fitting parameter erfc denotes the complementary error function Pressure unit in the original paper: cm	
Pereira and Fredlund (2000)	$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (h/\alpha_{PF})^{n_{PF}}]^{m_{PF}}}$	α_{PF}: fitting parameter which is primarily a function of air -entry value of soil n_{PF}: fitting parameter which is primarily a function of rate of water extraction from soil once air entry value has been exceed m_{PF}: fitting parameter which is primarily a function of residual water content Pressure unit in the original paper: kPa	(Fredlund, 2006), chapter 5

Model name	Model	Parameter	Reference
Pham et al. (2005) And Pham and Fredlund (2008)	$\begin{cases} \theta_1(\psi) = \theta_{1kPa} - S_1 \log(\psi) & 1 \le \psi < \psi_b \\ \theta_2(\psi) = \theta_b - S_2 \log\left(\frac{\psi}{h_b}\right) & h_b \le \psi < \psi_r \\ \theta_3(\psi) = S_3 \log\left(\frac{10^6}{\psi}\right) & \psi_r \le \psi < 10^6 \end{cases}$	S1, S2, S3: Slope of straight line portions of SMRC within each of three zones θ_b: water content at air entry value θ_1; θ_2; θ_3: water content in line segments 1,2 and 3 respectively Pressure unit in the original paper: kPa	(Fredlund, 2006), chapter 5
Seki (2007)	$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = W_{SK1} Q \frac{\ln\left(\frac{h}{h_{m_{SK1}}}\right)}{\sigma_{SK1}} + W_{SK2} Q \frac{\ln\left(\frac{h}{h_{m_{SK2}}}\right)}{\sigma_{SK2}}$ $m_i = 1 - 1/n_i$ $W_{SK1} + W_{SK2} = 1$	Q(x) is related to the complementary error function W_{SK1} and W_{SK2}: relative weights of the inter and intra aggregate pore population m_{SK1}; m_{SK1} (dimensionless): : equation parameter σ_{SK} is a dimensionless parameter to characterize the width of the pore-size distribution Pressure unit in the original paper: cm	SWRC Fit tool
Dexter et al. (2008)	$w = w_r + A_1 e^{\left(-\frac{h}{h_1}\right)} + A_2 e^{\left(-\frac{h}{h_2}\right)}$	Double exponential equation with 5 parameters: h: soil water suction (the opposite of matric potential) w_r: gravimetric residual moisture content A_1: the textural pore space h_1: the soil water suction characteristic for displacing water from the textural pores A_2: structural pore space h_2: the soil water suction characteristic for displacing water from the structural pores Pressure unit in the original paper: hPa	
Omuto (2009)	$\theta(h) = \theta_r + (\theta_1 e^{-\alpha_1 h} + \theta_2 e^{-\alpha_2 h})$	θ_1: represents the difference between saturated moisture and residual moisture content in the structural pore-space; θ_2: represent the difference between saturated moisture and residual moisture in the textural pore-space. $\alpha_1$represents the inverse of air-entry potential in the structural pore-space; α_2 represents the inverse of air-entry potential in the soil textural pore-space; θ_r is the sum of residual moisture contents in the structural pore-space and textural pore-space	
Hydraulic conductivity			
Brooks and Corey (1964)	$K(\theta) = K_{sat} * \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right)^{\frac{2}{(\lambda+4)}}$	λ_{BC}: pore size distribution index, dimensionless fitting parameter Pressure unit in the original paper: cm	

Model name	Model	Parameter	Reference
Campbell (1974)	$K(\theta) = K_{sat} * \left(\frac{\theta(\psi)}{\theta_s}\right)^{2b+3}$	b_C: equation parameter depending on soil texture Pressure unit in the original paper: bar	
Mualem (1976)	$K(\theta) = K_{sat} * \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right)^{l} * \left[1 - \left(1 - \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m}}\right)^{m}\right]^2$ $\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha * h)^n]^m}$	α: Scaling parameter of van Genuchten (1980) equation m,n, l: equation parameters m = 1 – 1/n Pressure unit in the original paper: cm	
Clapp and Hornberger (1978)	$K(\theta) = K_{sat} * \left(\frac{\theta(h)}{\theta_s}\right)^{(3+\frac{2}{\lambda})}$	λ_{HC}: pore size distribution index, dimensionless fitting parameter Pressure unit in the original paper: cm	
Kosugi (1996)	$K(\theta) = K_{sat}\sqrt{\left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right)} \left[\frac{1}{2} erfc \left(erfc^{-1} 2\left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right) + \frac{\sigma_K}{\sqrt{2}}\right)\right]^2$	σ_K is a dimensionless parameter to characterize the width of the pore-size distribution erfc denotes the complementary error function. Pressure unit in the original paper: cm	

Table B1.5 Tools available for estimating soil hydraulic properties

Tool and Description	Function	Accessibility	Method to get soil hydraulic properties	Input	Output format	Application
SOILPROP (Mishra & Parker, 1988; Mishra et al., 1989) FORTRAN code	(1) computing estimates of soil hydrological parameters; (2) estimating the error in individual parameters and an error covariance matrix to account for correlation among parameters	Licensed program	- Fit soil moisture retention curve (SMRC), *Brooks and Corey (1964)* and *van Genuchten (1980)*, using the *modified Arya and Paris (1981) PTFs* - Contain published PTFs PTFs | Parameters estimated *PTFs for estimating K_{sat}* Konzeny-Carman | K_{sat}			
RETC for Windows (Van Genuchten et al., 1991) Version: 6.xx (1998)	(1) analyse the soil water retention and hydraulic conductivity functions of unsaturated soils; (2) predict the hydraulic conductivity from observed soil water retention data assuming that one observed conductivity	Free	The program contains the following SMRC: *Brooks-Corey (1964)*, *van Genuchten (1990)*, the lognormal distribution model of *Kosugi (1996)*, the dual-permeability model of *Durner (1994)*			

Tool and Description	Function	Accessibility	Method to get soil hydraulic properties	Input	Output format	Application
	value (not necessarily at saturation) is available					
ROSETTA Model Version 1.0 (1999) Version 1.2 (Schaap et al., 2001) A stand-alone window based software and A simple version of Rosetta (Rosetta-Lite) is available as a plugin for external software for the computation of water retention and saturated hydraulic conductivity parameters. This plugin is currently included in the Hydrus-1 D and Hydrus 2D ROSETTA 3 (Zhang & Schaap, 2017) Provide an improved set of hierarchical PTFs ROSETTA Model API (Dylan Beaudette, Richard Reid, Todd Skaggs, 2021): a new, online, interface to the ROSETTA model Interactive version with copy/paste functionality.	(1) computing estimates of soil hydrological parameters (moisture retention, saturated and hydraulic conductivity); (2) estimating uncertainties of the predicted hydraulic parameters (coefficients of determination and root mean square errors); (3) containing dataset assembled contained 2134 soil samples for water retention with a total 20574 θ(h) points, most of the samples were derived from soils in temperate to subtropical climates of North America and Europe, saturated hydraulic conductivity was known for 235 soil samples which are solely derived from the database UNSODA	Free	- Neural network analyses combined with the bootstrap method - Rosetta offers five neural network-based PTFs that allow prediction of the hydraulic properties. The models use the following hierarchical sequence of input data: • Soil textural class • Sand, silt and clay percentages • Sand, silt and clay percentages and bulk density • Sand, silt and clay percentages, bulk density and a water retention point at 330 cm (33 kPa). • Sand, silt and clay percentages, bulk density and water retention points at 330 and 15000 cm (33 and 1500 kPa) PTFs | Parameters estimated Five hierarchical PTFs | *van Genuchten (1980)* model parameters | K_{sat} | Unsaturated hydraulic conductivity parameters according to van Genuchten (1980) and Mualem (1976) models - The first model is based on a lookup table that provides class average hydraulic parameters for each USDA soil textural class. The other four models are based on neural network analyses and provide more accurate predictions when more input variables are used. - ROSETTA 3 uses parameter uncertainty of the fit of the van Genuchten curve to the original retention data in the ANN calibration procedure to reduce bias of parameters predicted by the new PTF; 1000 bootstrap replicas were used to calibrate the new models compared to 60-100 in Rosetta 1; the optimal weights for van Genuchten parameters were determined	Access table	Non-spatial output	
SoilPAR 2.0 (Acutis & Donatelli, 2003)	(1) computing estimates of soil hydrological parameters; (2) creating θ(h) graphs; (3) exporting outputs to both	Free	- Contains published PTFs PTFs | Parameters estimated *PTFs for estimating soil moisture*	CropSyst files and MS Excel spreadsheets	Non-spatial output and spatial output	Tested with European soil

Tool and Description	Function	Accessibility	Method to get soil hydraulic properties		Input	Output format	Application
A stand-alone win 9x/2000 program or integrated as an application in the CropSyst software; an evolution of version 1.1 made available in 1996	CropSyst and MS Excel formats; (4) creating maps using the ESRI format; (5) importing data from CropSyst files and MS Excel spreadsheets; (6) storing soil data in a georeferenced database; (7) comparing the estimates against measured data using both statistical indices and graphics		*Baumer - EPIC/ASW*	θ_{FC}, θ_{PWP}	Each profile contains information of physical, hydrological and chemical parameters involved in PTFs, description, soil classification, latitude, longitude, altitude, slope and user notes	A mapping utility allows: (1) showing soil profile locations on a map, (2) retrieving the profile characteristics, and (3) creating an ESRI ArcView/ArcInfo shape file of the profiles shown. Other utilities to manage the data base (back-up, update etc.) are also available.	
			Brakensiek/Rawls-LeachM (Hutson and Wagenet, 1992)	soil water contents at several pressure			
			British Soil Survey topsoil - LeachM (Hutson and Wagenet, 1992)	soil water contents at several pressure			
			British Soil Survey subsoil - LeachM (Hutson and Wagenet, 1992)	soil water contents at several pressure			
			EPIC - EPIC/ASW	θ_{FC}, θ_{PWP}			
			Hutson- LeachM (Hutson and Wagenet, 1992)	soil water contents at several pressure			
			Manrique- EPIC/ASW	θ_{FC}, θ_{PWP}			
			Rawls - EPIC/ASW	θ_{FC}, θ_{PWP}			
			PTFs for estimating SMRC function parameters				
			Rawls and Brakensiek (1989)	*Brooks and Corey (1964)* model parameters			
			Vereecken et al. (1989)	*van Genuchten (1980)* model parameters			
			Campbell (1985)	*Campbell (1974)* model parameters			
			Mayr and Jarvis (1999)	*Hutson and Cass (1987)* model parameters			
			PTFs for estimating K_{sat}				
			Jabro (1992)	K_{sat}			
			Jaynes and Tyler (1984)	K_{sat}			
			Puckett et al. (1985)	K_{sat}			
			Campbell (1985)	K_{sat}			
			PTFs for estimating BD				
			Baumer - EPIC/ASW	BD			
			Rawls - EPIC/ASW	BD			
			- Fit SMRC: (1) *Campbell (1974)*; (2) *Campbell-Hutson-Cass (1987)*; (3) *Brooks and Corey function (1964)* and (4) *van Genuchten (1980)*				

<table>
<tr><th>Tool and Description</th><th>Function</th><th>Accessibility</th><th>Method to get soil hydraulic properties</th><th>Input</th><th>Output format</th><th>Application</th></tr>
<tr><td>Soil Water Characteristics - Hydraulic Properties Calculator – SPAW (Soil-Plant-Air-Water)

SPAW is a window-based package. The Soil Water Characteristics is a program included with the SPAW installation.

The SPAW hydrologic model Saxton and Willey, (2006) is a replacement for those reported by Saxton et al. (1986).</td><td>(1) computing estimates of hydrologic water holding using the soil texture selected from within the ranges shown on the graphical soil texture triangle and equations by Saxton et al. (1986) & Saxton and Willey, (2006); (2) creating θ(h) graphs</td><td>Free</td><td>- Contain published PTFs
<table><tr><th>PTFs</th><th>Parameters estimated</th></tr><tr><td>Saxton et al. (1986)</td><td>θ_s; θ_{FC}, θ_{PWP}; K_{sat}; PAW</td></tr><tr><td>Saxton and Willey, (2006);</td><td>θ_s; θ_{FC}, θ_{PWP}; K_{sat}; PAW</td></tr></table></td><td>Manual input via the provided table</td><td>Non-spatial output

Graph and output in text can be saved as image and printed</td><td>Applied in Nigeria (Aliku & Oshunsanya, 2018)</td></tr>
<tr><td>SWRC Fit (Seki, 2007) Version 3.0 was released on September 10, 2016

A stand-alone software and web interface is also available</td><td>(1) fitting soil hydraulic model to a soil moisture retention curve; (2) creating θ(h) graphs</td><td>Free</td><td>Performs nonlinear fitting of 6 SMRC: (1) Brooks and Corey (1964), (2) van Genuchten (1980), (3) Kosugi (1996), (4) Fredlund and Xing (1994), (5) Durner (1994) and (6) Seki 2007 using Levenberg-Marquardt method.</td><td>Manual input via the provided table or text file</td><td>Non-spatial output

Graph and output in text</td><td>This software was used in more than 80 scientific works</td></tr>
<tr><td>k-Nearest Neighbors (Nemes et al., 2008)</td><td>(1) computing estimates of soil moisture retention at –33 and –1500 kPa matric potentials (2) estimating uncertainty; (3) containing reference database (NRCS-SCS)</td><td>Free</td><td>k-Nearest Neighbor (k-NN) lazy learning algorithm to develop PTFs based on provided data</td><td>Manual input via the provided table or import MS Access or MS excel table</td><td>Non-spatial output</td><td></td></tr>
<tr><td>SVSOILS - Knowledge-Based Saturated/Unsaturated Soil Property Database - Soil vision (by Bentley)

More information can be found in the SVSOILS manual (accessed Aug 2020)</td><td>(1) computing estimates of soil hydraulic parameters (soil moisture retention curve, saturated and unsaturated hydraulic conductivity, water storage); (2) soil database contains saturated permeability data of over 2500 soils and unsaturated permeability data over 700 soils.</td><td>Licensed program</td><td>- Fit SMRC: Brooks and Corey (1964); Burdine (1953); Fredlund and Xing (1994); Gardner (1958); Gitirana and Fredlund (2004); van Genuchten (1980)

- Contains published PTFs
<table><tr><th>PTFs</th><th>Parameters estimated</th></tr><tr><td colspan="2">PTFs for estimating soil moisture</td></tr><tr><td>Arya and Paris (1981)</td><td></td></tr></table></td><td>Various types (ESRI Grid format, DXF format, SVOFFICE, CAD, CSV, manual input via the provided table)</td><td>Various types (ESRI Grid format, DXF format, SVOFFICE, CAD, CSV)</td><td></td></tr>
</table>

<table>
<tr><th>Tool and Description</th><th>Function</th><th>Accessibility</th><th>Method to get soil hydraulic properties</th><th>Input</th><th>Output format</th><th>Application</th></tr>
<tr><td></td><td></td><td></td><td>
<table>
<tr><td>Aubertin (2003)</td><td rowspan="4">Model based on the shape similarity between SWCC and particle size distribution (PSD)</td></tr>
<tr><td>Zapata (2000)</td></tr>
<tr><td>Fredlund and Wilson (1997)</td></tr>
<tr><td>Tyler and Wheatcraft (1989)</td></tr>
<tr><td colspan="2">Gupta and Larson (1979a, 1979b)</td></tr>
<tr><td colspan="2">PTFs for estimating SMRC function parameters</td></tr>
<tr><td>Torres (2011)</td><td>Fredlund and Xing (1994) model parameter</td></tr>
<tr><td>Scheinost (1996)</td><td>van Genuchten (1980) model parameter</td></tr>
<tr><td>Vereecken et. al, (1989)</td><td>van Genuchten (1980) model parameter</td></tr>
<tr><td>Rawls and Brakensiek (1985)</td><td>Brooks and Corey (1964) model parameter</td></tr>
<tr><td colspan="2">PTFs for estimating K_{sat}</td></tr>
<tr><td>Beyer (1964)</td><td>K_{sat}</td></tr>
<tr><td>Hazen's (1911)</td><td>K_{sat}</td></tr>
<tr><td>Kozeny (1989)</td><td>K_{sat}</td></tr>
<tr><td>Kruger (1992)</td><td>K_{sat}</td></tr>
<tr><td>Terzaghi (1981)</td><td>K_{sat}</td></tr>
<tr><td>Zamarin (1992)</td><td>K_{sat}</td></tr>
<tr><td>Fair-Hatch (1959)</td><td>K_{sat}</td></tr>
<tr><td>NAVFAC</td><td>K_{sat}</td></tr>
<tr><td>Chapuis (2003)</td><td>K_{sat}</td></tr>
<tr><td>Rawls and Brakensiek (1983)</td><td>K_{sat}</td></tr>
<tr><td>Rawls and Brakensiek (1993)</td><td>K_{sat}</td></tr>
<tr><td>Slitcher (1962)</td><td>K_{sat}</td></tr>
<tr><td>Kozeny-Carman (1989)</td><td>K_{sat}</td></tr>
<tr><td>Inverse K_{sat}</td><td>K_{sat}</td></tr>
</table>
- Unsaturated hydraulic conductivity is described by: Modified Campbell (1973) using the Fredlund and Xing (1994) fit; Fredlund, Xing and Huang (1994); Mualem van Genuchten; Leong and Rahardjo (1997);
</td><td></td><td></td><td></td></tr>
</table>

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<tr><td></td><td></td><td></td><td>Brooks and Corey (1964); Gardner (1956); Kunze (1968); Fredlund 2-Point (2008)</td><td></td><td></td><td></td></tr>
<tr><td>The computer program PTF calculator (CalcPTF)
- Multi-modeling with Pedotransfer Functions (USDA, 2010)

The code is written in FORTRAN and can be invoked from an Excel worksheet or run as a stand-alone</td><td>(1) computing estimates of soil hydraulic parameters (soil moisture retention curve, saturated and unsaturated hydraulic conductivity, water storage, infiltrability)

Water content at selected capillary pressures (θ_h) is in the Manual but not included in the tool</td><td>Free</td><td>- Contains published PTFs
<table>
<tr><th>PTFs</th><th>Parameters estimated</th></tr>
<tr><td colspan="2">PTFs for estimating SMRC functions parameters</td></tr>
<tr><td>Saxton et al. 1986 (USA)</td><td rowspan="7">Brooks and Corey (1964) model parameters</td></tr>
<tr><td>Campbell and Shiozawa, 1992 (No particular)</td></tr>
<tr><td>Rawls and Brakensiek, 1985 (USA)</td></tr>
<tr><td>Williams et al., 1992a (Australia)</td></tr>
<tr><td>Williams et al., 1992b (Australia)</td></tr>
<tr><td>Oosterveld and Chang, 1980 (Canada)</td></tr>
<tr><td>Mayr and Jarvice, 1999 (UK)</td></tr>
<tr><td>Wösten et al., 1999 (Europe)</td><td rowspan="4">van Genuchten (1980) model parameters</td></tr>
<tr><td>Varallyay et al., 1982 (Hungary)</td></tr>
<tr><td>Vereecken et al., 1989 (Belgium)</td></tr>
<tr><td>Wösten et al., 1999 (Europe)</td></tr>
</table>

- Five PTFs used to estimate pairs of (h, θ) for fitting the van Genuchten SMRC: Tomasella and Hodnett, 1998 (Brazil); Rawls et al., 1982 (USA); Gupta and Larson, 1979 (Central USA); Rajkai and Varallyay, 1992 (Hungary); Rawls et al., 1983 (USA). The fitting code is based on the optimisation procedure from the CFITM programme developed to determine transport parameters from solute displacement experiments.
- Point PTFs included in the manual including Peterson et al., 1968 (Pennsylvania, USA); Bruand et al., 1994 (Central France); Canarache, 1993 (Romania); Hall et al., 1977 (UK, England, Wales)</td><td>Manual input in excel table</td><td>Non-spatial output</td><td>Mostly Temperate climate (Jaiswal et al., 2013)</td></tr>
<tr><td>LUCI_PTFs
An ArcGIS toolbox, a component of LUCI, can</td><td>(1) computing estimates of soil hydraulic parameters (soil moisture content,</td><td>Free</td><td>- Published PTFs
<table>
<tr><th>PTFs</th><th>Parameters estimated</th></tr>
</table></td><td>Shapefile</td><td>Shapefile</td><td></td></tr>
</table>

Tool and Description	Function	Accessibility	Method to get soil hydraulic properties		Input	Output format	Application
be used as a stand-alone toolbox Last update: 2021	SMRC, saturated and HCC, water storage); (2) creating graph of SMRC and HCC; (3) mapping soil hydraulic properties (soil moisture content, saturated hydraulic conductivity, soil moisture states, water storage)		*Point PTFs for estimating soil moisture content*				
			Pidgeon (1972)	θ_{FC}; $\theta_{-10\,kPa}$; $\theta_{-33\,kPa}$; $\theta_{-1500\,kPa}$			
			Hall et al. (1977)	θ_{-5kPa}; θ_{-10kPa}; $\theta_{-33\,kPa}$; $\theta_{-200\,kPa}$; $\theta_{-1500\,kPa}$			
			Lal (1978)	$\theta_{-10\,kPa}$; $\theta_{-33\,kPa}$; $\theta_{-1500\,kPa}$			
			Gupta and Larson (1979)	$\theta_{-4\,kPa}$; $\theta_{-7\,kPa}$; $\theta_{-10\,kPa}$; $\theta_{-20\,kPa}$; $\theta_{-33\,kPa}$; $\theta_{-60\,kPa}$; $\theta_{-100\,kPa}$; $\theta_{-200\,kPa}$; $\theta_{-400\,kPa}$; $\theta_{-700\,kPa}$; $\theta_{-1000\,kPa}$; $\theta_{-1500\,kPa}$			
			Rawls et al. (1982)	$\theta_{-4\,kPa}$; $\theta_{-7\,kPa}$; $\theta_{-10\,kPa}$; $\theta_{-20\,kPa}$; $\theta_{-33\,kPa}$; $\theta_{-60\,kPa}$; $\theta_{-100\,kPa}$; $\theta_{-200\,kPa}$; $\theta_{-400\,kPa}$; $\theta_{-700\,kPa}$; $\theta_{-1000\,kPa}$; $\theta_{-1500\,kPa}$			
			Aina and Periaswamy (1985)	$\theta_{-33\,kPa}$; $\theta_{-1500\,kPa}$			
			Manrique and Jones (1991)	θ_{-33kPa}; $\theta_{-1500kPa}$			
			Batjes (1996)	θ_s; θ_{pF1}; $\theta_{pF1.5}$; $\theta_{pF1.7}$; $\theta_{pF2.0}$; $\theta_{pF2.3}$; $\theta_{pF2.5}$; $\theta_{pF2.7}$; $\theta_{pF3.4}$; $\theta_{pF4.2}$			
			Van Den Berg et al. (1997)	θ_{-10kPa}; $\theta_{-1500\,kPa}$			
			Tomasella and Hodnett (1998)	θ_{0kPa}; θ_{-1kPa}; θ_{-3kPa}; θ_{-6kPa}; θ_{-10kPa}; θ_{-33kPa}; $\theta_{-100kPa}$; $\theta_{-500kPa}$; $\theta_{-1500kPa}$			
			Adhikary et al. (2008)	$\theta_{-10\,kPa}$; $\theta_{-33\,kPa}$; $\theta_{-100\,kPa}$; $\theta_{-300\,kPa}$; $\theta_{-500\,kPa}$; θ-			

Tool and Description	Function	Accessibility	Method to get soil hydraulic properties		Input	Output format	Application
				$\theta_{-1000\ kPa}$; $\theta_{-1500\ kPa}$			
			Reichert et al. (2009)	$\theta_{-6\ kPa}$; $\theta_{-10\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-500\ kPa}$; $\theta_{-1500\ kPa}$			
			Dashtaki et al. (2010)	$\theta_{-10\ kPa}$; $\theta_{-30\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-300\ kPa}$; $\theta_{-500\ kPa}$; $\theta_{-1500\ kPa}$			
			Botula (2013)	$\theta_{-33\ kPa}$; $\theta_{-1500\ kPa}$			
			Shwetha and Varija (2013)	$\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-300\ kPa}$; $\theta_{-500\ kPa}$; $\theta_{-1000\ kPa}$; $\theta_{-1500\ kPa}$			
			Nguyen et al. (2014)	$\theta_{-1\ kPa}$; $\theta_{-3\ kPa}$; $\theta_{-6\ kPa}$; $\theta_{-10\ kPa}$; $\theta_{-20\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-1500\ kPa}$			
			Santra et al. (2018)	$\theta_{-33\ kPa}$; $\theta_{-1500\ kPa}$			
			PTFs for estimating SMRC functions parameters				
			Wösten et al., 1999 (Europe)	*van Genuchten (1980) model* parameters			
			Vereecken et al., 1989 (Belgium)				
			Hodnett and Tomasella (2002)				
			Zacharias and Wessolek (2007)				
			Weynants et al. (2009)				
			Dashtaki et al. (2010)				
			Cosby et al. (1984) (Equation with Sand, Silt, Clay & equation with Silt, Clay)	*Brooks and Corey (1964) model parameters*			
			Cosby et al. (1984) (Equation with Silt, Clay				
			Rawls and Brakensiek (1985)				

Tool and Description	Function	Accessibility	Method to get soil hydraulic properties		Input	Output format	Application
			Campbell and Shiozawa (1992)				
			Saxton et al. (1986)				
			Saxton et al. (2006)				
			PTFs for estimating K_{sat}				
			Cosby et al. (1984)	K_{sat}			
			Brakensiek et al. (1984)	K_{sat}			
			Puckett et al. (1985)	K_{sat}			
			Ahuja et al. (1989)	K_{sat}			
			Jabro (1992)	K_{sat}			
			Campbell and Shiozawa (1994)	K_{sat}			
			Minasny and McBratney (2000)	K_{sat}			
			Ferrer Julia et al. (2004)	K_{sat}			
			PTFs for estimating HCC parameters				
			Wösten et al. (1999)	Mualem van Genuchten model prameters			
			Weynants et al. (2009)				

(*) Users can explore another tools: REPM (Relative Effective Porosity Model) (Suleiman & Ritchie, 2001a); SWILIMITS (T. Ritchie et al., 1999); SH-Pro (Cresswell et al., 2001); Pedon-SEI (Ungaro & Calzolari, 2001); Neuro θ Theta (Minasny & McBratney, 2002); Neuro Multistep (Minasny et al., 2004) etc. In addition, many programmes simulating soil-water flow now have PTFs embedded in them to predict the soil hydraulic properties, e.g. SWAP (van Dam et al, 1997) uses the PTFs of Wösten 1999 and HYDRUS uses PTFS of Schaap et al. (2001)

Table B1.6 PTFs for estimating soil moisture content developed for temperate climate

Equation name	Equation	Input	Description
Point PTFs			
(1) Soil texture (Sa, Si, Cl); BD; OM/OC; and other soil properties			
Baumer (1992)	*Baumer (1992) PTFs found in Guber et al. (2006)* $w_{-1500\ kPa}$ (g g^{-1}) = 0.01*BD*(0.71 + 0.45*OM + 0.336*Cl + 0.117*Cl*($CA^{3/2}$) + 0.004*Cl*SAR) If Cl > 10% $w_{-33\ kPa}$ (g g^{-1}) = 0.01*BD*(15.84 + 0.746*OM + 2.2025*CA^2 – 0.137*Sa + 0.743* $w_{-1500\ kPa}$) If Cl ≤ 10% $w_{-33\ kPa}$ (g g^{-1}) = 0.01*BD*(15.84 + 0.746*OM + 0.02*CA^2*Cl^2 – 0.137*Sa + 0.743* $w_{-1500\ kPa}$)	*The PTFs in Guber et al. (2013)* Clay: Cl (%) Sand: Sa (%) Oganic Matter: OM (%) Bulk Density: BD (g cm^{-3}) Clay activity: CA, the ratio of cation exchange capacity of the mineral fraction to the clay content, mol_c kg^{-1}) Sodium adsoption ratio: SAR	- Original document was not found - Used the U.S. National Soil Survey database
Tóth et al. (2015)	*Original PTFs:* θ_S (cm^3cm^{-3}) = 0.6819 - 0.06480 * (1/(OC+1)) - 0.11900 * BD^2 - 0.02668 * T/S + 0.001489 * Cl + 0.0008031 * Si + 0.02321 * (1/(OC+1)) * BD^2 + 0.01908 * BD^2 * T/S - 0.0011090 * Cl * T/S - 0.00002315 * Si * Cl - 0.0001197 * Si * BD^2 - 0.0001068 * Cl * BD^2 θ_S (cm^3cm^{-3}) = 0.5653 - 0.07918 * BD^2 + 0.001671 * pH^2 + 0.0005438 * Cl + 0.001065 * Si + 0.06836 * T/S - 0.00001382 * Cl * pH^2 - 0.00001270 * Si * Cl - 0.0004784 * BD^2 * pH^2 - 0.0002836 * Si * BD^2 + 0.0004158 * Cl * BD^2 - 0.01686 *T/S * BD^2 - 0.0003541 * Si * T/S -0.0003152 * T/S * pH^2 $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = 0.2449 - 0.1887 * (1/(OC+1)) + 0.004527 * Cl + 0.001535 * Si + 0.001442 * Si * (1/(OC+1)) - 0.00005110 * Si * Cl + 0.0008676 * Cl * (1/(OC+1)) $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = 0.09878 + 0.002127* Cl - 0.0008366 * Si - 0.07670 *(1/(OC+1)) + 0.00003853 * Si * Cl + 0.002330 * Cl * (1/(OC+1)) + 0.0009498 * Si * (1/(OC+1))	*Original PTFs:* T/S: top/sub soil, T/S = 1 top soil, T/S=0 subsoil Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (100 g g^{-1}) Bulk Density: BD (g cm^{-3}) pH: pH in water	- Original document link, equation can be found in Supporting information - EU-HYDI soil database, European soils, contains information on taxonomic, chemical and physical soil properties and data on land use for 18,537 unique soil samples from 6,460 soil profiles across the continent - Main characteristics of the PTFs developing dataset: Sand (0-100%), Silt (0-86.8%), Clay (0-91.65), BD (0.09-2.02 g cm^{-3}), $CaCO_3$ (0-80%), pH (3.5-10.62) - Modified FAO texture class - 122 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
Hewelke et al. (2015)	*Original PTFs:* $\theta_{-2.5cm\ (pF0.4)}$ (% v/v) = 90.0056 - 33.4052*BD -1.62435*Si - 0.26377*Si*BD + 0.77502*Si*PD $\theta_{-10cm\ (pF1)}$ (% v/v) = 160.643- 43.1639*PD + 0.672707*Sa - 7.3989*Si - 0.52663*Sa*BD + 2.77686*Si*PD + 0.0714351*Sa*OM -1.03448*OM*BD $\theta_{-31.6cm\ (pF1.5)}$ (% v/v) = 325.823-109.108*PD - 2.4174*OM -13.6859*Si - 0.64342*Sa*BD + 0.333195*Sa*PD + 5.17961*Si*PD + 0.128288*Si*OM $\theta_{-100cm\ (pF2}$ (% v/v) = - 87.9967 + 122.001*BD - 213.517*ln(BD) + 1.63628*ln(BD)*Cl $\theta_{-201cm\ (pF2.7)}$ (% v/v) = 998.161-553.099*BD -366.053*PD - 12.1134*OM - 15.5097*Si - 0.238188*Sa*BD + 5.76494*Si*PD + 0.232813*Si*OM + 6.81292*OM*BD + 211.562 * PD*BD $\theta_{-2511cm\ (pF3.4)}$ (% v/v) = 624.813-348.437*BD – 229.55*PD – 7.62926*OM – 9.33429*Si - 0.159606*Sa*BD + 3.4551*Si*PD + 0.147551*Si*OM + 4.37701*OM*BD + 134.015*BD*PD $\theta_{-15848cm\ (pF4.2)}$ (% v/v) = 9.55007 - 0.0551704*Sa*BD + 0.26058*Si*BD - 0.180619*Si*PD + 0.0149768*Si*OM pF was defined as the logarithm of water in soil-matric potential (pF = $\log_{10}$ [-head (cm of water)]; e.g. a pressure head of -100 cm corresponds with pF 2.0	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (g cm^{-3}) Particular density: PD (g cm^{-3})	- Original document link - 62 soil layers, forest soils, Poland - Main characteristics of the PTFs developing dataset: Silt (0-40%), OC (0-11.3%) - 13 ciations from Google Scholar (accessed on 10 Aug 2020)
(2) Soil texture (Sa, Si, Cl); BD; OM/OC			

Equation name	Equation	Input	Description
Hall et al. (1977)*	*Original PTFs:* Top-soils (A horizons): θ_{-5kPa} (% v/v) = 47 + 0.25*Cl + 0.1*Si + 1.12*OC – 16.52*BD θ_{-10kPa} (% v/v) = 37.47 + 0.32*Cl + 0.12*Si + 1.15*OC – 1.25*BD $\theta_{-33\ kPa}$ (% v/v) = 22.66 + 0.36*Cl + 0.12*Si + 1*OC – 7.64*BD $\theta_{-200\ kPa}$ (% v/v) = 8.7 + 0.45*Cl + 0.11*Si + 1.03*OC $\theta_{-1500\ kPa}$ (% v/v) = 2.94 + 0.83*Cl – 0.0054*Cl^2 Sub-soils (E, B and C horizons): θ_{-5kPa} (% v/v) = 37.20 + 0.35*Cl + 0.12*Si – 11.73*BD θ_{-10kPa} (% v/v) = 27.87 + 0.41*Cl + 0.15*Si – 8.32*BD $\theta_{-33\ kPa}$ (% v/v) = 20.81 + 0.45*Cl + 0.13*Si – 5.96*BD $\theta_{-200\ kPa}$ (% v/v) = 7.57 + 0.48*Cl + 0.11*Si $\theta_{-1500\ kPa}$ (% v/v) = 1.48 + 0.84*Cl – 0.0054*Cl^2 In which: θ (% v/v): % volume moisture *Hall et al. (1977) PTFs found in Karlsson (1982)*: $\theta_{-1500\ kPa}$ (v/v %) = 1.48 + 0.84*Cl – 0.0054*Cl *Hall et al. (1977) PTFs found in USDA's CalcPTF tool (USDA, 2010):*	*Original PTFs:* Clay: Cl (%) Silt: Si (%) Organic carbon: OC (%) Bulk Density: BD (g cm^{-3}) *The PTFs in Karlsson (1982)*: Clay: Cl (%) *The PTFs in USDA's CalcPTF tool (USDA, 2010):* Clay: Cl (%) Silt: Si (%) Bulk Density: BD (g cm^{-3})	- Original document link; cannot access the online version, can access the hard copy. - Subsoil samples from 261 soil profiles throughout England and Wales - Particle size class: Clay, Silty clay, Silty clay loam, Clay loam, Sandy clay loam, Silt loam, Sandy silt loam, Sandy loam, Loamy sand, Sand - The PTFs were used in USDA's CalcPTF tool (USDA, 2010) (USDA's CalcPTF used the sub soil equation); in Dai et al. (2013) to develop soil hydraulic properties for China - The PTFs were used in Tanzania by Karlsson (1982) - 419 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
	θ_{-33kPa} (cm^3cm^{-3}) = 0.01*(20.81 + 0.45*Cl + 0.13*Si – 5.96*BD) $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = 0.01*(1.48 + 0.84*Cl – 0.0054*Cl^2) <u>Converted equations used in LUCI_PTFs:</u> Top-soils: θ_{-5kPa} (cm^3cm^{-3}) = (47 + 0.25*Cl + 0.1*Si + 1.12*OC – 16.52*BD) *10^{-2} θ_{-10kPa} (cm^3cm^{-3}) = (37.47 + 0.32*Cl + 0.12*Si + 1.15*OC – 1.25*BD) *10^{-2} $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = (22.66 + 0.36*Cl + 0.12*Si + 1*OC – 7.64*BD) *10^{-2} $\theta_{-200\ kPa}$ (cm^3cm^{-3}) = (8.7 + 0.45*Cl + 0.11*Si + 1.03*OC) *10^{-2} $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = (2.94 + 0.83*Cl – 0.0054*Cl^2) *10^{-2} Sub-soils: θ_{-5kPa} (cm^3cm^{-3}) = (37.20 + 0.35*Cl + 0.12*Si – 11.73*BD) *10^{-2} θ_{-10kPa} (cm^3cm^{-3}) = (27.87 + 0.41*Cl + 0.15*Si – 8.32*BD) *10^{-2} $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = (20.81 + 0.45*Cl + 0.13*Si – 5.96*BD) *10^{-2} $\theta_{-200\ kPa}$ (cm^3cm^{-3}) = (7.57 + 0.48*Cl + 0.11*Si) *10^{-2} $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = (1.48 + 0.84*Cl – 0.0054*Cl^2) *10^{-2}		

Equation name	Equation	Input	Description
Gupta and Larson (1979)*	*Original PTFs:* $\theta_{-4\ kPa}$ (cm^3cm^{-3}) = 7.053*10^{-3}*Sa + 10.242*10^{-3}*Si + 10.07*10^{-3}*Cl + 6.333*10^{-3}*OM -3.212*10^{-2}*BD $\theta_{-7\ kPa}$ (cm^3cm^{-3}) = 5.678*10^{-3}*Sa + 9.228*10^{-3}*Si + 9.135*10^{-3}*Cl + 6.103*10^{-3}*OM -26.96*10^{-2}*BD $\theta_{-10\ kPa}$ (cm^3cm^{-3}) = 5.018*10^{-3}*Sa + 8.548*10^{-3}*Si + 8.833*10^{-3}*Cl + 4.966*10^{-3}*OM -24.23*10^{-2}*BD $\theta_{-20\ kPa}$ (cm^3cm^{-3}) = 3.89*10^{-3}*Sa + 7.066*10^{-3}*Si + 8.408*10^{-3}*Cl + 2.817*10^{-3}*OM – 18.78*10^{-2}*BD $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = 3.075*10^{-3}*Sa + 5.886*10^{-3}*Si + 8.039*10^{-3}*Cl + 2.208*10^{-3}*OM – 14.34*10^{-2}*BD $\theta_{-60\ kPa}$ (cm^3cm^{-3}) = 2.181*10^{-3}*Sa + 4.557*10^{-3}*Si + 7.557*10^{-3}*Cl + 2.191*10^{-3}*OM – 9.276*10^{-2}*BD $\theta_{-100\ kPa}$ (cm^3cm^{-3}) = 1.563*10^{-3}*Sa + 3.62*10^{-3}*Si + 7.154*10^{-3}*Cl + 2.388*10^{-3}*OM -5.759*10^{-2}*BD $\theta_{-200\ kPa}$ (cm^3cm^{-3}) = 0.932*10^{-3}*Sa + 2.643*10^{-3}*Si + 6.636*10^{-3}*Cl + 2.717*10^{-3}*OM -2.214*10^{-2}*BD $\theta_{-400\ kPa}$ (cm^3cm^{-3}) = 0.483*10^{-3}*Sa + 1.943*10^{-3}*Si + 6.128*10^{-3}*Cl + 2.925*10^{-3}*OM -0.204 *10^{-2}*BD $\theta_{-700\ kPa}$ (cm^3cm^{-3}) = 0.214*10^{-3}*Sa + 1.538*10^{-3}*Si + 5.908*10^{-3}*Cl + 2.855*10^{-3}*OM + 1.53*10^{-2}*BD $\theta_{-1000\ kPa}$ (cm^3cm^{-3}) = 0.076*10^{-3}*Sa + 1.334*10^{-3}*Si + 5.802*10^{-3}*Cl + 2.653*10^{-3}*OM + 2.145*10^{-2}*BD $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = -0.059*10^{-3}*Sa + 1.142*10^{-3}*Si + 5.766*10^{-3}*Cl + 2.228*10^{-3}*OM+ 2.671*10^{-2}*BD	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (g cm^{-3})	- Original document link - 43 dredged sediments and soil materials from 10 locations in Eastern and Central US - The PTFs were used in USDA's CalcPTF tool (USDA, 2010); in Dai et al. (2013) to develop soil hydraulic properties for China - Main characteristics of the PTFs developing dataset: Sand (5-98%), Silt (1-72%), Clay (0-65%), OM (0-23%), BD (0.74-1.74 g/cm^3) - The PTFs were used in tropical regions: Congo by Botula Manyala (2013); Vietnam by Nguyen et al. (2015) - PTFs showed the best performance to predict soil moisture at -4kPa of United State (Abdelbaki, 2020) - 962 citations from Google Scholar by (accessed on Aug 2020)

Equation name	Equation	Input	Description
Rawls et al. (1982) *	*Original PTFs:* $\theta_{-04\ kPa}\ (cm^3cm^{-3}) = 0.7899 - 0.0037*Sa + 0.01*OM - 0.1315*BD$ $\theta_{-07\ kPa}\ (cm^3cm^{-3}) = 0.7135 - 0.003*Sa + 0.0017*Cl - 0.1693*BD$ $\theta_{-10\ kPa}\ (cm^3cm^{-3}) = 0.4188 - 0.0030*Sa + 0.0023*Cl + 0.0317*OM$ $\theta_{-20\ kPa}\ (cm^3cm^{-3}) = 0.3121 - 0.0024*Sa + 0.0032*Cl + 0.0314*OM$ $\theta_{-33\ kPa}\ (cm^3cm^{-3}) = 0.2576 - 0.002*Sa + 0.0036*Cl + 0.0299*OM$ $\theta_{-60\ kPa}\ (cm^3cm^{-3}) = 0.2065 - 0.0016*Sa + 0.0040*Cl + 0.0275*OM$ $\theta_{-100\ kPa}\ (cm^3cm^{-3}) = 0.0349 + 0.0014*Si + 0.0055*Cl + 0.0251*OM$ $\theta_{-200\ kPa}\ (cm^3cm^{-3}) = 0.0281 + 0.0011*Si + 0.0054*Cl + 0.0220*OM$ $\theta_{-400\ kPa}\ (cm^3cm^{-3}) = 0.0238 + 0.0008*Si + 0.0052*Cl + 0.0190*OM$ $\theta_{-700\ kPa}\ (cm^3cm^{-3}) = 0.0216 + 0.0006*Si + 0.0050*Cl + 0.0167*OM$ $\theta_{-1000\ kPa}\ (cm^3cm^{-3}) = 0.0205 + 0.0005*Si + 0.0049*Cl + 0.0154*OM$ $\theta_{-1500\ kPa}\ (cm^3cm^{-3}) = 0.026 + 0.005*Cl + 0.0158*OM$	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD ($g\ cm^{-3}$)	- Original document link - 5350 horizons of 1323 soils from 32 states in US - Main characteristics of the PTFs developing dataset: $5\% \leq Sa \leq 30\%$ if $8\% \leq Cl \leq 58\%$ and $30\% \leq Sa \leq 95\%$ if $5\% \leq Cl \leq 60\%$ (Castellini & Iovino, 2019) - The PTFs were used in USDA's CalcPTF tool (USDA, 2010); in Dai et al. (2013) to develop soil hydraulic properties for China - The PTFs were used in tropical regions: Congo by Botula Manyala (2013); Vietnam by Nguyen et al. (2015) - The PTFs were used in arid regions: Iran (Givi et al., 2004) - 1961 citations from Google Scholar (accessed on 10 Aug 2020)
Rawls et al. (1983)	*Rawls et al. (1983) PTFs found in Williams et al. (1992) and Donatelli et al. (2004):* $\theta_{-33kPa}\ (m^3m^{-3}) = 0.3486 - 0.0018*Sa + 0.0039*Cl + 0.0228*OM - 0.0738*BD$ $\theta_{-60kPa}\ (m^3m^{-3}) = 0.2819 - 0.0014*Sa + 0.0042*Cl + 0.0216*OM - 0.0612*BD$ $\theta_{-100kPa}\ (m^3m^{-3}) = 0.2352 - 0.0012*Sa + 0.0043*Cl + 0.0202*OM - 0.0517*BD$ $\theta_{-1500kPa}\ (m^3m^{-3}) = 0.0854 - 0.0004*Sa + 0.0044*Cl + 0.0122*OM - 0.0182*BD$	*The PTFs in Williams et al. (1992) and Donatelli et al. (2004)* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD ($g\ cm^{-3}$)	- Original document link: cannot access - 5350 horizons of 1323 soils from 32 states in US - Main characteristics of the PTFs developing dataset: $5\% \leq Sa \leq 30\%$ if $8\% \leq Cl \leq 58\%$ and $30\% \leq Sa \leq 95\%$ if $5\% \leq Cl \leq 60\%$ (Castellini, & Iovino, 2019) - The PTFs were used in Dai et al. (2013) to develop soil hydraulic properties for China - 204 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
Hutson and Wagenet (1992)*	*Hutson and Wagenet (1992) PTFs found in Donatelli et al. (2004):* Hutson: θ_{-33kPa} (m^3m^{-3}) = Exp (-3.43 + 0.419(Sa + Si)$^{0.5}$ – 1.83*0.001(Cl +Si)$^{1.5}$) $\theta_{-1500kPa}$ (m^3m^{-3}) = Exp (-4.384 + 0.404 (Cl + Si)$^{0.5}$ – 9.85* 0.0000001 (Cl + Si)^3) British soil service, Top-soils: θ_{-20kPa} (m^3m^{-3}) = 0.403 + 0.0034*Cl + 0.0013*Si + 0.004*OC – 0.125*BD θ_{-40kPa} (m^3m^{-3}) = 0.2668 + 0.0039*Cl + 0.0013*Si + 0.0046*OC – 0.0764*BD $\theta_{-200kPa}$ (m^3m^{-3}) = 0.0938 + 0.0047*Cl + 0.0011*Si + 0.0069*OC $\theta_{-1500kPa}$ (m^3m^{-3}) = 0.0611 + 0.004*Cl + 0.0005*Si + 0.005*OC	*The PTFs in Donatelli et al. (2004)* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Bulk Density: BD (g cm^{-3})	- Original document link: not available - British soils - The PTFs were used in arid region: Jordan Valley (Mohawesh, 2013) - 536 citations from Google Scholar (accessed on 10 Aug 2020)
Rajkai and Varallyay (1992)	*Rajkai and Varallyay (1992) PTFs found in USDA's CalcPTF tool (USDA, 2010):* θ_{0kPa} (cm^3cm^{-3}) = 89.75 -31.39*BD + 0.03*BD*Si θ_{-3kPa} (cm^3cm^{-3}) = 85.05 -27.17*BD - 0.024*BD*Sa θ_{-10kPa} (cm^3cm^{-3}) = 78.58 -23.94*BD -0.025*BD*Sa θ_{-32kPa} (cm^3cm^{-3}) = 69.78 -21.74*BD + 0.0011(Cl+Si)^2 $\theta_{-501kPa}$(cm^3cm^{-3}) = 20.87 + 0.29*(Cl+Si) -0.83*(Sa/Si) + 0.03*(Cl+Si)*(Sa/Si) +0.0051*(Sa/Si)^2 $\theta_{-2512kPa}$(cm^3cm^{-3}) = 2.19 +0.52*(Cl+Si) + 3.93*OM -0.07*(Cl+Si)*OM $\theta_{-15849kPa}$(cm^3cm^{-3}) = 1.39 + 0.36*(Cl+Si) +0.22*OM^2 $\theta_{-1258925kPa}$(cm^3cm^{-3}) = 0.73 + 0.32*OM + 0.0018*Cl^2	*The PTFs in USDA's CalcPTF tool (USDA, 2010):* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (g cm^{-3})	- Original document link: not available - Hungarian national soil database - Soil texture defined by USA - The PTFs were used in USDA's CalcPTF tool (USDA, 2010); in Dai et al. (2013) to develop soil hydraulic properties for China - 68 citations from Google Scholar (accessed on 10 Aug 2020)

Salchow et al. (1996)	*Original PTFs:* Field capacity: θ_{FC} (cm^3 cm^{-3}) = -0.00064*Sa + 0.00123*Si + 0.00104*Cl + 0.02026*OM + 0.11421*BD Silty clay loam soil: θ_{FC} (cm^3 cm^{-3}) = - 0.00293*Sa - 0.00035*Si + 0.00121*Cl + 0.00904*OM + 0.22974*BD Silt loam soil: θ_{FC} (cm^3 cm^{-3}) = -0.00035*Sa + 0.00092*Si - 0.00016*Cl + 0.03109*OM + 0.11827*BD Loam soil: θ_{FC} (cm^3 cm^{-3}) = 0.00017*Sa + 0.00192*Si + 0.00463*Cl - 0.00977*OM + 0.07973*BD Sandy loam soil: θ_{-FC} (cm^3 cm^{-3}) = - 0.00120*Sa + 0.00127*Si + 0.00365*Cl + 0.02605*OM + 0.09962*BD Permanent Wilting Point: $\theta_{-1500\ kPa}$ (cm^{3}cm^{-3}) = -0.00126*Sa + 0.00039*Si - 0.00124*Cl + 0.03538*OM + 0.08426*BD Silty clay loam soil: $\theta_{-1500\ kPa}$ (cm^{3}cm^{-3}) = -0.00118*Sa - 0.00041*Si - 0.00405*Cl + 0.04701*OM + 0.14723*BD Silt loam soil: $\theta_{-1500\ kPa}$ (cm^{3}cm^{-3}) = - 0.00122*Sa - 0.00028*Si - 0.00097*Cl + 0.04136*OM + 0.09334*BD Loam soil: $\theta_{-1500\ kPa}$ (cm^{3}cm^{-3}) = - 0.00041*Sa + 0.00166*Si + 0.00352*Cl - 0.00603*OM + 0.03506*BD Sandy loam soil: $\theta_{-1500\ kPa}$ (cm^{3}cm^{-3}) = - 0.00183*Sa - 0.00063*Si + 0.00006*Cl + 0.05737*OM + 0.08221*BD Available Water Content/Capacity: AWC (cm^{3}cm^{-3}) = 0.00076*Sa + 0.00144*Si + 0.00252*Cl - 0.02268* OM + 0.01920*BD	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (Mg m^{-3})	- Original document link - 108 soil samples (Entisols, Inceptisols) from 40 ha of the 260 ha Vanmeter farm in Pike County, Ohio, USA. Mean winter and summer temperatures are 0°C and 22°C; average precipitation is 970 mm per year - Main characteristics of the PTFs developing dataset: Sand (Mean 24.3%, CV 59%), Silt (Mean 53.4%; CV 18%); Clay (Mean 22.4%; CV25.2%), OM (Mean 2.93%, CV 27.3%), BD (Mean 1.45, CV 9.1 Mg m^{-3}) - The PTFs were used USDA classification system - The PTFs were used in tropical region: Vietnam by Nguyen et al. (2015) - 68 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
	Silty clay loam soil: AWC (cm^3cm^{-3}) = - 0.00174*Sa + 0.00006*Si + 0.00526*Cl - 0.03796*OM + 0.08250*BD Silt loam soil: AWC (cm^3cm^{-3}) = 0.00131*Sa + 0.00199*Si + 0.00153*Cl + 0.02247*OM + 0.00604*BD Loam soil: AWC (cm^3cm^{-3}) = 0.00058*Sa + 0.00026*Si + 0.00110*Cl -0.00374*OM + 0.04466*BD Sandy loam soil: AWC (cm^3cm^{-3}) = 0.00062*Sa + 0.00190*Si + 0.00359*Cl -0.03132*OM + 0.01740*BD		
Saxton and Rawls (2006) *	*Original PTFs:* θ_{33} (% v) = θ_{33t} + (1.283 * $(\theta_{33t})^2$ – 0.374*θ_{33t} - 0.015) θ_{33t} (% v) = -0.251*Sa + 0.195*Cl + 0.011*OM + 0.006*(Sa*OM) - 0.027*(Cl*OM) + 0.452*(Sa*Cl) + 0.299 θ_{1500} (% v) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (% v) = -0.024*Sa + 0.487*Cl + 0.006*OM + 0.005*(Sa*OM) - 0.013*(Cl*OM) + 0.068*(Sa*Cl) + 0.031 θ_s (% v) = θ_{33} + θ_{s-33} -0.097*Sa+0.043 θ_{s-33} (% v) = $\theta_{(s-33)t}$ + (0.636*$\theta_{(s-33)t}$ - 0.107) $\theta_{(s-33)t}$ (% v) =0.278*Sa+0.034*Cl+0.022*OM-0.018*(Sa*OM)-0.027*(Cl*OM) – 0.584*(Sa*Cl) + 0.078 In which: θ (% v): decimal percent by volume basis Converted equations used in LUCI_PTFs (old): θ_{33} (cm^3cm^{-3}) = (θ_{33t} + (1.283 * $(\theta_{33t})^2$ – 0.374*θ_{33t} - 0.015))*10^{-2} θ_{33t} (cm^3cm^{-3}) = -0.00251*Sa + 0.00195*Cl + 0.00011*OM + 0.0000006*(Sa*OM) - 0.0000027 *(Cl*OM) + 0.0000452*(Sa*Cl) + 0.299 θ_{1500} (cm^3cm^{-3}) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (cm^3cm^{-3}) = -0.00024*Sa + 0.00487*Cl + 0.00006*OM + 0.0000005*(Sa*OM) - 0.0000013*(Cl*OM) + 0.0000068*(Sa*Cl) + 0.031 θ_s (cm^3cm^{-3}) = θ_{33} + θ_{s-33} -0.00097*Sa+0.043 θ_{s-33} (cm^3cm^{-3}) = $\theta_{(s-33)t}$ + (0.636*$\theta_{(s-33)t}$ - 0.107)	*Original PTFs:* Sand: Sa (%w, decimal percent by weight basis) Clay: Cl (%w) Organic matter: OM (%) Bulk Density: BD (g cm^{-3}) *Converted PTFs:* Sand: Sa (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (g cm^{-3})	- Original document link - Objective: update the Saxton et al. (1986) - 4000 soil water characteristics (2000 A-horizon and 2000 B-C horizon samples) was used to derive the PTFs obtained from the USDA/NRCS National Soil Characterization database - Applicable for Cl<60% (w) and OM < 8% (w), BD (1-1.8 g cm^{-3}) - The PTFs are similar to those previously reported by Saxton et al. (1986) but include more variables and application rang - The PTFs were used in Soil Water Characteristic tool (SPAW model) - The PTFs were used in tropical regions: Vietnam by Nguyen et al. (2015) - 1920 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
	$\theta_{(s-33)t}$ (cm^3cm^{-3})=0.00278*Sa+0.00034*Cl+0.00022*OM-0.0000018*(Sa*OM)-0.0000027(Cl*OM) – 0.0000584(Sa*Cl) + 0.078		
Al Majou et al. (2007)	*Original PTFs:* θ_{-1kPa} (cm^3cm^{-3}) = 0.4701 + 0.0026*Cl + 0.0006*Si – 0.0006*OC – 0.1447*BD $\theta_{-3.3kPa}$ (cm^3cm^{-3}) = 0.3556 + 0.0029*Cl + 0.0008*Si – 0.0002*OC – 0.0939*BD θ_{-10kPa} (cm^3cm^{-3}) = 0.262 + 0.0034*Cl + 0.0012*Si + 0.0002*OC – 0.0647*BD θ_{-33kPa} (cm^3cm^{-3}) = 0.1301 + 0.0038*Cl + 0.0012*Si + 0.001*OC – 0.0084*BD $\theta_{-100kPa}$ (cm^3cm^{-3}) = 0.0184 + 0.0045*Cl + 0.0008*Si + 0.0017*OC + 0.0398*BD $\theta_{-330kPa}$ (cm^3cm^{-3}) = -0.0504 + 0.0047*Cl + 0.0005*Si + 0.0012*OC + 0.0697*BD $\theta_{-1500kPa}$ (cm^3cm^{-3}) = -0.0786 + 0.0045*Cl + 0.0003*Si + 0.0004*OC + 0.0710*BD	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Bulk Density: BD (g cm^{-3})	- Original document link - 320 horizons, comprising 90 topsoils (from 0 to 30 cm depth) and 230 subsoil horizons (> 30 cm depth) collected in Cambisols, Luvisols, Planosols, Albeluvi-sols, Podzols, and Fluvisols located mainly in the Paris basin and secondarily in the western coastal marshlands and Pyrenean piedmont plain. - Main characteristics of the PTFs developing dataset: Clay (1.0-92.9%), Silt (2.8-82.1%), Sand (0.1-90.1%), OC (0-28.8 g kg^{-1}), $CaCO_3$ (0-982 g kg^{-1}), CEC (0.8 – 52.8 $cmol_c$ kg^{-1}), BD (1 – 1.84 g cm^{-3}) - 33 citations from Google Scholar (accessed on 10 Aug 2020)
Liao et al. (2011)	*Original PTFs:* θ_{-10kPa} (cm^3cm^{-3}) = −1.902 + 1.433*BD + 0.291*ln(Sa) + 0.061*ln(OM) + 0.00012*Si^2 − 0.56*BD^2 −0005*Sa*OM + 0.000084*BD^2*Cl^2 θ_{-33kPa} (cm^3cm^{-3}) = −1.092 + 1.952*BD +0.069*ln(OM) − 0.715*BD^2 − 0.001*Sa*OM + 0.001*Si*OM $\theta_{-1500kPa}$ (cm^3cm^{-3}) = 0.24 + 0.032*ln(OM) − 0.00015*Si^2 − 0.069*BD^2 − 0.000085*Sa*Si + 0.002*Si*OM + 0.007*Si*BD − 0.046*BD*OM	*Original PTFs:* Sand: Sa (g kg^{-1}) Silt: Si (g kg^{-1}) Clay: Cl (g kg^{-1}) Organic matter: OM (g kg^{-1}) Bulk density: BD (g cm^{-3})	- Original document link - 107 soils samples taken from Qingdao, Shandong Province, China. the soils in the study area can be classified as brown soils, fluvo-aquic soils, Shajiang black soils, cinnamon soils, or coastal aquic saline soils, with the first three soil types cove-ring more than 98% of the area. - Main characteristics of the PTFs developing dataset: Sand (233 – 742 g kg^{-1}), Silt (120.2-506.9 g kg^{-1}), Clay (71.8-321 9 g kg^{-1}), OM (3.3 – 26.5 g kg^{-1}), BD (1.27 – 1.63 g cm^{-3}) - PTFs showed the best performance to predict soil moisture at -33kPa of United State (Abdelbaki, 2020), the PTFs was cited as Hua et.al. (2011) in the paper - 28 citations from Google Scholar (accessed on 10 Aug 2020

Equation name	Equation	Input	Description
(3) Soil texture (Sa, Si, Cl); OM/OC			
De Jong et al. (1983)	*Original PTFs:* For soil water suction (S) $\leq 10^t$, t = - 1.12 + 0.029 *Cl $w_{-S\ kPa}$ (% w/w) = a + (b_1 *(log S – t)) / 100 where a = 6.4 + 2.78*OC + 0.24*Cl b_1 = - 42.9 + 0.55*Cl w: gravimetric moisture content (% w/w) For soil water suction (S) > 10^t, t = - 1.12 + 0.029 *Cl $w_{-S\ kPa}$ (% w/w) = a + (b_2 *(log S – t)) / 100 where a = 6.4 + 2.78*OC + 0.24*Cl b_2 = - 1.56 – (0.028*(Si + Cl) + 0.24*OC)	*Original PTFs:* Soil water suction: S (kPa) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%)	- Original document link (Table 8) - 18 Saskatchewan soils, Canada - Equations were used in arid regions Iran (Givi et al., 2004) - Main characteristics of the PTFs developing dataset: Sand (11-69%), Clay (8-66%), Silt (11-57%), OC (0.32-6.69%) - 107 citations from Google Scholar (accessed on 10 Aug 2020)
Batjes (1996)*	*Original PTFs:* θ_{sat} (10^{-2} cm^3cm^{-3}) = 0.6903*Cl + 0.5482*Si + 4.2844*OC $\theta_{pF1.0}$ (10^{-2} cm^3cm^{-3}) = 0.6463*Cl + 0.5436*Si + 3.7091*OC $\theta_{pF1.5}$ (10^{-2} cm^3cm^{-3}) = 0.5980*Cl + 0.3745*Si + 3.7611*OC $\theta_{pF1.7}$ (10^{-2} cm^3cm^{-3}) = 0.6681*Cl + 0.2614*Si + 2.2150*OC $\theta_{pF2.0}$ (10^{-2} cm^3cm^{-3}) = 0.5266*Cl + 0.3999*Si + 3.1752*OC $\theta_{pF2.3}$ (10^{-2} cm^3cm^{-3}) = 0.5082*Cl + 0.4197*Si + 2.5043*OC $\theta_{pF2.5}$ (10^{-2} cm^3cm^{-3}) = 0.4600*Cl + 0.3045*Si + 2.0703*OC $\theta_{pF2.7}$ (10^{-2} cm^3cm^{-3}) = 0.5032*Cl + 0.3636*Si + 2.4461*OC $\theta_{pF3.4}$ (10^{-2} cm^3cm^{-3}) = 0.4611*Cl + 0.2390*Si + 1.5742*OC $\theta_{pF4.2}$ (10^{-2} cm^3cm^{-3}) = 0.3624*Cl + 0.1170*Si + 1.6054*OC AWC (10^{-2} cm^3cm^{-3}) = 0.0976*Cl + 0.1875*Si + 0.4649*OC (Method 1) AWC (10^{-2} cm^3cm^{-3}) = 0.1082*Cl + 0.1898*Si + 0.7705*OC (Method 2) In which: AWC: Available Water Capacity, refers to volume moisture held between pF 2.5 and pF 4.2. pF was defined as the logarithm of water in soil-matric potential (pF = $\log_{10}$ (-head(cm of water)); e.g. a pressure head of -100 cm corresponds with pF 2.0. Converted equations used in LUCI_PTFs:	*Original PTFs:* Clay: Cl (%) Silt: Si (%) Organic carbon: OC (%) *Converted equations:* Clay: Cl (%) Silt: Si (%) Organic carbon: OC (%)	- Original document link - WISE soil database, 4353 soil profiles are from Africa (1799); South West and North Asia (522); South East Asia (553); Australia and the Pacific Islands (122); Europe (492); North America (266); and, South America and the Caribbean (599) - Main characteristics of the PTFs developing dataset: the particle size Clay < 0.002mm < Silt < 0.05 mm < Sand < 2mm; % Sand, % Silt and % Clay should not smaller than 5; organic carbon content should not smaller than 0.1% - Equations were used in tropical areas: Amazon, (Medeiros et al., 2014) which gave best result of water content at -33kPa and -1500kPa - 232 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
	θ_{sat} (cm^3cm^{-3}) = (0.6903*Cl + 0.5482*Si + 4.2844*OC)/100 $\theta_{pF1(10cm)}$ (cm^3cm^{-3}) = (0.6463*Cl + 0.5436*Si + 3.7091*OC)/100 $\theta_{pF1.5(32cm)}$ (cm^3cm^{-3}) = (0.5980*Cl + 0.3745*Si + 3.7611*OC)/100 $\theta_{pF1.7(50cm)}$ (cm^3cm^{-3}) = (0.6681*Cl + 0.2614*Si + 2.2150*OC)/100 $\theta_{pF2.0(100cm)}$ (cm^3cm^{-3}) = (0.5266*Cl + 0.3999*Si + 3.1752*OC)/100 $\theta_{pF2.3(200cm)}$ (cm^3cm^{-3}) = (0.5082*Cl + 0.4197*Si + 2.5043*OC)/100 $\theta_{pF2.5(316cm)}$ (cm^3cm^{-3}) = (0.4600*Cl + 0.3045*Si + 2.0703*OC)/100 $\theta_{pF2.7(501cm)}$ (cm^3cm^{-3}) = (0.5032*Cl + 0.3636*Si + 2.4461*OC)/100 $\theta_{pF3.4(-2511cm)}$ (cm^3cm^{-3}) = (0.4611*Cl + 0.2390*Si + 1.5742*OC)/100 $\theta_{pF4.2(-15849cm)}$ (cm^3cm^{-3}) = (0.3624*Cl + 0.1170*Si + 1.6054*OC)/100 AWC (cm^3cm^{-3}) = 10^{-2}*(0.0976*Cl + 0.1875*Si + 0.4649*OC) (Method 1) AWC (cm^3cm^{-3}) = 10^{-2}*(0.1082*Cl + 0.1898*Si + 0.7705*OC) (Method 2)		
(4) Soil texture (Sa, Si, Cl); BD			
Canarache (1993)	*Canarache (1993) PTFs found in CalcPTF tool (USDA, 2010) and Dai el a. (2013)* θ_{-33kPa} (cm^3cm^{-3}) = 0.01*BD*(2.65+1.105*Cl-0.01896*Cl^2 +0.0001678Cl^3 +15.12*BD-6.745*BD^2 -0.1975*Cl*BD) $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) =0.01*BD*(0.2805*Cl+0.0009615*Cl^2)	*Equations in CalcPTF tool (USDA, 2010):* Clay: Cl (%) Bulk Density: BD (g cm^{-3})	- Original document link: cannot access - Romani soil samples - The PTFs were used in CalcPTF tool (USDA, 2010); in Dai et al. (2013) to develop soil hydraulic properties for China - 17 citations from Google Scholar (accessed on 10 Aug 2020)
Rubio (2008)	*Original PTFs:* θ_s ($cm^3\ cm^{-3}$) = 0.148–(0.112*BD) θ_r ($cm^3\ cm^{-3}$) = 0.857–(0.247*BD) α = 0.062+(0.018*Sa) – (0,009*Sa^2) + (2*10^{-4}*Sa^3) n = 1.229–(0.081*BD) Also included equations for grassland	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Bulk density: BD (g cm^{-3})	- Original equation link - Silt loam soils from 0.56 km^2 Can Vila research basin, Spain, sub-Mediterranean climate - Main characteristics of the PTFs developing dataset: Silt >60%, Sand (7-28%), Clay (15-28%), BD(0.86-1.41 g cm^{-3}) - 13 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
Merdun (2010)	*Original PTFs:* Multiple-linear regression θ_{FC} ($cm^3\ cm^{-3}$) = 1.112 – 0.735*Sa – 1.083*Si – 0.277*BD – 0.440*Sa^2 + 0.0258*Si^2 – 0.096*BD^2 – 0.142*Sa*Si + 0.506*Sa*BD + 0.575*Si*BD θ_{PWP} ($cm^3\ cm^{-3}$) = 0.793 – 0.523*Sa – 0.662*Si – 0.236*BD – 0.186*Sa^2 – 0.391*Si^2 – 0.025*BD^2 – 0.428*Sa*Si + 0.23*Sa*BD + 0.451*Si*BD θ_{AWC} ($cm^3\ cm^{-3}$) = 0.319 – 0.213*Sa – 0.422*Si – 0.041*BD – 0.254*Sa^2+ 0.417*Si^2 – 0.071*BD^2 – 0.071*BD^2 + 0.287*Sa*Si + 0.276*Sa*BD + 0.124*Si*BD Seemingly unrelated regression θ_{FC} ($cm^3\ cm^{-3}$) = 0.855209 – 0.37943*Sa – 0.49006*Si – 0.14043*BD – 0.61338*Sa^2 – 0.29137*Si^2 – 0.12441*BD^2 – 0.66798*Sa*Si + 0.463879*Sa*BD + 0.452956*Si*BD θ_{PWP} ($cm^3\ cm^{-3}$) = 0.747114 – 0.47414*Sa – 0.51323*Si – 0.22358*BD – 0.19830*Sa^2 – 0.50546*Si^2 – 0.02932*BD^2 – 0.55125*Sa*Si + 0.231767*Sa*BD + 0.446919*Si*BD θ_{AWC} ($cm^3\ cm^{-3}$) = 0.32401 + 0.2111*Sa + 0.41802*Si + 0.04301*BD + 0.24910*Sa^2 + 0.41703*Si^2 + 0.07070*BD^2 + 0.28201*Sa*Si + 0.27910*Sa*BD + 0.13010*Si*BD	*Original PTFs:* Sand: Sa, fraction (kg kg^{-1}) Silt: Si, fraction (kg kg^{-1}) Clay: Cl, fraction (kg kg^{-1}) Bulk density: BD (g cm^{-3})	- Original equation link - 135 samples from UNSODA database for PTFs development - Main characteristics of the PTFs developing dataset: 0.019 kg kg^{-1} <Sand < 0.958 kg kg^{-1}; 0.024 kg kg^{-1} <Silt< 0.799 kg kg^{-1}; 0.01 kg kg^{-1} <Clay< 0.581 kg kg^{-1}; BD (0.71 – 1.73 g cm^{-3}) - 13 citations from Google Scholar (accessed on 10 Aug 2020)
(5) Soil texture (Sa, Si, Cl)			
Petersen et al. (1968)	*Original PTFs:* *:* $\theta_{-33\ kPa}$ (% cm^3cm^{-3}) = 11.83 + 0.96*Cl - 0.008*Cl^2 $\theta_{-1500\ kPa}$ (% cm^3cm^{-3}) = 1.74 + 0.76*Cl - 0.005*Cl^2 *Equations in USDA's CalcPTF tool (USDA, 2010):* $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = 0.01*(11.83 + 0.96*Cl - 0.008*Cl^2) $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = 0.01*(1.74 + 0.76*Cl - 0.005*Cl^2)	*Original PTFs:* Clay: Cl (%) *The PTFs in USDA's CalcPTF tool (USDA, 2010):* Clay: Cl (%)	- Original document link; cannot access the online version, can access the hard version (Fig.3) - 401 silt loams surface and subsoil horizon in 27 Pennsylvania counties, US (humid continental climate), giving representative samples of the following soil orders: Entisols, Inceptisols, Spodosols, Alfisols and Ultisols. - Main characteristics of the PTFs developing dataset: 17.6 ≤ %Sand ≤ 24.4; 56.6 ≤ %Silt ≤ 64.4; 17.5 ≤ %Clay ≤ 20.7; 0.12 ≤ OC ≤ 1.58; 1.33 ≤ BD(g/cc) ≤ 1.7

Equation name	Equation	Input	Description
			- The PTFs were used in USDA's CalcPTF tool (USDA, 2010); in Dai et al. (2013) to develop soil hydraulic properties for China - 50 citations from Google Scholar (accessed on 10 Aug 2020)
Bruand et al. (1994)	*Original PTFs:* $\theta_{-33\ kPa}$ ($cm^3 g^{-1}$) = (0.043+0.004*Cl)/(0.471+0.00411*Cl) $\theta_{-1500\ kPa}$ ($cm^3\ g^{-1}$) = (0.008+0.00367*Cl)/(0.471+0.00411*Cl) *Equations in CalcPTF tool (USDA, 2010):* $\theta_{-33\ kPa}$ ($cm^3 cm^{-3}$) = (0.043+0.004*Cl)/(0.471+0.00411*Cl) $\theta_{-1500\ kPa}$ ($cm^3 cm^{-3}$) = (0.008+0.00367*Cl)/(0.471+0.00411*Cl)	*Original PTFs:* Clay: Cl (%) *Equations in CalcPTF tool (USDA, 2010):* Clay: Cl (%)	- Original document link - Clayey soil, 20 non-calcareous clayey Bt horizons from Paris Basin, France. The soils were sampled from an area of 500 km^2 - Main characteristics of the PTFs developing dataset: Clay (53.3 – 73%), OC (3.4 – 9.8 g/kg) - The PTFs were used in CalcPTF tool (USDA, 2010); in Dai et al. (2013) to develop soil hydraulic properties for China - 44 citations from Google Scholar (accessed on 10 Aug 2020)
SMRC parameters – Van Genuchten model $$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^m}$$ $$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha * h)^n]^m}$$ S_e: the effective saturation $\theta(h)$: the relationship between volumetric soil moisture content and pressure head θ_s: the saturated moisture content θ_r: the residual moisture content m, n: the empirical shape-defining parameters in the van Genuchten model			
(1) Soil texture (Sa, Si, Cl); BD; OM/OC; and other soil properties			
Rawls and Brakensiek (1985)	*Rawls and Brakensiek (1985) PTFs found* in *Carsel and Parrish (1988)* θ_r ($cm^3 cm^{-3}$) = - 0.0182482 + 0.0087269*Sa + 0.00513488*Cl + 0.02939286*θ_s – 0.0015395*Cl^2 – 0.0010827*Sa*θ_s + 0.0030703*Cl^2*θ_s – 0.0023584*Cl*θ_s^2 – 0.0018233* Cl^2*θ_s^2	*Original equations:* Sand: Sa (%) Clay: Cl (%) θ_s: total saturated water content ($cm^3\ cm^{-3}$)	- Document link to Carsel and Parrish (1988) - PTFs was tested with 95 soil samples (51 silt loams, 10 loams, 12 silty clay, and 22

Equation name	Equation	Input	Description
	$\ln(\alpha^{-1}) = 5.3396738 + 0.1845038*Cl – 2.48394546*\theta_s – 0.00213853*Cl^2 – 0.0435649 *Sa*\theta_s – 0.61745089*Cl*\theta_s – 0.00001282*Sa^2*Cl + 0.00895359*Cl^2*\theta_s – 0.0072472*Sa^2*\theta_s + 0.0000054*SaCl^2 + 0.00143598*Sa^2*\theta_s^2 – 0.00855375*Cl^2*\theta_s^2$ $\ln (n-1) = -0.7842813 + 0.0177544*Sa – 1.062498*Cl – 0.00005304*Sa^2 – 0.00273493*Cl^2 + 1.11134946*\theta_s^2 – 0.03088295*Sa*\theta_s – 0.00000235*Sa^2*Cl + 0.00798746* Cl^2*\theta_s – 0.00674491*Cl*\theta_s^2 + 0.00026587*Sa^2*\theta_s^2 – 0.00610522* Cl^2*\theta_s^2$		loamy sands and sands. The PTFs performed well with silt loam - Main characteristics of the PTFs developing dataset: Clay (5-60%); Sand (5-70%) - 640 citations from Google Scholar (accessed on 22 Sep 2020)
Wösten et al. (1995)	*Original PTFs for sandy siliceous, mesic soils :* $\alpha^* = 146.9 - 0.0832*OM - 0.395*topsoil - 102.1*BD + 22.61*BD^2 - 70.6*BD^{-1} - 1.872 *(Cl+Si)^{-1} - 0.3931*\ln(Cl + Si)$ $n^* = 1092 + 0.0957*(Cl + Si) + 1.336*M50 - 13,229*M50^{-1} - 0.001203*M50^2 - 234.6*\ln(M50) - 2.67 *BD^{-1} - 0.115*OM^{-1} - 0.4129*\ln(OM) - 0.0721*BD*(Cl + Si)$ $\theta_s(cm^3cm^{-3}) = - 13.6- 0.01533*(Cl + Si) + 0.0000836*(Cl + Si)^2 - 0.0973*(Cl + Si)^{-1} + 0.708*BD^{-1}$ $- 0.00703*M50 + 225.3*M50^{-1} + 2.614*\ln(M50) + 0.0084*OM^{-1} +0.02256*1n(OM) +0.00718*BD*(Cl + Si)$	*Original PTFs:* Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) M50: median sand particle size Bulk Density: BD (unit is not clear in the original equation)	- Original document link - 88 soil profiles (sandy, siliceous, mesic Typic Haplaquod) from the Netherlands - 277 citations from Google Scholar (accessed on 30 Aug 2020)
Tóth et al. (2015)	*Original PTFs:* Rule 1 If Sa $\geq$ 2.00, $\theta_r = 0.041$ Rule 2 If Sa < 2.00, $\theta_r = 0.179$ $\theta_s (cm^3cm^{-3}) = 0.83080 - 0.28217 * BD + 0.0002728 * Cl + 0.000187 * Si$ $\log_{10}(\alpha) = -0.43348 - 0.41729 * BD - 0.04762 * OC + 0.21810 * T/S - 0.01581 * Cl - 0.012$ $07 * Si$ $\log_{10}(n^{-1}) = 0.22236 - 0.30189 * BD -0.05558 * T/S - 0.005306 * Cl - 0.003084 * Si - 0.01072 * OC$ or $\theta_s (cm^3cm^{-3}) = 0.63052 - 0.10262 * BD^2 + 0.0002904 * pH^2 + 0.0003335 * Cl$ $\log_{10}(\alpha) = -1.16518 + 0.40515 * (1/(OC+1)) - 0.16063 * BD^2 - 0.008372 * Cl - 0.01300* Si + 0.002166 * pH^2 + 0.08233 * T/S$	*Original PTFs:* T/S: top/sub soil, T/S = 1 top soil, T/S=0 subsoil Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (100 $g\ g^{-1}$) Bulk Density: BD ($g\ cm^{-3}$) pH: pH in water	- Original document link, equation can be found in Supporting information - EU-HYDI soil database, European soils, contains information on taxonomic, chemical and physical soil properties and data on land use for 18,537 unique soil samples from 6460 soil profiles across the continent - Main characteristics of the PTFs developing dataset: Sand (0-100%), Silt (0-86.8%), Clay (0-91.65), BD (0.09-2.02 $g\ cm^{-3}$), $CaCO_3$ (0-80%), pH (3.5-10.62) - Modified FAO texture class - 122 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
	$\log_{10}(n^{-1})$ = -0.25929 + 0.25680 * (1/(OC+1)) - 0.10590 * BD^2 - 0.009004 * Cl - 0.001223 * Si		
Tóth et al. (2015)	*Original PTFs:* Rule 1 IF Sa >= 2.00 θ_r = 0.041 Rule 2 IF Sa < 2.00 θ_r = 0.179 θ_s = 0.5056 - 0.1437 * (1/(OC+1)) + 0.0004152 * Si $\log_{10}(\alpha)$ = -1.3050 - 0.0006123 * Si - 0.009810 * Cl + 0.07611 * (1/(OC+1)) - 0.0004508 * Si * Cl + 0.03472 * Cl * (1/(OC+1)) - 0.01226 * Si * (1/(OC+1)) $\log_{10}(n-1)$ = 0.01516 - 0.005775 * (1/(OC+1)) - 0.24885 * $\log_{10}$(CEC) - 0.01918 * Cl - 0.0005052 * Si - 0.007544 * pH^2 - 0.02159 * Cl * (1/(OC+1)) + 0.01556 * Cl * $\log_{10}$(CEC) + 0.01477 * (1/(OC+1)) * pH^2 + 0.0001121 * Si * Cl - 0.33198 * (1/(OC+1)) * $\log_{10}$(CEC)	*Original PTFs:* T/S: top/sub soil, T/S = 1 top soil, T/S=0 subsoil Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (100 g g^{-1}) Bulk Density: BD (g cm^{-3}) pH: pH in water CEC: cation exchange capacity ($cmol_c$ kg^{-1})	
(2) Soil texture (Sa, Si, Cl); BD; OM/OC			
Vereecken et al. (1989)*	*Original PTFs:* θ_s (cm^3cm^{-3}) = 0.81 – 0.283*BD + 0.001*Cl θ_r (cm^3cm^{-3}) = 0.015 + 0.005*Cl + 0.014*OC log(α) = -2.486 + 0.025*Sa – 0.351*OC – 2.617*BD – 0.023*Cl log(n) = 0.053 – 0.009*Sa – 0.013*Cl + 0.00015*Sa^2 m = 1 *Vereecken et al. (1989) found in Botula Manyala (2013) and USDA (2010)* θ_s (m^3m^{-3}) = 0.81 – 0.283*BD + 0.001*Cl θ_r (m^3m^{-3}) = 0.015 + 0.005*Cl + 0.014*OC α = exp(-2.486 + 0.025*Sa – 0.351*OC – 2.617*BD – 0.023*Cl) n = exp(0.053 – 0.009*Sa – 0.013*Cl + 0.00015*Sa^2) m = 1	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Bulk Density: BD (g cm^{-3}) *The PTFs in Botula Manyala (2013):* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Bulk Density: BD (Mg m^{-3})	- Original document link : cannot access - Belgium, 182 horizons of 40 different soil series - The PTF is applicable with Cl < 54.5% , Si <80.7%, 5.6 < Sa < 97.8% OC <6.6% and 1.04 < BD 1.23 g cm^{-3} - The PTFs were used in CalcPTF tool (USDA, 2010) - The PTFs were used in tropical regions: Congo by Botula Manyala (2013) - The PTFs were assessed with Norway soils: the PTFs showed overall good performance except for the pressure range -6 to -2 kPa. A explanation for this is that Vereecken uses a restriction of m = 1 in the van Genuchten equation, which gives a different slope or curvature of the SWRC in the wet to moist range compared with using m = 1–1/n (Kværnø & Haugen, 2011)

Equation name	Equation	Input	Description
			- 887 citations from Google Scholar (accessed on 10 Aug 2020)
Wösten et al. (1999) *	*Original PTFs:* θ_s(cm^{3}cm^{-3}) = 0.7919 + 0.001691*Cl – 0.29619*BD – 0.000001491*Si^2 + 0.0000821*OM^2 + 0.02427*Cl^{-1} + 0.01113*Si^{-1} + 0.01472*ln(Si) – 0.0000733*OM*Cl-0.000619*BD*Cl – 0.001183*BD*OM-0.0001664*topsoil*Si $\theta_r(cm^3cm^{-3}) = \begin{cases} 0.025, & Cl < 18\% \text{ and } Sa > 65\% \\ 0.01 & otherwise \end{cases}$ (Information in Table 4) α= exp (-14.96 + 0.03135*Cl + 0.0351*Si + 0.646*OM + 15.29*BD – 0.192*top soil – 4.671*BD^2 – 0.000781*Cl^2 – 0.00687*OM^2 + 0.0449*OM^{-1} + 0.0663*ln(Si) + 0.1482*ln(OM) – 0.04546*BD*Si – 0.4852*BD*OM + 0.00673*topsoil*Cl) n = exp (-25.23 – 0.02195*Cl + 0.0074*Si – 0.1940*OM + 45.5*BD – 7.24*BD^2 + 0.0003658*Cl^2 + 0.002885*OM^2 -12.81*BD^{-1}- 0.1524*Si^{-1}- 0.01958*OM^{-1} – 0.2876*ln(Si) – 0.0709*ln(OM) – 44.6*ln(BD) – 0.02264*BD*Cl + 0.0896*BD*OM + 0.00718*topsoil*Cl) + 1 m = 1 – 1/n l* = 0.0202 + 0.0006193*Cl^2 – 0.001136*OM^2 – 0.2316*ln(OM) – 0.03544*BD*Cl + 0.00283*BD*Si + 0.0488*BD*OM top soil=1 for top soil, = 0 for subsoil	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (unit is not clear in the original equation)	- Original document link - European soil - Using HYPRES database of 4030 horizons (the Netherlands, Spain, France, England, Scotland, Denmark, Italy, Greece, Portugal, Belgium, Sweden, Northern Ireland, Slovakia) - Texture classes used to classify the available data: Topsoil (Coarse) Clay<18% and Sand> 65%; Topsoil (Medium) 18%<Clay<35% and 15%<Sand or Clay<18% and 15%<sand<65%; Topsoil (Medium fine) Clay <35% and Sand <15%; Topsoil (Fine) 35% <Clay<60%; Topsoil (Very fine) 60%< Clay - The PTFs were used in CalcPTF tool (USDA, 2010) - The PTFs were used in arid region - Positive evaluation by Wagner et al. (2001) - The PTFs showed good performance for Norway soils (Kværnø & Haugen, 2011) - 1088 citations from Google Scholar (accessed on 10 Aug 2020)
Al Majou et al. (2007)	*Original PTFs:* θ_s (cm^{3}cm^{-3}) = 1.1658 − 0.0032*Cl − 0.4737*BD + 2*10^{-7}*Si^2 − 0.0001*OC^2 + 0.0373*Cl −1 + 0.0131*Si^{-1} − 0.0072*ln(Si) + 0.00003*OC*Cl + 0.0022*BD*Cl − 0.0002*BD*OC − 0.0001*Si (R^2 = 0.95) α* = 25.61 + 0.0439*Cl + 0.1129*Si + 1.1914*OC + 32.21*BD − 10.48*BD^2 − 0.0009*Cl^2 − 0.0146*OC^2 − 0.378*OC^{-1} − 0.0178*ln(Si) − 0.1032*ln(OC) − 0.1*BD*Si − 0.6001*BD*OC (R^2 = 0.26) n* = – 15.29 − 0.0659*Cl + 0.0115*Si − 0.2115*OC + 12.33*BD − 1.3578* BD^2 + 0.0006*Cl^2 + 0.0031*OC^2 + 4.0005*BD^{-1} + 2.2003*Si^{-1} + 0.1643*OC^{-1} − 0.1205*ln(Si) + 0.2693*ln(OC) − 9.9367*ln(BD) + 0.003*BD*Cl + 0.0694*BD*OC (R^2 = 0.35) m = 1-1/n θ_r (cm^{3}cm^{-3}) = fixed	*Original PTFs:* Silt: Si (%) Clay: Cl (%) Organic carbon: OC (g kg^{-1}) Bulk Density: BD (unit is not clear in the original equation)	- Original document link - 320 horizons, comprising 90 topsoils (from 0 to 30 cm depth) and 230 subsoil horizons (> 30 cm depth) collected in Cambisols, Luvisols, Planosols, Albeluvi-sols, Podzols, and Fluvisols located mainly in the Paris basin and secondarily in the western coastal marshlands and Pyrenean piedmont plain. - Main characteristics of the PTFs developing dataset: Clay (1.0-92.9%), Silt (2.8-82.1%), Sand (0.1-90.1%), OC (0-28.8 g kg^{-1}), $CaCO_3$ (0-982 g kg^{-1}), CEC (0.8 – 52.8 cmol$_c$ kg^{-1}), BD (1 – 1.84 g cm^{-3})

Equation name	Equation	Input	Description
	α^*, n^* are transformed model parameters in the Mualem–van Genuchten equations		- 33 citations from Google Scholar (accessed on 10 Aug 2020)
Li et al. (2007)	*Original PTFs:* $\ln(\theta_s) = -1.531+0.212*\ln(Sa)+0.006*Si-0.051*OM-0.566*\ln(BD)$ $\ln(\alpha) = -67.408 - 0.040*Si - 0.670*\ln(Si) - 2.189*OM + 1.410*\ln(OM) + 78.4*BD - 121.331*\ln(BD)$ $n = 1.488 + 0.002*\ln(Si) + 0.013*Cl - 0.248*\ln(Cl) + 0.048*\ln(OM) + 0.451*\ln(BD)$	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk density: BD (g cm^{-3})	- Original documentation link - θ_r was not estimated - 64 soil water retention curves from Fengqiu County in the North China Plain. Fengqiu County soils are mainly classified as two types: Ochric Aquic Cambisol and Ustic Sandic Entisol according to the Chinese Soil Taxonomy System - Main characteristics of the PTFs developing dataset: OM (0.13 – 0.96%), BD (1.38 -1.47 g cm^{-3}) - 79 citations from Google Scholar (accessed on 10 Aug 2020)
Matula (2007)	*Original PTFs:* θ_s (m^3 m^{-3}) = $0.75608 + 0.05616*Cl + 0.11152*BD + 0.00003*Si^2 + 0.00423*OM^2 + 0.29552*Cl^{-1} - 1.55257*Si^{-1} - 0.12207*\ln(Si) + 0.02102*OM*Cl - 0.04672*BD*Cl - 0.08348*BD*OM - 0.00031*topsoil*Si$ $\alpha^* = -103.709 - 0.287*Cl + 0.092*Si + 47.929*OM + 98.173*BD + 4.019*topsoil - 37.314*BD^2 + 0.001*Cl^2 - 13.943*OM^2 + 18.577*OM^{-1} - 5.625*\ln(Si) + 0.155*OM*BD$ $n^* = \ln(7.0186 + 0.0595*Cl - 0.0133*Si - 2.0409*OM + 18.6714*BD - 15.1404*BD^2 - 0.0007*Cl^2 - 19.9935*BD^{-1} + 10.7434*Si^{-1} - 0.8598*OM^{-1} + 1.3763*\ln(Si) - 4.3084*\ln(OM) + 6.1984*\ln(BD) + 3.5008*BD*OM - 0.0214*topsoil*Cl)$ $\alpha^* = \ln\alpha$, $n^* = \ln(n-1)$; topsoil = a qualitative parameter (1 for topsoil, 0 for subsoil)	*Original PTFs:* Silt (2–50 µm): Si (%) Clay (0–2 µm): Cl (%) Organic matter: OM (%) Bulk Density: BD (Mg m^{-3} or g cm^{-3})	- Original documentation link - Soils from several sites (Brozany, Černičí, Cerhovice, Ovesná Lhota, Tupadly, Džbánov, Podlesí and Žichlínek), Cezch Republic - Main characteristics of the PTFs developing dataset: Clay (0 – 48.3%), Silt (6 – 66%), Sand (3.6-97.9%), OM (0.22-2.2%), BD (1.3-1.87 g cm^{-3}) - 15 citations from Google Scholar (accessed on 10 Aug 2020)
Weynants et al. (2009)*	*Original PTFs:* θ_r (m^3 m^{-3}) = 0 θ_s (m^3 m^{-3}) = $0.6355 + 0.0013*Cl - 0.1631*BD$ $\alpha^* = -4.3003 - 0.0097*Cl + 0.0138*Sa - 0.0992*OC$ $n^* = -1.0846-0.0236*Cl-0.0085*Sa+0.0001*Sa^2$ $\alpha^* = \ln\alpha$, $n^* = \ln(n-1)$ $l = -1.8642 - 0.1317*Cl + 0.0067*Sa$	*Original PTFs:* Sa: Sand (%) Si: Silt (%) Cl: Clay (%) OC: Organic carbon (g kg^{-1})	- Original document link - 182 horizons, total 39 soil profiles from Belgium - Main characteristics of the PTFs developing dataset: Sand (7.37-96.1%), Clay (3.9-42.7%), BD (1.28-1.59 g cm^{-3}), OC (1.4 – 60.8 g kg^{-1})

Equation name	Equation	Input	Description
		BD: Bulk density ($g\ cm^{-3}$)	- 141 citations from Google Scholar (accessed on 10 Aug 2020)
Merdun (2010)	*Original PTFs:* *Multiple-linear regression* $-\ln(\theta_r)\ (cm^3cm^{-3}) = -31.61 + 40.78*Si + 53.34*Cl + 36.52*BD – 15.66*Si^2 – 30.20*Cl^2 – 8.92*BD^2 + 0.843*Si*Cl – 17.83*Si*BD – 24.50*Cl*BD$ $\theta_s\ (cm^3cm^{-3}) = 1.391 – 0.289*Cl – 1.007*BD – 0.026*OM – 0.096*Cl^2 + 0.22*BD^2 – 0.00039*OM^2 + 0.3*Cl*BD + 0.0233*Cl*OM + 0.0229*BD*OM$ $-\ln(\alpha) = 4.647 – 6.425*Sa + 0.795*BD – 0.427*OM + 2.567*Sa^2 – 0.057*BD^2 + 0.0024*OM^2 + 0.943*Sa*BD + 0.456*Sa*OM + 0.0914*BD*OM$ $\ln(n) = 0.710 – 1.413*Sa – 2.533*Si – 0.068*BD + 2.263*Sa^2 + 2.807*Si^2 + 0.124*BD^2 + 3.268*Sa*Si – 0.624*Sa*BD – 0.219*Si*BD$ Seemingly unrelated regression $-\ln(\theta_r)\ (cm^3cm^{-3}) = -33.3305 + 40.28644*Si + 58.57803*Cl + 38.36318*BD – 15.9138*Si^2 – 30.5357*Cl^2 – 90.34917*BD^2 + 1.810918*Si*Cl – 17.4892*Si*BD – 28.3829*Cl*BD$ $\theta_s\ (cm^3cm^{-3}) = 1.419680 – 0.37696*Cl – 1.04082*BD – 0.02362*OM + 0.085484*Cl^2\ 0.230911*BD^2 + 0.000020*OM^2 + 0.322291*Cl*BD + 0.004189*Cl*OM + 0.022525*BD*OM$ $-\ln(\alpha) = -2.03482 – 2.70633*Sa + 8.547309*BD + 0.365279*OM + 2.439804*Sa^2 – 2.28273*BD^2 – 0.00292*OM^2 – 1.115*Sa*BD – 0.06837*Sa*OM – 0.37115*BD*OM$ $\ln(n) = 0.028513 – 0.30159*Sa – 1.52086*Si + 0.433897*BD + 1.699044*Sa^2 + 2.775716*Si^2 + 0.068137*BD^2 + 2.472513*Sa*BD – 0.95821*Sa*BD – 0.83048*Si*BD$	*Original PTFs:* Sand: Sa, fraction ($kg\ kg^{-1}$) Silt: Si, fraction ($kg\ kg^{-1}$) Clay: Cl, fraction ($kg\ kg^{-1}$) Bulk density: BD ($g\ cm^{-3}$) OM	- Original equation link - 135 samples from UNSODA database for PTFs development - Main characteristics of the PTFs developing dataset: 0.019 $kg\ kg^{-1}$ <Sand < 0.958 $kg\ kg^{-1}$; 0.024 $kg\ kg^{-1}$ <Silt< 0.799 $kg\ kg^{-1}$; 0.01 $kg\ kg^{-1}$ <Clay< 0.581 $kg\ kg^{-1}$; BD (0.71 – 1.73 $g\ cm^{-3}$) - 13 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
Liao et al. (2011)	*Original PTFs:* θ_s (cm^3cm^{-3}) = 0.591 + 0.027*ln(OM) − 0.615*ln(BD) θ_r (cm^3cm^{-3}) = −3.192 + 4.11*BD − 0.084*ln(OM) − 1.274*BD^2 + 0.004*Sa*OM + 0.005*Si*OM + 0.006*Cl*OM − 0.293*BD*OM α = 1.483 − 1.892*BD + 0.00036*Cl^2 + 0.595*BD^2 − 0.002*Sa*OM − 0.003*Si*OM − 0.003*Cl*OM + 0.177*BD*OM − 0.00016*BD^2*Cl^2 n = −2.061 + 2.751*BD	*Original PTFs:* Sand: Sa (g kg^{-1}) Silt: Si (g kg^{-1}) Clay: Cl (g kg^{-1}) Organic matter: OM (g kg^{-1}) Bulk density: BD (g cm^{-3})	- Original document link - 107 soils samples taken from Qingdao, Shandong Province, China. the soils in the study area can be classified as brown soils, fluvo-aquic soils, Shajiang black soils, cinnamon soils, or coastal aquic saline soils, with the first three soil types cove-ring more than 98% of the area. - Main characteristics of the PTFs developing dataset: Sand (233 – 742 g kg^{-1}), Silt (120.2-506.9 g kg^{-1}), Clay (71.8-321 9 g kg^{-1}), OM (3.3 – 26.5 g kg^{-1}), BD (1.27 – 1.63 g cm^{-3}) - The PTFs were cited as Hua et.al. (2011) - 28 citations from Google Scholar (accessed on 10 Aug 2020)
Tóth et al. (2015)	*Original PTFs:* Rule 1 If Sa ≥ 2.00, θ_r = 0.041 Rule 2 If Sa < 2.00, θ_r = 0.179 θ_s (cm^3cm^{-3}) = 0.83080 - 0.28217 * BD + 0.0002728 * Cl + 0.000187 * Si log_{10}(α) = -0.43348 - 0.41729 * BD - 0.04762 * OC + 0.21810 * T/S - 0.01581 * Cl - 0.012 07 * Si log_{10}(n^{-1}) = 0.22236 - 0.30189 * BD -0.05558 * T/S - 0.005306 * Cl - 0.003084 * Si - 0.01072 * OC or θ_s (cm^3cm^{-3}) = 0.63052 - 0.10262 * BD^2 + 0.0002904 * pH^2 + 0.0003335 * Cl log_{10}(α) = -1.16518 + 0.40515 * (1/(OC+1)) - 0.16063 * BD^2 - 0.008372 * Cl - 0.01300* Si + 0.002166 * pH^2 + 0.08233 * T/S log_{10}(n^{-1}) = -0.25929 + 0.25680 * (1/(OC+1)) - 0.10590 * BD^2 - 0.009004 * Cl - 0.001223 * Si	*Original PTFs:* T/S: top/sub soil, T/S = 1 top soil, T/S=0 subsoil Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (100 g g^{-1}) Bulk Density: BD (g cm^{-3}) pH: pH in water	- Original document link, equation can be found in Supporting information - EU-HYDI soil database, European soils, contains information on taxonomic, chemical and physical soil properties and data on land use for 18 537 unique soil samples from 6460 soil profiles across the continent - Main characteristics of the PTFs developing dataset: Sand (0-100%), Silt (0-86.8%), Clay (0-91.65), BD (0.09-2.02 g cm^{-3}), $CaCO_3$ (0-80%), pH (3.5-10.62) - Modified FAO texture class - 122 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
Qiao et al. (2018)	*Original PTFs:* $\alpha = 0.012 + 0.0002*Sa - 0.007*BD$ $n = 5.507 + 6.966*Cl^{-1} - 7.272*BD^2 + 0.186*OC^{-1} - 4.399*BD^{-1}$ $\theta_s\ (cm^3cm^{-3}) = -0.779 - 0.608*BD^2 + 0.016*lnSa + 1.712*BD - 0.000027*Sa^2$	*Original PTFs:* The paper did not mention unit of Sand, Silt, Clay, BD and OC	- Original equation link - Lack equation for θ_r - Soil hydraulic properties collected were 30, 100, and 76 for Yangling, Changwu, and An'sai, respectivelyin Loess Plateau, China - 2 citations from Google Scholar (accessed on 10 Aug 2020)
(3) Soil texture (Sa, Si, Cl); OM/OC			
			-
(4) Soil texture (Sa, Si, Cl); BD			
Varallyay et al. (1982)	*Varallyay et al. (1982) PTFs found in CalcPTF tool (USDA, 2010) and (Guber et al., 2006) :* $\theta_r\ (cm^3cm^{-3}) = 0$ For A horizons: $\theta_s\ (cm^3\ cm^{-3}) = 0.01(-56.4*BD + 0.00205*Cl^2 + 123.79)$ $\alpha = 10^{-0.0427*BD*Cl - 1.51*BD}$ (in Guber et al, 2006) $\alpha = 10^{0.417-0.0427*BD*Cl - 1.51*BD}$ (in Guber et al, 2006) $n = 0.336*BD - 0.053$ For C horizons: $\theta_s\ (cm^3\ cm^{-3}) = 0.01(-46.8*BD + 125.39)$ $\alpha = 10^{-0.0326*BD*Cl - 0.865*BD*BD - 0.301}$ $n = 0.00439*BD*Cl + 0.625$ $m = 1$	*Equations in CalcPTF tool (USDA, 2010):* Clay: Cl (%) Bulk Density: BD ($g\ cm^{-3}$)	- Original document in Russian - Hungarian national soil database - The PTFs for A horizons - The PTFs were used in CalcPTF tool (USDA, 2010) - 13 citations from Google Scholar (accessed on 10 Aug 2020)
Schaap et al. (2001)	van Genuchten (1980) retention parameters generated by the Rosetta software with Sa, Si, Cl, BD as predictors using ANNs		- Original documentation link - ROSETTA model - Data set for calibration and testing from USA - The PTFs were used in arid regions: Turkey by Tombul et al. (2004) - The PTFs were used in tropical regions: Congo by Botula Manyala (2013) - The PTF of Schaap showed poorer performance than its regression based

Equation name	Equation	Input	Description
			counterparts with Norway soils (Kværnø & Haugen, 2011) - 2106 citations from Google Scholar (accessed on 10 Aug 2020)
Zacharias and Wessolek (2007)*	*Original PTFs:* Sand content < 66.5% θ_r (cm^3 cm^{-3}) = 0 θ_s (cm^{3}cm^{-3}) = 0.788 + 0.001*Cl - 0.263*BD lnα = −0.648 + 0.023*Sa + 0.044*Cl - 3.168*BD n = 1.392 – 0.418*Sa$^{-0.024}$ + 1.212*Cl$^{-0.704}$ m = 1-1/n Sand content ≥ 66.5% θ_r (cm^{3}cm^{-3}) = 0 θ_s (cm^{3}cm^{-3}) = 0.89 - 0.001*Cl - 0.322*BD lnα = −4.197 + 0.013*Sa + 0.076*Cl – 0.276*BD n = -2.562 + 7*10^{-9}*Sa$^{4.004}$ + 3.75*Cl$^{-0.016}$ m = 1-1/n	*Original PTFs:* Sand: Sa (%) Clay: Cl (%) Bulk density: BD (g cm^{-3})	- Original documentation link - 676 measured water retention curves from IGBP-DIS + UNSODA databases - Main characteristics of the PTFs developing dataset: Sand (1 – 987 g kg^{-1}), Silt (4-872 g kg^{-1}), Clay (6-927 g kg^{-1}), BD (1.08 – 1.88 g cm^{-3}), OM (0-144.8 g kg^{-1}) - The PTFs showed the best performance in medium and coarse soils of United State (Abdelbaki, 2020) - 119 citations from Google Scholar (accessed on 10 Aug 2020)
(5) Soil texture (Sa, Si, Cl)			
Schaap et al. (2001)	van Genuchten (1980) retention parameters generated by the Rosetta software with Sa, Si, Cl, BD as predictors using ANNs		- Original documentation link - ROSETTA model - Data set for calibration and testing from USA - The PTFs were used in arid regions: Turkey by Tombul et al. (2004) - The PTFs were used in tropical regions: Congo by Botula Manyala (2013) - 2106 citations from Google Scholar (accessed on 10 Aug 2020)
SMRC - Brooks and Corey (1964) model			

$$\frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = \begin{cases} \left(\frac{h_b}{h}\right)^{\lambda}, & b > h_b \\ 1, & h \leq h_b \end{cases}$$

<table>
<tr><th>Equation name</th><th>Equation</th><th>Input</th><th>Description</th></tr>
<tr><td colspan="4">

$$S_e = \frac{\theta(h)-\theta_r}{\phi-\theta_r} = \begin{cases} 1, & h \le h_b \\ \left(\frac{h_b}{h}\right)^{\lambda_{BC}}, & h > h_b \end{cases}$$

Or:

$$\theta(h) \begin{cases} \phi, & h \le h_b \\ \theta_r + \frac{(\phi-\theta_r){h_b}^{\lambda_{BC}}}{h^{\lambda_{BC}}}, & h > h_b \end{cases}$$

The equation has been also written as (Beven, 2012; Pan et al., 2019):

$$S_e = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = \begin{cases} 1, & h \le h_b \\ \left(\frac{h_b}{h}\right)^{\lambda_{BC}}, & h > h_b \end{cases}$$

Or:

$$\theta(h) \begin{cases} \theta_s, & h \le h_b \\ \theta_r + \frac{(\theta_s-\theta_r){h_b}^{\lambda_{BC}}}{h^{\lambda_{BC}}}, & h > h_b \end{cases}$$

S_e: the effective saturation
θ(h): the relationship between volumetric soil moisture content and pressure head
ϕ: prorosity
θ_s: the saturated moisture content
θ_r: the residual moisture content
h_b: the air-entry pressure
m, n: the empirical shape-defining parameters in the van Genuchten model
</td></tr>
<tr><td colspan="4">(1) Soil texture (Sa, Si, Cl); BD; OM/OC; and other soil properties</td></tr>
<tr><td>Rawls and Brakensiek (1985)*</td><td>Original PTFs:
h_b =exp(5.3396738 + 0.1845038* Cl - 2.48394546* Φ - 0.00213853* Cl^2 - 0.04356349*Sa*Φ - 0.61745089*Cl*Φ +0.00143598*Sa^2*$Φ^2$ -0.00855375* Cl^2*$Φ^2$ - 0.00001282*Sa^2*Cl + 0.00895359*Cl^2*Φ - 0.00072472*Sa^2*Φ +0.0000054*Cl^2*Sa + 0.50028060*$Φ^2$*Cl)</td><td>Original PTFs:
Sand: Sa (%)
Clay: Cl (%)
Porosity: Φ (fraction)</td><td>- Equations were used in USDA's CalcPTF tool (USDA, 2010), Fortran code
- PTFs was tested with 95 soil samples (51 silt loams, 10 loams, 12 silty clay, and 22 loamy sands and sands. The PTFs performed well with silt loam</td></tr>
</table>

Equation name	Equation	Input	Description
	λ = exp(-0.7842831 + 0.0177544*Sa - 1.062498*Φ - 0.00005304* Sa^2 - 0.00273493* Cl^2 + 1.11134946*Φ^2 - 0.03088295*Sa*Φ + 0.00026587*Sa^2*Φ^2 - 0.00610522 Cl^2*Φ^2 - 0.00000235*Sa^2*Cl + 0.00798746*Cl^2*Φ - 0.00674491*Φ^2*Cl) θ_r= -0.0182482 + 0.00087269*Sa + 0.00513488*Cl + 0.02939286*Φ - 0.00015395*Cl^2 - 0.0010827*Sa*Φ - 0.00018233*Cl^2*Φ^2 + 0.00030703*Cl^2*Φ - 0.0023584*Φ^2*Cl		- Main characteristics of the PTFs developing dataset: Clay (5-60%); Sand (5-70%) - 640 citations from Google Scholar (accessed on 22 Sep 2020)
Saxton and Rawls (2006) *	*Original PTFs:* θ_{33} (% v) = θ_{33t} + (1.283 * $(\theta_{33t})^2$ – 0.374*θ_{33t} - 0.015) θ_{33t} (% v) = -0.251*Sa + 0.195*Cl + 0.011*OM + 0.006*(Sa*OM) - 0.027*(Cl*OM) + 0.452*(Sa*Cl) + 0.299 θ_{1500} (% v) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (% v) = -0.024*Sa + 0.487*Cl + 0.006*OM + 0.005*(Sa*OM) - 0.013*(Cl*OM) + 0.068*(Sa*Cl) + 0.031 θ_s (% v) = θ_{33} + θ_{s-33} -0.097*Sa+0.043 θ_{s-33} (% v) = $\theta_{(s-33)t}$ + (0.636*$\theta_{(s-33)t}$ - 0.107) $\theta_{(s-33)t}$ (% v) =0.278*Sa+0.034*Cl+0.022*OM-0.018*(Sa*OM)-0.027*(Cl*OM) – 0.584*(Sa*Cl) + 0.078 θ_{1500} (% v) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (% v) = -0.024*Sa + 0.487*Cl + 0.006*OM + 0.005*(Sa*OM) - 0.013*(Cl*OM) + 0.068*(Sa*Cl) + 0.031 h_{bt} (kPa) = - 21.67* Sa – 27.93*Cl - 81.97* $\theta_{(s-33)t}$ + 71.12*Sa* $\theta_{(s-33)t}$ + 8.29*Cl* $\theta_{(s-33)t}$ + 0.001405*Sa*Cl + 27.16 h_b (kPa) = h_{bt} + (0.02* h_{bt}^2 – 0.113* h_{bt} - 0.70) In which: θ (% v): decimal percent by volume basis <u>Converted equations used in LUCI_PTFs:</u> θ_{33} (cm^3cm^{-3}) = (θ_{33t} + (1.283 * $(\theta_{33t})^2$ – 0.374*θ_{33t} - 0.015))*10^{-2} θ_{33t} (cm^3cm^{-3}) = -0.00251*Sa + 0.00195*Cl + 0.00011*OM + 0.0000006*(Sa*OM) - 0.0000027 *(Cl*OM) + 0.0000452*(Sa*Cl) + 0.299 θ_{1500} (cm^3cm^{-3}) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (cm^3cm^{-3}) = -0.00024*Sa + 0.00487*Cl + 0.00006*OM + 0.0000005*(Sa*OM) - 0.0000013*(Cl*OM) + 0.0000068*(Sa*Cl) + 0.031 θ_s (cm^3cm^{-3}) = θ_{33} + θ_{s-33} -0.00097*Sa+0.043	*Original PTFs:* Sand: Sa (%w, decimal percent by weight basis) Clay: Cl (%w) Organic matter: OM (%) Bulk Density: BD (g cm^{-3}) *Converted PTFs:* Sand: Sa (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (g cm^{-3})	- Original document link - Objective: update the Saxton et al. (1986) - 4000 soil water characteristics (2000 A-horizon and 2000 B-C horizon samples) was used to derive the PTFs obtained from the USDA/NRCS National Soil Characterization database - Applicable for Cl<60% (w) and OM < 8% (w), BD (1-1.8 g cm^{-3}) - The PTFs are similar to those previously reported by Saxton et al. (1986) but include more variables and application rang - The PTFs were used in Soil Water Characteristic tool (SPAW model) - The PTFs were used in tropical regions: Vietnam by Nguyen et al. (2015) - 1920 citations from Google Scholar (accessed on 10 Aug 2020)

Equation name	Equation	Input	Description
	θ_{s-33} (cm^3cm^{-3}) = $\theta_{(s-33)t}$ + (0.636*$\theta_{(s-33)t}$ - 0.107) $\theta_{(s-33)t}$ (cm^3cm^{-3})=0.00278*Sa+0.00034*Cl+0.00022*OM-0.0000018*(Sa*OM)-0.0000027(Cl*OM) – 0.0000584(Sa*Cl) + 0.078 h_{bt} (kPa = - 0.2167* Sa - 0.2793*Cl - 81.97* $\theta_{(s-33)t}$ + 0.7112*Sa* $\theta_{(s-33)t}$ + 0.0829*Cl* $\theta_{(s-33)t}$ + 0.001405*Sa*Cl + 27.16 h_b (kPa) = h_{bt} + (0.02* h_{bt} ^{2} – 0.113* h_{bt} - 0.70) $\lambda = 1/B$ B=[ln(1500)- ln(33)]/[ln(θ_{33}) - ln(θ_{1500})		
(4) Soil texture (Sa, Si, Cl); BD			
Campbell and Shiozawa (1992)*	*Original PTFs:* h_b =100*(h_{es} *(BD/1.3)$^{0.67b}$) h_{es}=0.05/ sqrt(dg) b=-20*(-h_{es}) + 0.2*Sg dg=exp(-0.80 – 0.0317*Si – 0.0761*Cl) Sg=(exp(0.133*Si +0.477*Cl - ln^{2}d$_g$))$^{1/2}$ λ = 1/b	*Original PTFs:* Silt: Si (%) Clay: Cl (%) Bulk density: BD (1.3 g cm^{-3})	- 6 soil samples (USDA, 2010) - The PTFs were used were used in USDA's CalcPTF tool (USDA, 2010), Fortran code - 305 citations from Google Scholar (accessed on 19 Feb 2021)
Williams et al. (1989)	*Original PTFs:* θ_r = 0 lnθ =A+Blnh A = 1.839 + 0.257*ln(Cl) + 0.381*2.0 - 0.0001*Sa^2 B = -0.303 + 0.093*ln(BD) + 0.0565*ln(Cl) - 0.00003*Sa^2 When OM is available A = 2.57 + 0.238*ln(Cl) - 0.000192*Sa^2 - 0.0137*Sa - 0.0926*ln(OM) + 0.0412*OM B = -0.403 + 0.0871*ln(Cl) - 0.00077*Sa	*Original PTFs:* Sand: Sa (%) Clay: Cl (%) Bulk density: BD (g cm^{-3}) Organic matter content: OM (%)	- 196 Australian soil samples for PTFs development - The PTFs were used in USDA's CalcPTF tool (USDA, 2010), Fortran code - 132 citations from Google Scholar (accessed on 19 Feb 2021)
Mayr and Jarvis (1999)	*Original PTFs:* set θ_r = 0 and porosity Φ equal to the saturated water θ_s in the Brooks-Corey equation $\theta = \theta_s (h/a)^{-1/b}$ $\theta < \theta_i$ with a parabolic equation for the wet range:	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%)	- 306 UK soil samples (Soil Survey and Land Research Centre containing) 5000 horizons from 1500 soil profiles) for PTFs development - The PTFs were used in USDA's CalcPTF tool (USDA, 2010), Fortran code

Equation name	Equation	Input	Description
	$\theta(h) = \theta_s - \frac{\theta_s h^2\left(1-\frac{\theta_i}{\theta_s}\right)}{a^2\left(\frac{\theta_i}{\theta_s}\right)^{-2b}}$ $\theta(h) \geq \theta_i$ The water content θ_i and the equivalent capillary pressure hi at the matching point are given by: $$\theta_i = \frac{2b\theta_s}{1+2b}$$ and $$h_i = a\left(\frac{2b}{1+2b}\right)^{-b}$$ log(a)= -4.98 + 0.05*Sa + 0.157*Si + 0.12*BD - 0.16*OC -0.0022*Si^2 + 0.00001438*Si^3 + 0.000804*Cl^2 + 0.0044067117*OC^2 log(1/b) = - 0.8467 - 0.00468*Sa + 0.0092*Si - 0.4543*BD -0.04979*OC + 0.000329*Sa^2 + 0.000001689*Sa^3 + 0.0011225373*OC^2 θ_s = 0.2346 + 0.00466*Sa + 0.0088*Si + 0.006434*Cl - 0.3028*BD + 0.179*10^{-4}*Sa^2 - 0.313*10^{-4}*Si^2	Bulk density: BD (g cm^{-3}) Organic carbon content: OC (%)	- 131 citations from Google Scholar (accessed on 19 Feb 2021)
(5) Soil texture (Sa, Si, Cl)			
Cosby et al. (1984)*	*Original PTFs:* Using Sand, Silt, Clay: $\log(h_b)$ = 1.54 – 0.0095*Sa + 0.0063*Si 1/ λ = 3.10 + 0.157*Cl – 0.003*Sa θ_s = (50.5 – 0.037*Cl – 0.142*Sa)/100 Using Sand, Clay: $\log(h_b)$ = 1.88 – 0.013*Sa 1/ λ = 2.91 + 0.159*Cl θ_s = 0.489 – 0.00126*Sa	*Original PTFs:* Sa: Sand (%) Si: Silt (%) Cl: Clay (%)	- Original document link - Data are from Holtan et al. (1968) and Rawls et al. (1976), 1448 soil samples taken from 35 locations in 23 states from USA - Main characteristics of PTFs developing dataset: Sand (6-92%), Silt (5-70%), Clay (3-58%) - The PTFs were used in ROSETTA model, in Dai et al. (2013) to develop soil hydraulic properties for China - Positive evaluation by Tietje and Hennings (1996) - 1580 citations from Google Scholar (accessed on 10 Aug 2020)
Saxton et al. (1986)*	*Equations in Saxton et al. (1986)*:* θ_{0kPa} (m^3m^{-3}) = θ_{sat} = 0.332 - 7.251×10^{-4}*Sa + 0.1276*$\log_{10}$Cl A=100*exp(-4.396-0.0715*Cl-0.000488*Sa^2 -0.00004285*Sa^2*Cl)	*Original equations:* Sand: Sa (%) Clay: Cl (%)	- Original document link (Table 2) - Soil samples from USA

Equation name	Equation	Input	Description
	$B = -3.140 - 0.00222*Cl^2 - 0.00003484*Sa^2*Cl$ $\lambda = -1/B$ $\theta_r = 0$ h_b (kPa)= $A* \Phi^B$ Φ was replaced by θ_s in Dai et al. (2013)		- Textures defined by the USDA system: Clay < 0.002mm < Silt < 0.05 mm < Sand < 2mm - The equations appear quite valid with 5% ≤ % Sand ≤ 30% with 8% ≤ % clay ≤ 58% and 30% ≤ % sand ≤ 95 with 5% ≤ % clay ≤ 60% - The PTFs were used in USDA's CalcPTF tool (USDA, 2010), in Dai et al. (2013) to develop soil hydraulic properties for China - The PTFs showed the best performance in very fine soils of United State (Abdelbaki, 2020) - 2200 citations from Google Scholar (accessed on 24 Aug 2020)

Table B1.7 PTFs for estimating soil moisture content developed for tropical climate

Equation name	Equation	Parameter	Description
Point PTFs			
(1) Soil texture (Sa, Si, Cl); BD; OM/OC; and other soil properties			
Bell and Keulen (1995)	*Bell and Keulen (1995)PTFs found in Oliveira et al. (2002):* w_{-33kPa} (kg kg^{-1}) = (6.93 + 0.286*Cl/10)/100 $w_{-1500kPa}$ (kg kg^{-1}) = (5.72 + 0.433*Cl/10)/100 *Equation in Reichert et al. (2009):* $w_{-1500kPa}$ (g 100 g^{-1}) = -0.992 + 0.351*Cl + 0.47*OM (R^2 = 0.85) $w_{-1500kPa}$ (g 100 g^{-1}) = -1.62 + 0.436*CEC_{pH7} + 0.436*OM (R^2 = 0.9)	*The PTFs in Oliveira et al. (2002):* *Clay:* Cl (g kg^{-1}) *The PTFs in Reichert et al. (2009):* Clay: Cl (g 100 g^{-1}) Organic matter: OM (g 100 g^{-1}) CEC (cmo$_{lc}$ kg^{-1})	- Original document was not found - Mexico soils - 160 citations from Google Scholar (accessed on 10 Aug 2020)

Van den Berg (1996)	*Van den Berg (1996) found in van Den Berg et al. (1997):* θ_{-10kPa} (m^3m^{-3} 10^2) = 4.5 + 0.42*(Cl + Si) – 0.37*Fe_2O_3 + 6.3*BD $\theta_{-1500\ kPa}$ (m^3m^{-3} 10^2) = 2 + 0.27*(Cl+Si)	*The PTFs found in van Den Berg et al. (1997):* Silt: Si (kg $kg^{-1}10^2$) Clay: Cl (kg $kg^{-1}10^2$) Bulk density: BD (kg dm^{-3}) Unit of Fe_2O_3 was not mentioned	- Original document was not found - Soils in South East and Southern Brazil - 6 citations from Google Scholar (accessed on 10 Aug 2020)
Chakraborty et al. (2011)	*Original PTFs:* $w_{-33\ kPa}$ (g g^{-1},%) (1) = 0.297*Cl + 0.478*Si + 4.600 $w_{-33\ kPa}$ (g g^{-1},%) (2) = -0.377*Sa – 0.215*BD + 41.114 $w_{-33\ kPa}$ (g g^{-1},%) (3) = 0.28*Cl + 0.481*Si – 7.566*BD +17.095 $w_{-33\ kPa}$ (g g^{-1},%) (4) = 0.078*Cl + 0.248*Si – 0.241*Sa + 27.447 $w_{-33\ kPa}$ (g g^{-1},%) (5) = 0.093 *Cl + 0.276*Si – 0.213*Sa – 4.481*BD +32.210 $w_{-33\ kPa}$ (g g^{-1},%) (6) = 0.095 *Cl + 0.268*Si – 0.206*Sa + 2.42*OC – 4.402*BD + 30.960 $w_{-100\ kPa}$ (g g^{-1},%) (1) = 0.27*Cl + 0.379*Si + 2.988 $w_{-100\ kPa}$ (g g^{-1},%) (2) = -0.33*Sa + 2.611*BD + 30.160 $w_{-100\ kPa}$ (g g^{-1},%) (3) = 0.262*Cl + 0.38*Si – 3.167*BD + 8.219 $w_{-100\ kPa}$ (g g^{-1},%) (4) = 0.049*Cl + 0.147*Si – 0.242*Sa + 25.945 $w_{-100\ kPa}$ (g g^{-1},%) (5) = 0.048*Cl + 0.145*Si – 0.245*Sa + 0.37*BD + 25.551 $w_{-100\ kPa}$ (g g^{-1},%) (6) = 0.053*Cl + 0.113*Si – 0.23*Sa + 6.434*OC + 1.528*BD + 21.236 $w_{-500\ kPa}$ (g g^{-1},%) (1) = 0.251*Cl + 0.185*Si + 2.958 $w_{-500\ kPa}$ (g g^{-1},%) (2) = -0.224*Sa – 0.795*BD + 27.495 $w_{-500\ kPa}$ (g g^{-1},%) (3) = 0.244*Cl + 0.187*Si – 3.079*BD + 8.046 $w_{-500\ kPa}$ (g g^{-1},%) (4) = 0.067*Cl - 0.008*Si – 0.204*Sa + 22.216 $w_{-500\ kPa}$ (g g^{-1},%) (5) = 0.067*Cl – 0.008*Si – 0.203*Sa – 0.135*BD + 22.359 $w_{-500\ kPa}$ (g g^{-1},%) (6) = 0.069*Cl – 0.017*Si – 0.195*Sa + 2.461*OC + 0.079*BD + 20.895 $w_{-1500\ kPa}$ (g g^{-1},%) (1) = 0.184*Cl + 0.144*Si + 3.702 $w_{-1500\ kPa}$ (g g^{-1},%) (2) = -0.187*Sa + 1.241*BD + 19.320 $w_{-1500\ kPa}$ (g g^{-1},%) (3) = 0.183*Cl + 0.144*Si – 0.689*BD + 4.840 $w_{-1500\ kPa}$ (g g^{-1},%) (4) = 0.021*Cl - 0.028*Si – 0.179*Sa + 20.69 $w_{-1500\ kPa}$ (g g^{-1},%) (5) = 0.014*Cl – 0.041*Si – 0.192*Sa + 2.093*BD + 18.47	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Moisture equivalent: Me (%) Bulk density: BD (Mg m^{-3})	- Original equation link - 187 soil samples were collected from three locations in India - Main characteristics of the PTFs developing dataset: BD (0.2-11.8 Mg m^{-3}), OC (0.2-11.8 g kg^{-1}) - The PTFs were tested in: Congo by Botula Manyala (2013) - 12 citations from Google Scholar (accessed on 10 Aug 2020)

	$w_{-1500\,kPa}$ (g g^{-1},%) (6) = 0.017*Cl – 0.053*Si – 0.184*Sa + 2.950*OC + 2.327*BD + 16.802		
(2) Soil texture (Sa, Si, Cl); BD; OM/OC			
van Den Berg et al. (1997)*	*Original equations:* θ_{-10kPa} (m^3m^{-3} 10^2) = 13.96 + 0.387*Cl (R^2 = 0.76) θ_{-10kPa} (m^3m^{-3} 10^2) = 11.27 + 0.367*Cl + 0.226*Si (R^2 = 0.84) θ_{-10kPa} (m^3m^{-3} 10^2) = 12.19 + 0.212*Cl + 0.208*Si + 0.107*SS (R^2 = 0.87) θ_{-10kPa} (m^3m^{-3} 10^2) = 10.88 + 0.347*Cl + 0.211*Si + 1.756*OC (R^2 = 0.86) θ_{-10kPa} (m^3m^{-3} 10^2) = 17.90+0.231*SS (R^2 = 0.76) $\theta_{-1500\,kPa}$ (m^3m^{-3} 10^2) = 6.35 + 0.284*C1 (R^2 = 0.70) $\theta_{-1500\,kPa}$ (m^3m^{-3} 10^2) = 3.83 + 0.272*Cl + 0.212*Si (R^2 = 0.80) $\theta_{-1500\,kPa}$ (m^3m^{-3} 10^2) = 0.363* Cl_{vol} (R^2 = 0.78) $\theta_{-1500\,kPa}$ (m^3m^{-3} 10^2) = 3.89 + 0.258 *(Si + Cl) (R^2 = 0.79) $\theta_{-1500\,kPa}$ (m^3m^{-3} 10^2) = 0.334*Cl_{vol} + 0.104*Si_{vol} (R^2 = 0.83) *van Den Berg et al. (1977) PTFs found in Tomasella and Hodnett (2004):* θ_{-10kPa} (m^3m^{-3}) = 0.1088 + 0.00347*Cl + 0.00211*Si + 0.01756*OC (R^2 = 0.86) $\theta_{-1500\,kPa}$ (m^3m^{-3}) = 0.00334*Cl*BD + 0.00104*Si*BD (R^2 = 0.83) *Converted equations:* θ_{-10kPa} (cm^3 cm^{-3}) = (10.88 + 0.347*Cl + 0.211*Si + 1.756*OC)*10^{-2} (R^2 = 0.86) $\theta_{-1500\,kPa}$ (cm^3 cm^{-3}) = (0.334*Cl*BD + 0.104*Si*BD)*10^{-2} (R^2 = 0.83)	*Original equations:* Sand: Sa (kg $kg^{-1}10^2$) Silt: Si (kg $kg^{-1}10^2$) Clay: Cl (kg $kg^{-1}10^2$) Organic carbon: OC (kg $kg^{-1}10^2$) Cl_{vol} and Si_{vol} means Cl and Si are in mass per volume soil in percent (kg dm^{-3} 10^2) SS: specific surface area (m^2 g^{-1}) *Equations in Tomasella and Hodnett (2004):* Silt: Si (%) Clay: Cl (%) Organic carbon: OC (g kg^{-1}) Bulk Density: BD (Mg m^{-3})	- Original document link - World Oxisols and related soils from from South America, Africa and South East Asia, 2 sets of data (Set 1: 91 samples from 31 profiles, Set 2: 35 samples from 13 profiles) - Main characteristics of the PTFs developing dataset: Clay (2-95%), OC (0.1-6.95), BD (0.7-1.8 kg dm^{-3}) - The PTFs are suitable for Ferralsols and related soils - The PTFs were used in tropical regions: Congo by Botula Manyala (2013); Vietnam by Nguyen et al. (2015) - 183 citations from Google Scholar (accessed on 10 Aug 2020)

Tomasella et al. (2003)	*Original PTFs:* x_{14}= - 1.05501 + 0.0650857 *Sa x_{15} = -2.07588 + 0.0423954*Cl x_{16} = -6.03402 + 4.80572*BD x_{17} = -2.18409 + 8.84963*Me $z_9 = 0.175202 + 1.18513*x_{17} - 0.0996042*(x_{17})^2 + 0.327915*x^{16} - 0.0758657*(x_{16})^2$ $z_{10} = 0.929344*z_9 + 0.132519*x_{14}$ θ_{-10kPa} ($m^3 m^{-3}$) = $0.339255 + 0.112526*z_{10}$ $z_{11} = 0.191452 + 1.25652*x_{17} - 0.079098*(x_{17})^2 + 0.393814*x_{16} + 0.152095*x_{17}*x_{16}$ θ_{33} ($m^3 m^{-3}$) = $0.28951 + 0.103815*z_{11}$ $z_{12} = 0.231205 - 0.0968656*(x_{15})^2 + 0.0799528*(x_{15})^3 + 1.28868*x_{17} + 0.13082*x_{15}*x_{17} - 0.143115*(x_{17})^2 - 0.126294*x_{15}*(x_{17})^2 + 0.429792*x_{16} + 0.133537*x_{17}*x_{16} - 0.0661431*x_{17}*x_{16}*x_{15}$ $\theta_{-100\ kPa}$ ($m^3 m^{-3}$) = $0.257093 + 0.0952908*z_{12}$ $z_{13} = 0.235084 + 0.33033*x_{15} - 0.191838*(x_{15})^2 + 0.0543679*(x_{15})^3 + 0.977685*x_{17} + 0.304174*x_{15}*x_{17} - 0.218857*(x_{17})^2 - 0.164373*x_{15}*(x_{17})^2 + 0.0415057*(x_{17})^3 + 0.373361*x_{16} + 0.0811861*x_{17}*x_{16} - 0.0768087*x_{17}*x_{16}*x_{15}$ $\theta_{-1500\ kPa}$ ($m^3 m^{-3}$) = $0.214008 + 0.0862945*z_{13}$	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Moisture equivalent: Me (%) Bulk density: BD (g cm^{-3})	- Original document link - 838 samples Brazil soils - Main characteristics of the PTFs developing dataset: Coarse sand (0-74.6%), Fine sand (0-65%), Silt (0-71%), Clay (1.7-96%), OC (0-6.39%), BD (0.72-1.91 g cm^{-3}) - 186 citations from Google Scholar (accessed on 10 Aug 2020)
Mdemu (2002)	*Original PTFs:* θ_{0kPa} (cm^3cm^{-3}) = 35.22 + 0.1*Cl + 3.09*OC θ_{-1kPa} (cm^3cm^{-3}) = 16.19 + 0.27*Cl + 5.03*OC θ_{-10kPa} (cm^3cm^{-3}) = -4.37 + 0.32*Cl + 5.16*OC + 11.84*BD θ_{-20kPa} (cm^3cm^{-3}) = -8.76 + 0.32*Cl + 5.16*OC + 11.84*BD θ_{-33kPa} (cm^3cm^{-3}) = -12.33 + 0.31*Cl +5.52*OC +15.33*BD θ_{-50kPa} (cm^3cm^{-3}) = -12.62 + 0.31*Cl + 5.37*OC +15.06*BD $\theta_{-100kPa}$ (cm^3cm^{-3}) = -13.35 + 0.31*Cl + 5.01*OC +14.38*BD $\theta_{-15000kPa}$ (cm^3cm^{-3}) = -23.6 +0.41*Cl + 0.03*Si + 1.25*OC + 16.15*BD	*Original PTFs:* Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Bulk density: BD (g cm^{-3})	- Original document link - 51 soil samples from 14 profiles located in central part of the Sokoine University of Agriculture (SUA) farm, Morogoro, Tanzania - 11 citations from Google Scholar (accessed on 10 Aug 2020
Reichert et al. (2009)*	*Original PTFs:* Equations generated using all soil properties (1): $w_{-6\ kPa}$ (kg kg^{-1}) = 0.415 + 0.26 *(Cl +Si) + 0.61*OM -0.207*BD $w_{-10\ kPa}$ (kg kg^{-1}) = 0.268 + 0.05*Cl + 0.24*(Cl + Si) + 0.85*OM – 0.127*BD	*Original PTFs:* Sand: Si (kg kg^{-1}) Silt: Si (kg kg^{-1}) Clay: Cl (kg kg^{-1})	- Original document link (Table 4) - 725 datasets were gathered from literatures of soil samples in Brazil - Main characteristics of the PTFs developing dataset: Clay (0.01-0.82 kg kg^{-1}), Silt (0.01-

	$w_{-33\,kPa}\ (kg\ kg^{-1}) = 0.106 + 0.29*(Cl + Si) + 0.93*OM - 0.048*BD$ $w_{-100\,kPa}\ (kg\ kg^{-1}) = 0.102 + 0.23*(Cl + Si) - 0.08*(Si+Sa) + 1.08*OM$ $w_{-500\,kPa}\ (kg\ kg^{-1}) = 0.268 - 0.11*Si - 0.31*Sa + 1.28*OM + 0.031*BD$ $w_{-1500\,kPa}\ (kg\ kg^{-1}) = -0.04 + 0.15*Cl + 0.17*(Cl+Si) + 0.91*OM + 0.026*BD$ Equation generated using particle sizes (2): $w_{-10\,kPa}\ (kg\ kg^{-1}) = 0.037 + 0.38*(Cl+Si)$ $w_{-33\,kPa}\ (kg\ kg^{-1}) = 0.366 - 0.34*Sa$ $w_{-1500\,kPa}\ (kg\ kg^{-1}) = 0.236 + 0.045*Cl - 0.21*Sa$ <u>Converted equations (1) used in LUCI_PTFs:</u> $\theta_{-6\,kPa}\ (cm^3cm^{-3}) = BD*(0.415 + 0.26*10^{-2}*(Cl + Si) + 0.61*10^{-2}*OM - 0.207*BD)$ $\theta_{-10\,kPa}\ (cm^3cm^{-3}) = BD*(0.268 + 0.05*10^{-2}*Cl + 0.24*10^{-2}*(Cl + Si) + 0.85*10^{-2}*OM - 0.127*BD)$ $\theta_{-33\,kPa}\ (cm^3cm^{-3}) = BD*(0.106 + 0.29*10^{-2}*(Cl + Si) + 0.93*10^{-2}*OM - 0.048*BD)$ $\theta_{-100\,kPa}\ (cm^3cm^{-3}) = BD*(0.102 + 0.23*10^{-2}*(Cl + Si) - 0.08*10^{-2}*(Si+Sa) + 1.08*10^{-2}*OM)$ $\theta_{-500\,kPa}\ (cm^3cm^{-3}) = BD*(0.268 - 0.11*10^{-2}*Si - 0.31*10^{-2}*Sa + 1.28*10^{-2}*OM + 0.031*BD)$ $\theta_{-1500\,kPa}\ (cm^3cm^{-3}) = BD*(-0.04 + 0.15*10^{-2}*Cl + 0.17*10^{-2}*(Cl+Si) + 0.91*10^{-2}*OM + 0.026*BD)$ <u>Converted equations (2) used in LUCI_PTFs:</u> $\theta_{-10\,kPa}\ (cm^3cm^{-3}) = BD*(0.037 + 0.38*10^{-2}*(Cl+Si))$ $w_{-33\,kPa}\ (cm^3cm^{-3}) = BD*(0.366 - 0.34*10^{-2}*Sa)$ $w_{-1500\,kPa}\ (cm^3cm^{-3}) = BD*(0.236 + 0.045*10^{-2}*Cl - 0.21*10^{-2}*Sa)$	Organic matter: OM (kg kg^{-1}) Bulk density: BD (kg dm^{-3})	0.78 kg kg^{-1}), Sand (0.01-0.99 kg kg^{-1}), BD (0.86-1.85 kg dm^{-3}), OM (0-0.1 kg kg^{-1}) - 100 citations from Google Scholar (accessed on 10 Aug 2020)
Minasny and Hartemink (2011)	*Original PTFs:* $\theta_{-10\,kPa}\ (v/v, \%) = 59.9 - 8.78*BD - 0.31*Sa$ $\theta_{-33\,kPa}\ (v/v, \%) = 56.5 - 7.49*BD - 0.34*Sa$ $\theta_{-1500\,kPa}\ (v/v, \%) = 7.95 + 0.86*OC + 0.4*Cl - 0.004*(Cl - 0.377)^2$	*Original PTFs:* Sand: Sa (%) Clay: Cl (%) Organic carbon: OC (%) Moisture equivalent: Me (%) Bulk density: BD (g cm^{-3})	- Original document link - Soil samples from Tropical regions (ISRIC database) - The PTFs were used in tropical regions: Vietnam by Nguyen et al. (2015) - 183 citations from Google Scholar (accessed on 10 Aug 2020)
Costa et al. (2013)	*Original PTFs:* Surface $\theta_{FC}\ (m^3\,m^{-3}) = 0.39 + 0.0044*Sa*OM + 3.4304*Si^2*Cl^2 - 0.5955*Sa^2*Si^2 - 0.3014*Sa^2 - 0.0012*1/Sa$	*Original PTFs:* Sand: Si (kg kg^{-1}) Silt: Si (kg kg^{-1}) Clay: Cl (kg kg^{-1})	- Original document link - Soil samples from the State of Santa Catarina, Brazil

	θ_{PWP} ($m^3 m^{-3}$) = 0.39 + 0.0041*Sa*OM - 9.649*Sa^2*Si^2 – 0.403*Sa^2 AWC ($m^3 m^{-3}$) = 0.07 + 3.9*Sa*OM + 0.163*Si^2 AWC ($m^3 m^{-3}$) = 0.10 + 0.8*Si*OM + 0.191*Sa*Si Subsoil: θ_{FC} ($m^3 m^{-3}$) = 0.34 + 0.0008*(1000/√(OM/0.001) + 0.0303*Sa*OM - 10.752*Sa^2 θ_{FC} ($m^3 m^{-3}$) = −0.50 - 0.383*Cl^2 + 1.25 (√Clay) + 0.066 (1/√Clay)	Organic matter: OM (g kg^{-1}) Bulk density: BD (Mg m^{-3})	- Main characteristics of the PTFs developing dataset (top-soils): Sand (17-973 g kg^{-1}), Silt (12-581 g kg^{-1}), Clay (15-789 g kg^{-1}), BD (0.52-1.74 Mg m^{-3}), OM (7-243 g kg^{-1}) - 18 citations from Google Scholar (accessed on 10 Aug 2020)
Obalum and Obi (2013)	*Original PTFs:* θ_{0kPa} (v/v, %) = 47.244 + 12.122*OM θ_{-6kPa} (v/v, %) = 64.715 – 0.268*Sa θ_{-10kPa} (v/v, %) = 68.571 – 0.344*Sa θ_{-33kPa} (v/v, %) = 54.068 – 0.247*Sa $\theta_{-100kPa}$ (v/v, %) = 51.568 – 0.252*Sa $\theta_{-300kPa}$ (v/v, %) = 51.568 – 0.276*Sa $\theta_{-1500kPa}$ (v/v, %) = 2.033 + 0.722*Cl Equations available for different soil layers	*Original PTFs:* Sand: Sa (%) Clay: Cl (%) Organic matter: OM (%) Bulk density: BD (g cm^{-3})	- Original document link - 54 soil sets in South-eastern Nigeria soils - Main characteristics of the PTFs developing dataset: Coarse sand (27.3-73.2%), Fine sand(11.3-48.4%), Silt (1.1-15.1%), Clay(5.1-22.2%), OM(0.14-2.96%), BD (1.22-1.98 g cm^{-3}) - 13 citations from Google Scholar (accessed on 10 Aug 2020)
Nguyen et al. (2014)*	*Original PTFs:* $\theta_{-1\ kPa}$ (cm^3cm^{-3}) = 0.002*Cl + 0.055 *Log (OC) – 0.144*BD + 0.575 $\theta_{-3\ kPa}$ (cm^3cm^{-3}) = 0.002*Cl + 0.067 *Log (OC) – 0.125*BD + 0.527 $\theta_{-6\ kPa}$ (cm^3cm^{-3}) = 0.001*Si + 0.003*Cl + 0.12* Log (OC) – 0.062*BD + 0.367 $\theta_{-10\ kPa}$ (cm^3cm^{-3}) = 0.001*Si + 0.003*Cl + 0.127* Log (OC) + 0.228 $\theta_{-20\ kPa}$ (cm^3cm^{-3}) = -0.002*Sa + 0.002*Cl + 0.066* Log (OC) -0.058*BD + 0.415 $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = -0.002*Sa + 0.001*Cl – 0.118*BD + 0.493 $\theta_{-100\ kPa}$ (cm^3cm^{-3}) = -0.003*Sa – 0.107*BD + 0.497 $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = -0.002*Sa + 0.002*Cl – 0.032*BD + 0.234	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) Bulk density: BD (g cm^{-3})	- Original document link - 160 soil samples from Mekong River Delta, Vietnam - Main characteristics of the PTFs developing dataset: Sand (0.13-98.6%), Silt (0-64.9%), Clay (1.4-76.8%), OC (0.08 – 12.3%), BD (0.7-1.9 Mg m^{-3}) - 10 citations from Google Scholar (accessed on 10 Aug 2020)
(3) Soil texture (Sa, Si, Cl); OM/OC			

Pidgeon (1972)*	*Original PTFs:* w_{FC} (w/w %) = 36.16 – 0.25*Sa (r = 0.86) w_{FC} (w/w %) = 34.27 – 0.27*Sa + 1.25*OM (r = 0.958) w_{FC} (w/w %) = 7.38 + 0.16*Si + 0.3*Cl + 1.54*OM (r = 0.964) w_{FC} (w/w %) = 37.10 – 0.27*Sa + 0.37*OM (r = 0.879) w_{FC} (w/w %) = 10.10 + 0.27 *Si + 0.21*Cl + 0.76*OM (r = 0.961) w_{FC} (v/v %) = 38.15 – 0.17*Sa = 0.77*OM (r = 0.619) $w_{-10\ kPa}$ (w/w %) = (w_{FC} – 2.54)/0.91 (r = 0.98) $w_{-33\ kPa}$ (w/w %) = (w_{FC} – 3.77)/0.95 (r = 0.98) $w_{-33\ kPa}$ (w/w %) = (w_{FC} – 3.77)/0.95 (r = 0.98) $w_{-1500\ kPa}$ (w/w %) = 28.41 – 0.20*Sa (r = 0.982) $w_{-1500\ kPa}$ (w/w %) = 33.57 – 0.36*Sa (r = 0.972) $w_{-1500\ kPa}$ (w/w %) = 32.90 – 0.37*Sa + 0.44*OM (r = 0.979) $w_{-1500\ kPa}$ (w/w %) = -4.19 + 0.19*Si + 0.39*Cl + 0.9*OM (r = 0.986) $w_{-1500\ kPa}$ (w/w %) = 37.34 – 0.38*Sa – 0.79*OM Silt in the original equations were determined as fraction 2-20 µm *Pidgeon (1972) PTFs found in Tomasella and Hodnett (2004):* w_{FC} (g g^{-1}) = 0.0738 + 0.0016*Si + 0.003*Cl + 0.03*OC $w_{-10\ kPa}$ (g g^{-1}) = (100* w_{FC} – 2.54)/91 $w_{-33\ kPa}$ (g g^{-1}) = (100* w_{FC} – 3.77)/95 $w_{-1500\ kPa}$ (g g^{-1}) = -0.0419 + 0.0019*Si + 0.0039*Cl + 0.009*OC <u>Converted equations used in LUCI_PTFs:</u> θ_{FC} (cm^3cm^{-3}) = (7.38 + 0.16*Si + 0.3*Cl + 1.54*OM)*BD*10^{-2} $\theta_{-10\ kPa}$ (cm^3cm^{-3}) = (w_{FC} *100– 2.54)/91 $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = (w_{FC}*100 – 3.77)/95 $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = (-4.19 + 0.19*Si + 0.39*Cl + 0.9*OM)*BD*10^{-2}	*Original PTFs:* Silt: Si (%) Clay: Cl (%) Organic matter: OM (%), used factor of 2 to convert OC to OM *The PTFs in Tomasella and Hodnett (2004):* Silt: Si (%) Clay: Cl (%) Organic carbon: OC (g kg^{-1})	- Original document link (The equations are in page 435 and 439) - Soil samples (Ferralitic soils dominated by Kaolinite) from Uganda. A wide textural range of soils were chosen from loamy sands to clays - Equations were used in tropical regions: Congo by Botula Manyala (2013) - 75 citations from Google Scholar (accessed on 10 Aug 2020)

Lal (1981)	*Original PTFs:* $w_{-10\ kPa-1500\ kPa}$ ($g\ g^{-1}\ 10^2$) = 2.35*OC + 8.3 (r = 0.63) $w_{-33\ kPa}$ ($g\ g^{-1}\ 10^2$) = 4.42*OC + 9.3 (r = 0.68) $w_{-1500\ kPa}$ ($g\ g^{-1}\ 10^2$) = 0.48*Cl + 4.5 (r=0.77) r: Correlation coefficient w: gravimetric water content θ = w*BD	*Original PTFs:* Clay: Cl (%) Organic carbon: OC (%)	- Original document is not available online, hard version can be accessed from the Victoria University of Wellington library - Nigeria soils, mostly strongly weathered soils. Some hydromorphic soils and soils with high-activity clay included - Main characteristics: - 48 citations from Google Scholar (accessed on 10 Aug 2020)
Batjes (1996)*	*Original PTFs:* θ_{sat} ($10^{-2}\ cm^3cm^{-3}$) = 0.6903*Cl + 0.5482*Si + 4.2844*OC $\theta_{pF1.0}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.6463*Cl + 0.5436*Si + 3.7091*OC $\theta_{pF1.5}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.5980*Cl + 0.3745*Si + 3.7611*OC $\theta_{pF1.7}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.6681*Cl + 0.2614*Si + 2.2150*OC $\theta_{pF2.0}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.5266*Cl + 0.3999*Si + 3.1752*OC $\theta_{pF2.3}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.5082*Cl + 0.4197*Si + 2.5043*OC $\theta_{pF2.5}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.4600*Cl + 0.3045*Si + 2.0703*OC $\theta_{pF2.7}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.5032*Cl + 0.3636*Si + 2.4461*OC $\theta_{pF3.4}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.4611*Cl + 0.2390*Si + 1.5742*OC $\theta_{pF4.2}$ ($10^{-2}\ cm^3cm^{-3}$) = 0.3624*Cl + 0.1170*Si + 1.6054*OC AWC ($10^{-2}\ cm^3cm^{-3}$) = 0.0976*Cl + 0.1875*Si + 0.4649*OC (Method 1) AWC ($10^{-2}\ cm^3cm^{-3}$) = 0.1082*Cl + 0.1898*Si + 0.7705*OC (Method 2) In which: AWC: Available Water Capacity, refers to volume moisture held between pF 2.5 and pF 4.2. pF was defined as the logarithm of water in soil-matric potential (pF = $\log_{10}$ (-head (cm of water)); e.g. a pressure head of -100 cm corresponds with pF 2.0. <u>Converted equations used in LUCI_PTFs:</u>	*Original PTFs:* Clay: Cl (%) Silt: Si (%) Organic carbon: OC (%)	- Original document link - WISE soil database, 4353 soil profiles are from Africa (1799); South West and North Asia (522); South East Asia (553); Australia and the Pacific Islands (122); Europe (492); North America (266); and, South America and the Caribbean (599) - Main characteristics of the PTFs developing dataset: the particle size Clay < 0.002mm < Silt < 0.05 mm < Sand < 2mm; % Sand, % Silt and % Clay should not smaller than 5; organic carbon content should not smaller than 0.1% - Equations were used in tropical areas: Amazon, (Medeiros et al., 2014) which gave best result of water content at -33kPa and -1500kPa - 232 citations from Google Scholar (accessed on 10 Aug 2020)

	θ_{sat} (cm^3cm^{-3}) = (0.6903*Cl + 0.5482*Si + 4.2844*OC) * 10^{-2} $\theta_{-10cm\ (pF1)}$ (cm^3cm^{-3}) = (0.6463*Cl + 0.5436*Si + 3.7091*OC) * 10^{-2} $\theta_{-32cm\ (pF1.5)}$ (cm^3cm^{-3}) = (0.5980*Cl + 0.3745*Si + 3.7611*OC) * 10^{-2} $\theta_{-50cm\ (pF1.7)}$ (cm^3cm^{-3}) = (0.6681*Cl + 0.2614*Si + 2.2150*OC) * 10^{-2} $\theta_{-100cm\ (pF2.0)}$ (cm^3cm^{-3}) = (0.5266*Cl + 0.3999*Si + 3.1752*OC) * 10^{-2} $\theta_{-200cm\ (pF2.3)}$ (cm^3cm^{-3}) = (0.5082*Cl + 0.4197*Si + 2.5043*OC) * 10^{-2} $\theta_{-316cm\ (pF2.5)}$ (cm^3cm^{-3}) = (0.4600*Cl + 0.3045*Si + 2.0703*OC) * 10^{-2} $\theta_{-501cm\ (pF2.7)}$ (cm^3cm^{-3}) = (0.5032*Cl + 0.3636*Si + 2.4461*OC) * 10^{-2} $\theta_{-2511cm\ (pF3.4)}$ (cm^3cm^{-3}) = (0.4611*Cl + 0.2390*Si + 1.5742*OC) * 10^{-2} $\theta_{-15849cm(pF4.2)}$ (cm^3cm^{-3}) = (0.3624*Cl + 0.1170*Si + 1.6054*OC) * 10^{-2} AWC (cm^3cm^{-3}) = 10^{-2}*(0.0976*Cl + 0.1875*Si + 0.4649*OC) (Method 1) AWC (cm^3cm^{-3}) = 10^{-2}*(0.1082*Cl + 0.1898*Si + 0.7705*OC) (Method 2)		
Tomasella and Hodnett (1998)*	*Original PTFs:* θ_{0kPa} (%cm^3cm^{-3}) = 2.24*OC + 0.298*Si + 0.159*Cl + 37.937 θ_{-1kPa} (%cm^3cm^{-3}) = 0.53*Si + 0.255*Cl + 23.839 θ_{-3kPa} (%cm^3cm^{-3}) = 0.552*Si + 0.262*Cl + 18.495 θ_{-6kPa} (%cm^3cm^{-3}) = 0.576*Si + 0.3*Cl + 12.333 θ_{-10kPa} (%cm^3cm^{-3}) = 0.543*Si + 0.321*Cl + 9.806 θ_{-33kPa} (%cm^3cm^{-3}) = 0.426*Si + 0.404*Cl + 4.046 $\theta_{-100kPa}$ (%cm^3cm^{-3}) = 0.369*Si + 0.351*Cl + 3.198 $\theta_{-500kPa}$ (%cm^3cm^{-3}) = 0.258*Si + 0.361*Cl + 1.567 $\theta_{-1500kPa}$ (%cm^3cm^{-3}) = 0.15*Si + 0.396*Cl + 0.91 <u>Converted equations used in LUCI_PTFs:</u> θ_{0kPa} (cm^3cm^{-3}) = (2.24*OC + 0.298*Si + 0.159*Cl + 37.937) * 10^{-2} θ_{-1kPa} (cm^3cm^{-3}) = (0.53*Si + 0.255*Cl + 23.839) * 10^{-2} θ_{-3kPa} (cm^3cm^{-3}) = (0.552*Si + 0.262*Cl + 18.495) * 10^{-2} θ_{-6kPa} (cm^3cm^{-3}) = (0.576*Si + 0.3*Cl + 12.333) * 10^{-2} θ_{-10kPa} (cm^3cm^{-3}) = (0.543*Si + 0.321*Cl + 9.806) * 10^{-2} θ_{-33kPa} (cm^3cm^{-3}) = (0.426*Si + 0.404*Cl + 4.046) * 10^{-2} $\theta_{-100kPa}$ (cm^3cm^{-3}) = (0.369*Si + 0.351*Cl + 3.198) * 10^{-2} $\theta_{-500kPa}$ (cm^3cm^{-3}) = (0.258*Si + 0.361*Cl + 1.567) * 10^{-2} $\theta_{-1500kPa}$ (cm^3cm^{-3}) = (0.15*Si + 0.396*Cl + 0.91) * 10^{-2}	*Original PTFs:* Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%)	- Original equation link - 613 soil samples from Brazilian Amazonia - The PTFs were used in USDA's CalcPTF tool (USDA, 2010); in Dai et al. (2013) to develop soil hydraulic properties for China - Main characteristics: Clay (0-100%), Silt (0-70%), the average OC content of the data set is 0.975% - 277 citations from Google Scholar (accessed on 10 Aug 2020) - The authors suggested that these PTFs would be more adapted to soils under the tropics than most PTFs already published and developed for soils from temperate regions
Santos et al. (2013)	*Original PTFs:* 0-20cm w_{-33kPa} (dag kg^{-1}) = 24.88952 + 1.46274*OM – 0.24526*CoarseSa – 0.23454*FineSa	*Original PTFs:* Coarse sand: CoarseSa (dag kg^{-1})	- Original document link - 800 soil samples from the center-south portion of Rio Grande do Sul, Brazil

	$w_{-1500kPa}$ (dag kg^{-1}) = 9.944674 + 1.01884*OM + 0.14405*Cl – 0.09538*CoarseSa – 0.10520*FineSa 40-70cm w_{-33kPa} (dag kg^{-1}) = 26.18555 + 1.84737*OM + 0.07352*Cl – 0.28332*CoarseSa – 0.26753*FineSa $w_{-1500kPa}$ (dag kg^{-1}) = 11.50346 + 1.55563*OM + 0.14390*Cl – 0.13118*CoarseSa – 0.16458*FineSa The paper also includes equations for different soil types (Red Argisol, Hapic Cambisol, Red-Yellow Argisoil, Yellow Argisol, Regolithic Neosol, Litholic Neosol, Haplic Planosol	Fine sand: FineSa (dag kg^{-1}) Clay: Cl (dag kg^{-1}) Organic matter: OM (dag kg^{-1})	- Main characteristics of the PTFs developing dataset: Clay (5-80%), Silt (2-51%), Coarse Sand (1-69%), Fine Sand (1-65%) - 11 citations from Google Scholar (accessed on 10 Aug 2020)
(4) Soil texture (Sa, Si, Cl); BD			
Soil Survey Staff (1975)	*Soil Survey Staff (1975) found in van Den Berg et al. (1997) and Minasny and Hartemink (2011)* $w_{-1500\ kPa}$ (kg $kg^{-1}10^2$) = 0.4*Cl w: gravimetric water content θ = w*BD	*The PTFs in van Den Berg et al. (1997)* Clay: Cl (kg $kg^{-1}10^2$) Bulk density: BD (kg dm^{-3})	- Original document was not found - Oxic horizons - 66 citations from Google Scholar (accessed on 10 Aug 2020)
Soil Survey Staff (1990)	*Soil Survey Staff (1990) PTFs in van Den Berg et al. (1997) and Minasny and Hartemink (2011)* $w_{-1500\ kPa}$ (kg $kg^{-1}10^2$) = 1/3*Cl w: gravimetric water content θ = w*BD	*The PTFs in van Den Berg et al. (1997)* Clay: Cl (kg $kg^{-1}10^2$) Bulk density: BD (kg dm^{-3})	- Original document was not found - Oxic horizons
Soil Survey Staff (1992)	*Soil Survey Staff (1992) found in van Den Berg et al. (1997) and Minasny and Hartemink (2011)* $w_{-1500\ kPa}$ (kg $kg^{-1}10^2$) = 1/3*Cl + c $w_{-1500\ kPa}$: gravimetric water content θ = w*BD	*The PTFs in van Den Berg et al. (1997)* Clay: Cl (kg $kg^{-1}10^2$) Bulk density: BD (kg dm^{-3})	- Original document was not found - Oxic horizons
Aina and Periaswamy (1985)*	*Aina and Periaswamy (1985)PTFs found in Botula Manyala (2013)* $\theta_{-33\ kPa}$ (m^3m^{-3}) = 0.6788 – 0.0055*Sa – 0.0013*BD $\theta_{-1500\ kPa}$ (m^3m^{-3}) = 0.00213 + 0.0031*Cl *Aina and Periaswamy (1985)PTFs found in Medeiros et al. (2014)*	*The PTFs in Botula Manyala (2013)* Sand: Sa (%) Clay: Cl (%) Bulk Density: BD (Mg m^{-3})	- Original equation link: cannot access - Soil samples (Alfisols, Ultisols) in Western Nigeria - 79 citations from Google Scholar (accessed on 10 Aug 2020)

	$\theta_{-33\ kPa}$ (m^3m^{-3}) = 0.6788 – 0.0055*Sa – 0.0013*BD $\theta_{-1500\ kPa}$ (m^3m^{-3}) = 0.00213 + 0.0031*Cl *Aina and Periaswamy (1985)PTFs found in Tomasella and Hodnett (2004)* $\theta_{-33\ kPa}$ (m^3m^{-3}) = 0.6788 – 0.0055*Sa – 0.0013*BD $\theta_{-1500\ kPa}$ (m^3m^{-3}) = 0.00213 + 0.0031*Cl	*The PTFs in Tomasella and Hodnett (2004):* Sand: Sa (%) Clay: Cl (%) Bulk Density: BD (Mg m^{-3})	- The PTFs were used in tropical regions: Congo by Botula Manyala (2013); Amazon by Medeiros et al. (2014)
Manrique and Jones (1991)*	*Manrique and Jones (1991) found in Donatelli et al. (2004):* Sand ≥75 %: θ_{-33kPa} (m^3m^{-3}) = 0.73426 – Sa* 0.00145 – BD*0.29176 If Sand < 75% θ_{-33kPa} (m^3m^{-3}) = 0.5784 + Cl*0.002227 – BD*0.28438) $\theta_{-1500kPa}$ (m^3m^{-3}) = 0.02413 + Cl*0.00373	*The PTFs in Donatelli et al. (2004)* Sand: Sa (%) Clay: Cl (%) BD: Bulk density (g cm^{-3})	- Original document link: cannot access - 12000 soil pedons from the continental USA, Hawaii, Puerto Rico and some foreign countries - The PTFs were used in arid region: Mohawesh (2013) - 232 citations from Google Scholar (accessed on 10 Aug 2020)
Oliveira et al. (2002)	*Original PTFs:* w_{-33kPa} (kg kg^{-1}) = 0.000333*Si + 0.000387*Cl $w_{-1500kPa}$ (kg kg^{-1}) = $3.8*10^{-5}$*Sa + 0.000153*Si + 0.000341*Cl + 0.030861*BD	*Original PTFs:* Sand: Sa (g kg^{-1}) Silt: Si (g kg^{-1}) Clay: Cl (g kg^{-1}) Bulk density: BD (tonne m^{-3})	- Original document link (in Portuguese) - Soils in North-East Brazil - The PTFs were used in tropical regions: Congo by Botula Manyala (2013) - 58 citations from Google Scholar (accessed on 10 Aug 2020
Giarola et al. (2002)	*Original PTFs:* θ_{-10kPa} (cm^3cm^{-3}) = 0.081 + 0.005*Si + 0.004*Cl (R^2 = 0.79) A Horizon $\theta_{-1500kPa}$ (cm^3cm^{-3}) = -0.031 + 0.005*Si + 0.003*Cl (R^2 = 0.81) B Horizon $\theta_{-1500kPa}$ (cm^3cm^{-3}) = 0.024 + 0.005*Si + 0.003*Cl (R^2 = 0.81)	*Original PTFs:* Silt: Si (g kg^{-1}) Clay: Cl (g kg^{-1}) Bulk density: BD (g cm^{-3})	- Original document link (in Portuguese) - Brazil soils - 42 citations from Google Scholar (accessed on 10 Aug 2020

Botula Manyala (2013)*	*Original PTFs:* PTFs developed based on Sa, Si, Cl $\theta_{-1\ kPa}$ (% v/v) = 37.234 + 0.139*Cl $\theta_{-3\ kPa}$ (% v/v) = 37.785 – 0.072*Sa + 0.093*Cl $\theta_{-6\ kPa}$ (% v/v) = 44.196 – 0.252 *Sa $\theta_{-10\ kPa}$ (% v/v) = 43.520 – 0.296 *Sa $\theta_{-20\ kPa}$ (% v/v) = 42.302 – 0.344 *Sa $\theta_{-33\ kPa}$ (% v/v) = 41.929 – 0.349*Sa $\theta_{-100\ kPa}$ (% v/v) = 34.137 – 0.283*Sa + 0.071*Cl $\theta_{-1500\ kPa}$ (% v/v) = 21.046 -0.170*Sa + 0.175*Cl PTFs developed based on Sa, Si, Cl, pH and OC $\theta_{-1\ kPa}$ (% v/v) = 36.988 + 0.117*Cl + 0.507*OC $\theta_{-3\ kPa}$ (% v/v) = 37.253 – 0.068*Sa + 0.081*Cl + 0.366*OC $\theta_{-6\ kPa}$ (% v/v) = 53.135 – 0.247*Sa – 1.769*pH $\theta_{-10\ kPa}$ (% v/v) = 55.061 – 0.289*Sa – 2.275*pH $\theta_{-20\ kPa}$ (% v/v) = 53.98 – 0.337*Sa – 2.311*pH $\theta_{-33\ kPa}$ (% v/v) = 53.776 – 0.343*Sa – 2.345*pH $\theta_{-100\ kPa}$ (% v/v) = 43.657 – 0.264*Sa + 0.089*Cl – 2.141*pH $\theta_{-1500\ kPa}$ (% v/v) = 28.004 – 0.156*Sa + 0.188*Cl – 1.564*pH PTFs developed based on Sa, Si, Cl, pH, OC and CEC $\theta_{-1\ kPa}$ (% v/v) = 31.168 + 0.053*Sa + 0.156*Cl + 0.339*OC + 0.276*CEC $\theta_{-3\ kPa}$ (% v/v) = 37.253 – 0.068*Sa + 0.081*Cl + 0.366*OC $\theta_{-6\ kPa}$ (% v/v) = 50.374 – 0.225*Sa – 1.801*pH + 0.230*CEC $\theta_{-10\ kPa}$ (% v/v) = 51.633 – 0.262*Sa – 2.314*pH + 0.230*CEC $\theta_{-20\ kPa}$ (% v/v) = 50.995 – 0.313*Sa – 2.346*pH + 0.249*CEC $\theta_{-33\ kPa}$ (% v/v) = 50.293 – 0.315*Sa – 2.385*pH + 0.290*CEC $\theta_{-100\ kPa}$ (% v/v) = 40.565 – 0.236*Sa + 0.097*Cl – 2.201*pH + 0.220*CEC $\theta_{-1500\ kPa}$ (% v/v) = 28.004 – 0.156*Sa + 0.188*Cl – 1.564*pH PTFs developed based on Sa, Si, Cl, and BD $\theta_{-1\ kPa}$ (% v/v) = 67.228 + 0.089*Cl – 20.057*BD $\theta_{-3\ kPa}$ (% v/v) = 48.080 – 0.081*Sa + 0.067*Cl – 6.344*BD $\theta_{-6\ kPa}$ (% v/v) = 44.196 – 0.252*Sa $\theta_{-10\ kPa}$ (% v/v) = 43.520 – 0.296*Sa $\theta_{-20\ kPa}$ (% v/v) = 42.302 – 0.344*Sa $\theta_{-33\ kPa}$ (% v/v) = 41.929 – 0.349*Sa $\theta_{-100\ kPa}$ (% v/v) = 26.478 – 0.276*Sa + 0.091*Cl + 4.720*BD	*Original PTFs:* Sand: Sa (%) Clay: Cl (%) Bulk density: BD (Mg m^{-3})	- Original document link (Chapter 8) - 196 soil samples of highly weathered soils from Lower Congo - Main characteristics of the PTFs developing dataset: Sand (4-90%), Silt (2-62%), Clay (1-72%), OC (0.09-5.36%), BD (0.85-1.68 Mg m^{-3}), CEC (0.68-28.04 $cmol_c$ kg^{-1}) - The PTFs were used in tropical regions: Vietnam by Nguyen et al. (2015) - 11 citations from Google Scholar (accessed on 10 Aug 2020)

	$\theta_{-1500\ kPa}$ (% v/v) = 8.405 – 0.159*Sa + 0.207*Cl + 7.789*BD <u>Converted equations used in LUCI_PTFs:</u> $\theta_{-1\ kPa}$ (cm^3cm^{-3}) = (67.228 + 0.089*Cl – 20.057*BD) *10^{-2} $\theta_{-3\ kPa}$ (cm^3cm^{-3}) = (48.080 – 0.081*Sa + 0.067*Cl – 6.344*BD) *10^{-2} $\theta_{-6\ kPa}$ (cm^3cm^{-3}) = (44.196 – 0.252*Sa) *10^{-2} $\theta_{-10\ kPa}$ (cm^3cm^{-3}) = (43.520 – 0.296*Sa) *10^{-2} $\theta_{-20\ kPa}$ (cm^3cm^{-3}) = (42.302 – 0.344*Sa) *10^{-2} $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = (41.929 – 0.349*Sa) *10^{-2} $\theta_{-100\ kPa}$ (cm^3cm^{-3}) = (26.478 – 0.276*Sa + 0.091*Cl + 4.720*BD) *10^{-2} $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = (8.405 – 0.159*Sa + 0.207*Cl + 7.789*BD) *10^{-2}		
Shwetha and Varija (2013)*	*Original PTFs:* $\theta_{-33\ kPa}$ (cm^3cm^{-3}) = −4.263 + 0.00194*Sa + 0.02839*Si + 5.568* BD − 0.00005*Sa^2 −0.00011*Sa*Si + 0.00106*Sa*BD − 0.00005*Si^2 − 0.01158*Si*BD − 1.78*BD^2 $\theta_{-100\ kPa}$ (cm^3cm^{-3}) = −2.081 − 0.00776*Sa + 0.00589*Si + 3.452*BD − 0.00007*Sa^2 − 0.00018*Sa*Si + 0.01047*Sa*BD + 0.0000003*Si^2 + 0.00402*Si*BD − 1.4*BD^2 $\theta_{-300\ kPa}$ (cm^3cm^{-3}) = −2.029 − 0.00039*Sa + 0.02393*Si + 2.859*BD − 0.00007*Sa^2 − 0.000178*Sa*Si + 0.00614*Sa*BD − 0.000150*Si^2 − 0.00352*Si*BD − 1.092*BD^2 $\theta_{-500\ kPa}$ (cm^3cm^{-3}) = −1.079 + 0.01539*Sa + 0.02272*Si + 0.961*BD − 0.00009*Sa^2 − 0.00021*Sa*Si − 0.00275*Sa*BD − 0.000171*Si^2 − 0.00146*Si*BD − 0.287*BD^2 $\theta_{-1000\ kPa}$ (cm^3cm^{-3}) = −2.488 − 0.01215*Sa + 0.00750*Si + 4.051*BD − 0.00007*Sa^2 − 0.00016*Sa*Si + 0.01333*Sa*BD + 0.00002*Si^2 + 0.00131*Si*BD − 1.633*BD^2 $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = −1.076 − 0.00234*Sa − 0.00334*Si + 1.920*BD − 0.00003*Sa^2 + 0.00003*Sa*Si + 0.00101*Sa*BD + 0.00006*Si^2 − 0.00077*Si*BD − 0.666*BD^2	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Bulk density: BD (g cm^{-3})	- Original document link - Soil samples in the Pavanje river basin in the Dakshina Kannada district of coastal Karnataka, Inida - Main characteristics of the PTFs developing dataset: Sand (46-89%), Silt (10-52%), Clay (1-5%), BD (1.36-1.65 g cm^{-3}), OM (0.24-2.52%) - 14 citations from Google Scholar (accessed on 10 Aug 2020)
(5) Soil texture (Sa, Si, Cl)			

Stirk (1957)	*Stirk (1957) PTF found in Minasny and Hartemink (2011):* θ_{PWP} (%v/v) = 2/5*Cl	*The PTF in Minasny and Hartemink (2011):* Clay: % clay	- Original document was not found - One of the first studies in PTFs in tropical region - Permanent wilting point (PWP) was estimated for soils with clay contents up to 60% - Tropical North Queensland, Australia - 5 citations from Google Scholar (accessed on 10 Aug 2020)
FAO (1974)	*Original PTFs:* $w_{-1500\ kPa}$ (w/w%) = 0.23*Cl + 10 w: gravimetric water content θ = w*BD Unit of water content is not clear in the original equation, unit in van Den Berg et al. (1997) is kg $kg^{-1}10^2$	*The PTFs in van Den Berg et al. (1997)* Clay: Cl (kg $kg^{-1}10^2$)	- Original document link - The PTFs were developed for ferralitic horizons (mostly found at tropic regions) - The PTFs were listed in van Den Berg et al. (1997) and Minasny and Hartemink (2011) as widely used PTFs. - The PTFs were used in tropical regions: Tanzania by Karlsson (1982) - 50 citations from Google Scholar (accessed on 10 Aug 2020)

Lal (1978)*	*Original PTFs:* Group I: $w_{0\ kPa}$ (g g^{-1}) = 0.004*Cl + 0.289 (r = 0.75) $w_{0\ kPa}$ (g g^{-1}) = -0.003*Sa + 0.579 (r = -0.74) $w_{-10\ kPa}$ (g g^{-1}) = 0.003*Cl + 0.102 (r = 0.84) $w_{-10\ kPa}$ (g g^{-1}) = -0.003*Sa + 0.102 (r = - 0.79) $w_{-33\ kPa}$ (g g^{-1}) = 0.004*Cl + 0.065 (r = 0.88) $w_{-33\ kPa}$ (g g^{-1}) = -0.003*Sa + 0.334 (r = -0.81) $w_{-1500\ kPa}$ (g g^{-1}) = 0.003*Cl + 0.006 (r = 0.9) $w_{-1500\ kPa}$ (g g^{-1}) = -0.003*Sa + 0.247 (r = -0.83) $w_{-1500\ kPa}$ (g g^{-1}) = 0.005* Si + 0.053 (r = 0.37) Group II: $w_{0\ kPa}$ (g g^{-1}) = 0.004*Cl + 0.296 (r = 0.48) $w_{0\ kPa}$ (g g^{-1}) = -0.004*Sa + 0.645 (r = -0.48) $w_{-10\ kPa}$ (g g^{-1}) = 0.003*Cl + 0.080 (r = 0.68) $w_{-10\ kPa}$ (g g^{-1}) = -0.0035*Sa + 0.406 (r = - 0.70) $w_{-33\ kPa}$ (g g^{-1}) = 0.003*Cl + 0.047 (r = 0.64) $w_{-33\ kPa}$ (g g^{-1}) = -0.003*Sa + 0.349 (r = -0.66) $w_{-1500\ kPa}$ (g g^{-1}) = 0.0022*Cl + 0.025 (r = 0.70) $w_{-1500\ kPa}$ (g g^{-1}) = -0.0024*Sa + 0.284 (r = -0.70) r: Correlation coefficient w: gravimetric water content θ = w*BD Converted equations used in LUCI_PTFs: Group I: θ_{0kPa} (cm^3cm^{-3}) = (0.004*Cl + 0.289) *BD (r = 0.75) $\theta_{-10\ kPa}$ (cm^3cm^{-3}) = (0.003*Cl + 0.102)*BD (r = 0.84)	*Original PTFs:* Clay: Cl (%) Bulk density: BD (g cm^{-3})	- Original document link (Table V and VI) - 119 soil samples from 23 profiles from southern Nigeria - PTFs are based on soil separates - Main characteristics of the PTFs developing dataset: Sand (surface horizon 32-80%, sub-surface horizon 20-78%), Silt (surface horizon 3-20%, sub-surface horizon 0.4-18%), Clay (surface horizon 11-28%, sub-surface horizon 13-56%), OC (surface horizon 0.31-4.17%, sub-surface horizon 0.16 – 1.11%) - Group I consist of 11 soil profiles representative of well-drained upland positions in western Nigeria. The particle size classes are mostly coarse or fine loamy in the surface horizon and the subsoils are dominantly fine loamy to clayey. The gravel concentrations in the gravelly horizons range from 27-73% by weight. The average silt/clay ratio ranges from 0.9 in the surface layers to 0.3 at about 1 m depth and to about 0.5 at 150-170 cm depth. - Group II consist of 12 profiles. These soils have deep profiles. The particle size classes of the surface soils are sandy to fine loamy to some depth and those of the lower horizons are fine loamy to fine clayey with little texture differentiation to 250 cm or deeper. The silt/clay ratio declines from 0.7 in the surface layer to 0.2 at 100 cmm with slight or no decrease beyond 1 meter depth. - The PTFs were used in tropical regions: Congo by Botula Manyala (2013) - 104 citations from Google Scholar (accessed on 10 Aug 2020)

	$\theta_{-33\ kPa}$ (cm^3cm^{-3}) = (0.004*Cl + 0.065)*BD (r = 0.88) $\theta_{-1500\ kPa}$ (cm^3cm^{-3}) = (0.003*Cl + 0.006)*BD (r=0.9) Group II: $w_{0\ kPa}$ ($g\ g^{-1}$) = (0.004*Cl + 0.296)*BD (r = 0.48) $w_{-10\ kPa}$ ($g\ g^{-1}$) = (0.003*Cl + 0.080)*BD (r = 0.68) $w_{-33\ kPa}$ ($g\ g^{-1}$) = (0.003*Cl + 0.047)*BD (r = 0.64) $w_{-1500\ kPa}$ ($g\ g^{-1}$) = (0.0022*Cl + 0.025)*BD (r = 0.70)		
Karlsson (1982)	*Original PTFs:* $\theta_{-1500\ kPa}$ (v/v %) = 5.1 + 0.5*Cl (r=0.91)	*Original PTFss:* Clay: Cl (%)	- Original document link - Tanzanian subsoil samples - 7 citations from Google Scholar (accessed on 10 Aug 2020)
Arruda et al. (1987)	*Arruda et al. (1987)PTFs found in van Den Berg et al. (1997)* w_{-33kPa} ($kg\ kg^{-1}\ 10^2$) = 0.29*(Cl + Si) + 9.93 $w_{-1500\ kPa}$ ($kg\ kg^{-1}\ 10^2$) = 0.27*(Cl + Si) + 1.07 *Arruda et al. (1987)PTFs found in Tomasella and Hodnett (2004)* w_{-33kPa} ($g\ g^{-1}$) = $6.71198*10^{-2}$ *exp($4.28*10^{-2}$*(Si+Cl) – $3.949*10^{-4}$*$(Si+Cl)^2$ + $6.68*10^{-7}$*$(Si+Cl)^3$) $w_{-1500kPa}$ ($g\ g^{-1}$) = $2.3662*10^{-2}$*$(Si + Cl)^{1.20408 – 0.0872025 \log (Si + Cl)}$ *Arruda et al. (1987)PTFs found in Reichert et al. (2009)* w_{-33kPa} ($g\ 100\ g^{-1}$) = 3.074 + 0.629*(Si+Cl) – 0.003438*$(Silt+Clay)^2$) $w_{-1500kPa}$ ($g\ 100\ g^{-1}$) = 1.074 + 0.2712*(Si+Cl) *Arruda et al. (1987)PTFs found in Botula Manyala (2013):* w_{-33kPa} ($kg\ kg^{-1}$) = 0.29*(Cl + Si) + 9.93 $w_{-1500\ kPa}$ ($kg\ kg^{-1}$) = 0.27*(Cl + Si) + 1.07 Si (2–20µm) *Arruda et al. (1987)PTFs found in Medeiros et al. (2014)* w_{-33kPa}(m^3m^{-3}) = (3.07439 + 0.629239*(Si+Cl) – 0.00343813*$(Silt+Clay)^2$)/100 $w_{--1500kPa}$(m^3m^{-3}) = (1398.889*(Si + Cl)/(1308.09 + (Si + Cl)))/100	*The PTFs in van Den Berg et al. (1997)* Silt: Si ($kg\ kg^{-1}10^2$) Clay: Cl ($kg\ kg^{-1}10^2$) *The PTFs in Tomasella and Hodnett (2004):* Sand: Sa (%) Clay: Cl (%) *The PTFs in Botula Manyala (2013):* Silt: Si (%) Clay: Cl (%)	- Original document was not found - South-east Brazil soils - The PTFs were different in publications by Reichert et al. (2020); Botula Manyala (2013) and Medeiros et al. (2014) - The PTFs were used in tropical regions: Congo by Botula Manyala (2013), Amazon by Medeiros et al. (2014) - 10 citations from (https://ainfo.cnptia.embrapa.br) (accessed on 22 Aug 2021)
Dijkerman (1988)	*Original PTFs:* w_{-33kPa} (v/v%) = 36.97 – 0.35*Sa (R^2 = 0.88) $w_{-1500kPa}$(v/v%) = 0.74 + 0.39*Cl (R^2 = 0.92)	*Original PTFs:* Sand: Sa (%) Clay: Cl (%)	- Original equation link - Soil samples (Ultisols, Oxisols, Inceptisols) from Sierra Leone

			- The PTFs were used in tropical regions: Congo by Botula Manyala (2013), Amazon by Medeiros et al. (2014), Vietnam by Nguyen et al. (2015) - The PTFs were listed in Tomasella and Hodnett (2004) (unit of water content is g^1g^{-1}) as PTFs for tropical region - 37 citations from Google Scholar (accessed on 10 Aug 2020)
Bell and Keulen (1995)	*Bell and Keulen (1995) PTFs found in Oliveira et al. (2002):* w_{-33kPa} (kg kg^{-1}) = (6.93 + 0.286*Cl/10)/100 $w_{-1500kPa}$ (kg kg^{-1}) = (5.72 + 0.433*Cl/10)/100 *Bell and Keulen (1995) PTFs found in Reichert et al. (2009):* $w_{-1500kPa}$ (g 100 g^{-1}) = -0.992 + 0.351*Cl + 0.47*OM (R^2 = 0.85) $w_{-1500kPa}$ (g 100 g^{-1}) = -1.62 + 0.436*CEC_{pH7} + 0.436*OM (R^2 = 0.9)	*The PTFs in Oliveira et al. (2002):* *Clay:* Cl (g kg^{-1}) *The PTFs in Reichert et al. (2009):* Clay: Cl (g 100 g^{-1}) Organic matter: OM (g 100 g^{-1}) CEC (cmo_{lc} kg^{-1})	- Original document was not found - Mexico soils - 160 citations from Google Scholar (accessed on 10 Aug 2020)
Masutti (1997)	*Masutti (1997) PTFs found in Oliveira et al. (2002):* w_{-33kPa} (kg kg^{-1}) = (-1.5691 + 0.4289*(Cl + Si)/10)/100 $w_{-33kPa – 1500kPa}$ (kg kg^{-1}) = (-0.530482 + 0.301235*Si/10 + 0.092822*Cl/10)/100 *Masutti (1997) PTFs found in Reichert et al. (2009):* w_{-33kPa} (g 100 g^{-1}) = -1.569 + 0.429*(Si + Cl) $w_{-1500kPa}$ (g 100 g^{-1}) = -0.53 + 0.301*Si + 0.0928*Cl	*The PTFs in Oliveira et al. (2002):* Clay: Cl (g kg^{-1}) Silt: Si (g kg^{-1}) *The PTFs in Reichert et al. (2009):* Clay: Cl (g 100 g^{-1}) Silt: Si (g 100 g^{-1})	- Original document: cannot access - Brazil soil - 9 citations from Google Scholar (accessed on 10 Aug 2020)
Adhikary et al. (2008)*	*Original PTFs:* $\theta_{-10\ kPa}$ (v/v, %) = 62.5 – 0.58*Sa -0.21*Si $\theta_{-33\ kPa}$ (v/v, %) = 56.37 – 0.51*Sa – 0.27*Si $\theta_{-100\ kPa}$ (v/v, %) = 12.58 – 0.09*Sa + 0.4*Cl $\theta_{-300\ kPa}$ (v/v, %) = 8.5 – 0.07*Sa + 0.38*Cl $\theta_{-500\ kPa}$ (v/v, %) = 4.73 – 0.04*Sa + 0.42*Cl $\theta_{-1000\ kPa}$ (v/v, %)) = 0.35 + 0.45*Cl $\theta_{-1500\ kPa}$ (v/v, %) = 0.71 + 0.44*Cl Converted equations used in LUCI_PTFS: $\theta_{-10\ kPa}$ ($cm^3\ cm^{-3}$) = 0.625 – 0.0058*Sa -0.0021*Si	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%)	- Original document link - 200 samples from India - These data represented 8 major soil groups, alluvial (Entisol, Inceptisol, Alfisol, Aridisol); black (Vertisol), red (Alfisol and Ultisol), mixed (i.e. red and yellow), or red and black lateritic (Oxisol and Alfisol); desert (Aridisol and Entisol); mountain and hill (Alfisol and Inceptisol); and foot hill and tarai soils (Ultisol)

	$\theta_{-33\ kPa}$ ($cm^3\ cm^{-3}$) = 0.5637 – 0.0051*Sa – 0.0027*Si $\theta_{-100\ kPa}$ ($cm^3\ cm^{-3}$) = 0.1258 – 0.0009*Sa + 0.004*Cl $\theta_{-300\ kPa}$ ($cm^3\ cm^{-3}$) = 0.085 – 0.0007*Sa + 0.0038*Cl $\theta_{-500\ kPa}$ ($cm^3\ cm^{-3}$) = 0.0473 – 0.004*Sa + 0.0042*Cl $\theta_{-1000\ kPa}$ ($cm^3\ cm^{-3}$) = 0.0035 + 0.0045*Cl $\theta_{-1500\ kPa}$ ($cm^3\ cm^{-3}$) = 0.0071 + 0.0044*Cl		- Main characteristics of the PTFs developing dataset: Sand (2.3-98.5%), Silt (1.0 – 51.5%), Clay (2.5 – 69.2%), BD (1.12-1.76%), OC (0.04-1.18%) - The PTFs were used in tropical regions: Vietnam by Nguyen et al. (2015) - The PTFs showed the best performance in very fine soils of United State (Abdelbaki, 2020) - 56 citations from Google Scholar (accessed on 10 Aug 2020)
SMRC parameters – Van Genuchten model $S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^m}$ $\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha * h)^n]^m}$ S_e: the effective saturation $\theta(h)$: the relationship between volumetric soil moisture content and pressure head θ_s: the saturated moisture content θ_r: the residual moisture content m, n: the empirical shape-defining parameters in the van Genuchten model			
(1) Soil texture (Sa, Si, Cl); BD; OM/OC; and other soil properties			
van Den Berg et al. (1997)	*Original PTFs:* θ_r ($m^3m^{-3}10^2$) = 3.49 + 0.255*Cl – 5.91*Al_{dith} + 0.714*Fe_{dith} or θ_r ($m^3m^{-3}10^2$) = 0.308*Cl α = exp(-0.627) m = 0.494 – 0.0025*(Si + Cl) – 0.150*Al_{dith} + 0.020*Fe_{dith} or m = 0.503 – 0.0027*(Si + Cl) – 0.066*OC% + 0.0094*CEC θ_s ($m^3m^{-3}10^2$) = 84.1 – 0.206*Cl – 0.322*(Sa + Si)	*Original PTFs:* Sand: Sa (kg $dm^{-3}10^2$) Silt: Si (kg $dm^{-3}10^2$) Clay: Cl (kg $dm^{-3}10^2$) Organic carbon: OC (kg $dm^{-3}10^2$) Al content: Al (kg $dm^{-3}10^2$) Fe content: Fe (kg $dm^{-3}10^2$)	- Original equation link - World Oxisols and related soils from from South America, Africa and South East Asia, 2 sets of data (Set 1: 91 samples from 31 profiles, Set 2: 35 samples from 13 profiles) - Main characteristics of the PTFs developing dataset: Clay (2-95%), OC (0.1-6.95), BD (0.7-1.8 kg dm^{-3}) - 183 citations from Google Scholar (accessed on 10 Aug 2020)
Tomasella et al. (2000)	*Original PTFs:* ln α = 2.644658 + 0.012123*Cl – 3.786112*Me – 3.283456*BD + 5.2*10^{-}	*Original PTFs:* Sand: Sa (%) Silt: Si (%)	- Original equation link

	^{5}*CoarseSa*FineSa + 7.75*10^{-4}*CoarseSa*Sa + 9.63**10^{-4}*FineSa*Cl + 6.16*10^{-4}*CoarseSa^{2} n = 2.190951 – 1.529655*Me – 2.99*10^{-4}*CoarseSa*Si – 3.45*10^{-4}*FineSa*Cl – 1.05*10^{-4}*CoarseSa^{2} + 2.5*10^{-5}*FineSa^{2} θ_s (cm^3 cm^{-3}) = 0.821929 – 1.77*10^{-4}*Si + 0.232383*Me – 0.286741*BD + 4.9*10^{-5}*CoarseSa*Si – 2.9*10^{-5}*CoarseSa*Cl + 2.7*10^{-5}*FineSa*Cl – 8*10^{-6}* CoarseSa^{2} θ_r (cm^3 cm^{-3}) = - 0.133652 + 0.002497*Si + 0.003379*Cl + 0.399141*Me + 0.076764*BD – 4.8*10^{-5}*Si^{2} 1.3*10^{-5}*Cl^{2}	Clay: Cl (%) Coarse Sand: CoarseSa (%) Fine Sand: FineSa (%) Moisture equivalent: Me (g g^{-1}) Bulk density: BD (g cm^{-3})	- 613 samples Brazil soils, 500 samples were used to developed PTFs and 113 samples were used to validate the PTFs - Main characteristics of the PTFs developing dataset: Coarse sand (0-74.6%), Fine sand (0-65%), Silt (0-71%), Clay (1.7-96%), OC (0-6.39%), BD (0.72-1.91 g cm^{-3}) - 259 citations from Google Scholar (accessed on 10 Aug 2020)
Hodnett and Tomasella (2002)*	*Original PTFs:* ln α = -0.02294 – 0.03526*Si + 0.024*OC – 0.0076 *CEC – 0.11331*pH + 0.00019*Si^{2} ln n = 0.62986 – 0.00833*Cl – 0.00529*OC + 0.00593*pH + 7*10^{-5} *Cl^{2} – 1.4*10^{-4} *Sa*Si θ_s (m^3 m^{-3}) = 0.81799 + 9.9*10^{-4}*Cl – 0.3142*BD + 1.8*10^{-4}*CEC + 0.00451*pH – 5*10^{-6} *Sa*Cl θ_r (m^3 m^{-3}) = 0.22733 – 0.00164*Sa + 0.00235*CEC – 0.00831*pH + 1.8*10^{-5}*Cl^{2} + 2.6*10^{-5}*Sa*Cl *Hodnett and Tomasella (2002) PTFs found in Tomasella and Hodnett (2004) and Botula Manyala (2013)* ln α = -0.02294 – 0.03526*Si + 0.024*OC – 7.6E-3 *CEC – 0.11331*pH ln n = 0.62986 – 0.00833*Cl – 0.00529*OC + 0.00593*pH + 7*10^{-5} *Cl^{2} – 1.4*10^{-4} *Sa*Si θ_s (m^3 m^{-3}) = 0.81799 + 9.9*10^{-4}*Cl – 0.3142*BD + 1.8*10^{-4}*CEC + 0.00451*pH – 5*10^{-6} *Sa*Cl θ_r (m^3 m^{-3}) = 0.22733 – 0.00164*Sa + 0.00235*CEC – 0.00831*pH + 1.8*10^{-5}*Cl^{2} + 2.6*10^{-5}*Sa*Cl	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic carbon: OC (%) CEC (cmol kg^{-1}) Bulk density: BD (Mg m^{-3})	- Original equation link - 771 soil horizons from World tropical soils, IGBP-DIS soil database - Main characteristics of the PTFs developing dataset: Sand (0.5-99%), Silt (0.4-77.4%), Clay (0-95.4%), OC(0-30.8%), CEC (0-93.7 cmol kg^{-1}), BD (0.28-1.88 Mg m^{-3}), pH (3.6-9.6) - The PTFs performs very well in estimating measured soil moisture contents at various soil moisture potentials for horizons of soil profiles situated in the Limpopo river basin in semi-arid regions Sub Sahara (Wösten et al., 2013) - 292 citations from Google Scholar (accessed on 10 Aug 2020)
Medrado and Lima (2014)	*Original PTFs:* θ_s (kg kg^{-1}) = (−0.01831805*Cl$^{0.89935543}$ −0.01131157*Sa$^{1.00134021}$ −0.00684340*Si$^{1.11564515}$ + 0.01622120*OM$^{0.48555009}$ + 2.01973831)* θ_p θ_p = (1/BD-1/PD) θ_r (kg kg^{-1}) = 0.13461391*BD $^{-1.58555722}$ + 0.04883605*Cl$^{0.19647777}$ −0.00949548*Sa$^{0.56355803}$ −0.00005212*Si$^{1.43345189}$ + 0.01057297*OM$^{1.14951659}$ + 0.01153532	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) CEC (cmol kg^{-1}) Bulk density: BD (Mg m^{-3})	- Original document link - 1401 soil layers from 413 locations located inthe following Brazilian States: Amazon, Bahia, the Federal District, Goiás, Maranhão, MinasGerais, MatoGrosso, Pará, Tocantins - Main characteristics of the PTFs developing dataset: Clay (4.79-91.51%), Silt (0.029 – 55.03%), Total sand (1.18-32.90.046%), OM (0-7.8%), BD (0.59-1.95 g cm^{-3})

	$n = 1.82865464*BD^{-0.57582713} - 0.04262312*Cl^{0.59924802} + 1.51361637*Sa^{0.00985830} - 0.67293635*Si^{0.05966974} - 0.00163216*OM^{2.66119588} - 0.64209861$ $\alpha = -0.00351317*BD^{2.42317427} - 0.03460735*Cl^{0.58034639} - 0.01845649*Sa^{0.85117517} - 0.04897867*Si^{0.59621217} - 0.00001279*OM^{5.38486557} - 1.58532681$	PD: particle density (Mg m^{-3})	
(2) Soil texture (Sa, Si, Cl); BD; OM/OC			
Barros (2010)	*Barros (2010) PTFs found in Medeiros et al. (2014):* θ_s ($m^3 m^{-3}$) = 1 - 0.00037*BD θ_r ($m^3 m^{-3}$) = 0.0858 - 0.1671*Sa + 0.3516*Cl + 1.1846*OC + 0.000029*BD α = 0.8118+0.8861*Sa -1.1907*Cl - 0.001514*BD n = 1.1527 + 0.7427*Sa + 0.4135*Si -5.5341*OC	*The PTFs in Medeiros et al. (2014):* Sand: Sa (g kg^{-1}) Silt: Si (g kg^{-1}) Clay: Cl (g kg^{-1}) Organic carbon: OC (g kg^{-1}) Bulk density: BD (Mg m^{-3})	- Original equation link in Portuguese - 3 citations from Google Scholar (accessed on 10 Aug 2020)
Shwetha and Varija (2013)*	*Original PTFs:* θ_r (g cm^{-3}) = 1.004 − 0.00286*Sa − 0.01348*Si − 0.572*BD − 0.00004*Sa^2 + 0.00001* Si + 0.00306*Sa*BD + 0.00001*Si^2 + 0.00832*Si*BD + 0.01413*BD^2 θ_s (g cm^{-3}) = 0.760 + 0.00319*Sa − 0.2980*BD + 0.08499*OM + 0.00001*Sa^2 − 0.00294*Sa*BD + 0.00007*Sa*OM + 0.06126*BD^2 − 0.06824*BD*OM + 0.005*OM^2 α = 0.923 − 0.03433*Sa − 0.01367*Si + 0.12629*OM + 0.00027*Sa^2 + 0.00045*Sa*Si − 0.00171*Sa*OM − 0.00016*Si^2 + 0.00071*Si*OM − 0.02398*OM^2 n = −33.82 + 0.171*Si + 44.43*BD − 1.611*OM + 0.00108*Si^2 − 0.139*Si*BD − 0.02981*Si*OM − 13.87*BD^2 + 1.544*BD*OM + 0.08174*OM^2	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk density: BD (g cm^{-3})	- Original document link - Soil samples in the Pavanje river basin in the Dakshina Kannada district of coastal Karnataka, Inida - Main characteristics of the PTFs developing dataset: Sand (46-89%), Silt (10-52%), Clay (1-5%), BD (1.36-1.65 g cm^{-3}), OM (0.24-2.52%) - 14 citations from Google Scholar (accessed on 10 Aug 2020)

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SMRC- *Brooks and Corey (1964) model*

$$S_e = \frac{\theta(h)-\theta_r}{\phi-\theta_r} = \begin{cases} \left(\frac{h_b}{h}\right)^{\lambda}, & h > h_b \\ 1, & h \le h_b \end{cases}$$

The Brooks and Corey (1964) model was commonly rewritten as:

$$S_e = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r} = \begin{cases} \left(\frac{h_b}{h}\right)^{\lambda}, & h > h_b \\ 1, & h \le h_b \end{cases}$$

S_e: the effective saturation
$\theta(h)$: the relationship between volumetric soil moisture content and pressure head
ϕ: prorosity
θ_s: the saturated moisture content
θ_r: the residual moisture content
h_b: the air-entry pressure
m, n: the empirical shape-defining parameters in the van Genuchten model

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<td>Shwetha and Varija (2013)*</td>
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Original PTFs:
θ_r (g cm^{-3}) = 0.428 + 0.00345*Ss − 0.463*BD + 0.359*OM − 0.00001*Sa^2 − 0.00425*Sa* BD + 0.0018*Sa*OM + 0.273*BD^2 − 0.317*BD*OM + 0.00587*OM^2

h_b = −7.766 − 1.582*Sa + 5.548*Si + 28.38*OM + 0.01667*Sa^2 − 0.02579*Sa*Si − 0.407*Sa*OM − 0.06874*Si^2 − 0.345*Si*OM + 3.344*OM^2

λ = −0.613 + 0.04239*Sa − 0.01461*Si + 0.295*OM − 0.00029*Sa^2 − 0.00052*Sa*Si + 0.00425*Sa*OM + 0.00100*Si^2 − 0.02484*Si*OM + 0.09701*OM^2

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Original PTFs:
Sand: Sa (%)
Silt: Si (%)
Clay: Cl (%)
Organic matter: OM (%)
Bulk density: BD (g cm^{-3})

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- Original document link
- Soil samples in the Pavanje river basin in the Dakshina Kannada district of coastal Karnataka, Inida
- Main characteristics of the PTFs developing dataset: Sand (46-89%), Silt (10-52%), Clay (1-5%), BD (1.36-1.65 g cm^{-3}), OM (0.24-2.52%)
- 14 citations from Google Scholar (accessed on 10 Aug 2020)
(accessed on 10 Aug 2020)

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Table B1.8 PTFs for estimating soil moisture content developed for arid climate

Equation name	Equation	Parameter	Description
Point PTFs			
(1) Soil texture (Sa, Si, Cl); BD; OM/OC; and other soil properties			
			-
(2) Soil texture (Sa, Si, Cl); BD; OM/OC			
Mohamed and Ali (2006)	*Original PTFs:* $\theta_{SAT\ kPa}$ (%) = -0.8667*Cl - 1.426*Sa - 84.2817*BD - 0.0151*Si^2 + 0.0012*Sa^2 - 7.9188*Ln(Si) + 112.0333*Ln(BD) - 0.0064*Cl*Si - 0.2835*Cl*BD - 0.0068*Si*Sa + 0.177*Si*OM + 266.768 $\theta_{FC\ kPa}$ (%) = 0.0023*Si^2 - 8.491*BD^2 - 3.2498*OM^2 + 153.59021/Cl - 101.21431/Si-9.02181/Sa + 8.52011/OM + 20.9002*Ln(OM) + 0.355*Cl*BD - 0.2388*Cl*OM + 10.1357*BD*OM + 16.4788 $\theta_{PWP\ kPa}$ (%) = -0.7409*Si + 0.0126*Si^2 - 7.4396*BD^2 - 2.8807*OM^2 + 136.151/Cl - 98.33231/Si - 23.99671/Sa + 9.03681/OM + 20.7999*Ln(OM) + 0.4598*Cl*BD - 0.2579*Cl*OM + 9.1905*BD*OM + 9.8444	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) BD: Bulk density (Mg m^{-3})	- Original document link - 147 soil samples containing contains Cambisols, Vertisols, Calcisols and Fluvisols mainly from the Ariana plain with some from Mornag, Tunisia. 109 samples were used to develop PTFs. - Texture fractions defined by USDA system: Sand (0.75-87.51%), Silt (1-68%), Clay (1-68%), OM (0.2-3.2 %), BD (1.23-1.79 g cm^{-3}) - 23 citations from Google Scholar (accessed on 30 Aug 2020)
Santra et al. (2018)*	*Original PTFs:* Local PTFs developed with soils data from hot arid Western India	*Original PTFs:* Sand: Sa (%) Clay: Cl (%) Organic carbon: OC (g kg^{-1}) BD: Bulk density (Mg m^{-3})	- Original document link (Table 6 and 7) - 380 soil samples from arid Western India (western part of Rajasthan and north-western part of Gujarat with some parts of Haryana and Punjab at its northeast and east, respectively and 1789 soil samples from arid regions of USA taken from the NCCS Soil Characterization Database - Main characteristics of PTFs developing dataset: Sand (4-97%), Silt (4.31-61.06%), Clay (6-84.53%), OC (0.1-11 g kg^{-1}) - FC at 1/3 bar - 12 citations from Google Scholar (accessed on 10 Aug 2020)

	PTFs developed based on Sa, Si, Cl $\theta_{-33\ kPa}$ (%, g/g) = 29.27 – 0.264*Sa + 0.207*Cl $\theta_{-1500\ kPa}$ (%, g/g) = 5.04 – 0.0385*Sa + 0.232*Cl – 0.00057*Sa*Cl PTFs developed based on Sa, Si, Cl and OC $\theta_{-33\ kPa}$ (%, g/g) = 29.77 – 0.263*Sa + 0.206*Cl + 0.0110*OC $\theta_{-1500\ kPa}$ (%, g/g) = 1.516 + 0.325*Cl – 0.00147*Sa*Cl + 0.00247*Sa*OC – 0.00469*Cl*OC Global PTFs developed with soil data from arid Western Indian and arid regions of USA PTFs developed based on Sa, Si, Cl $\theta_{-33\ kPa}$ (%, g/g) = 27.8 – 0.231*Sa + 0.262*Cl $\theta_{-1500\ kPa}$ (%, g/g) = 10.06 – 0.0847*Sa + 0.303*Cl – 0.00286*Sa*Cl*0.1 PTFs developed based on Sa, Si, Cl and OC $\theta_{-33\ kPa}$ (%, g/g) = 24.98 – 0.205*Sa + 0.28*Cl + 0.192*OC $\theta_{-1500\ kPa}$ (%, g/g) = 4.341 + 0.435*Cl – 0.00431*Sa*Cl + 0.00190*Sa*OC + 0.00169*Cl*OC Converted equations used in LUCI_PTFs: $\theta_{-33\ kPa}$ ($cm^3\ cm^{-3}$) = (24.98 – 0.205*Sa + 0.28*Cl + 0.192*OC*10)*BD*10^{-2} $\theta_{-1500\ kPa}$ ($cm^3\ cm^{-3}$) = (4.341 + 0.435*Cl – 0.00431*Sa*Cl + 0.00190*Sa*OC*10 + 0.00169*Cl*OC*10) *BD*10^{-2}		
(3) Soil texture (Sa, Si, Cl); OM/OC			
Gaiser et al. (2000)	*Original PTFs:* θ_{-33} ($m^3\ m^{-3}$) = 0.208*OC + 0.6*Cl + 0.166*Si $\theta_{-1500\ kPa}$ ($m^3\ m^{-3}$) = 0.088*OC + 0.34*Cl + 0.057*Si	*Original PTFs:* Silt: Si (%) Clay: Cl (%)R Organic carbon: OC (g/kg)	- Original document link - 663 soil horizons from semi-arid tropical regions in SE Niger and NE Brazil (annual precipitation 500-800 mm) - Main characteristics of the PTFs developing dataset: Sand (3-98%), Clay (0.2-85%), OC (0-4.8%) - Field capacity at -33 kPa

			- The PTFs were developed for Semiarid Tropical regions - 62 citations from Google Scholar (accessed on 30 Aug 2020)
Mohamed and Ali (2006)	*Original PTFs:* $\theta_{SAT\ kPa}$ (%) = 0.7264*Si + 0.2026*Sa - 0.0083*Si^2 - 13.75491/(Sa) - 7.7387*Ln(Sa) + 2.2103*Ln(OM) - 0.0043*Cl*Si + 0.0051*Cl*Sa - 0.0047*Si*Sa + 53.4646 $\theta_{FC\ kPa}$ (%) = 0.2239*Cl - 57.95441/(Si) - 11.69741/(Sa) + 6.90031/(OM) - 3.5324*Ln(Sa) + 24.0966*Ln(OM) + 0.0031*Cl*Sa - 0.1886*Cl*OM + 36.7918 $\theta_{PWP\ kPa}$ (%) = -181.7238*Cl - 183.5092*Si - 182.4525*Sa - 0.0048*Cl^2 + 0.0114*Si^2 - 0.0031*Sa^2 + 128.78961/(Cl) - 83.0451/(Si) + 6.52931/(Sa) + 9.18951/(OM) + 27.4919*Ln(OM) + 0.0043*Cl*Si - 0.2411	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) BD: Bulk density (Mg m^{-3})	- Original document link - 147 soil samples containing contains Cambisols, Vertisols, Calcisols and Fluvisols mainly from the Ariana plain with some from Mornag, Tunisia. 109 samples were used to develop PTFs. - Texture fractions defined by USDA system: Sand (0.75-87.51%), Silt (1-68%), Clay (1-68%), OM (0.2-3.2 %), BD (1.23-1.79 g cm^{-3}) - 23 citations from Google Scholar (accessed on 30 Aug 2020)
(4) Soil texture (Sa, Si, Cl); BD			
Mohamed and Ali (2006)	*Original PTFs:* $\theta_{SAT\ kPa}$ (%) = 0.4602*Cl + 1.1343*Si - 86.8963*BD - 0.011*Si^2 - 9.4193*Ln(Si) + 110.5222*Ln(BD) - 0.256*Cl*BD - 0.002*Si*Sa + 0.0405*Sa*BD + 135.5837 $\theta_{FC\ kPa}$ (%) = 148.39031/(Cl) - 43.85161/(Si) - 5.17411/(Sa) + 16.6718*Ln(Cl) + 0.0011*Cl*Si - 0.0999*Cl*BD + 0.0025*Si*Sa - 24.1522 $\theta_{PWP\ kPa}$ (%) = -1.2152*Si - 0.4877*Sa - 0.0057*Cl^2 + 0.0087*Si^2 + 85.84361/(Cl) - 88.0331/(Si) + 0.0012*Cl*Si + 0.2129*Cl*BD + 59.6137	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) BD: Bulk density (Mg m^{-3})	- Original document link - 147 soil samples containing contains Cambisols, Vertisols, Calcisols and Fluvisols mainly from the Ariana plain with some from Mornag, Tunisia. 109 samples were used to develop PTFs. - Texture fractions defined by USDA system: Sand (0.75-87.51%), Silt (1-68%), Clay (1-68%), OM (0.2-3.2 %), BD (1.23-1.79 g cm^{-3}) - 23 citations from Google Scholar (accessed on 30 Aug 2020)
Dashtaki et al. (2010)*	*Original PTFs:* PTFs developed based on Sa, Si, Cl and BD: $\theta_{-10\ kPa}$ (% v) = 34.3 – 0.38*Sa + 12.4*BD (R^2 = 80)	*Original PTFs:* Sand: Sa (%) Silt: Silt (%) Clay: Cl (%) Bulk density: BD (g cm^{-3}) dg (geometric mean diameter); Sg (geometric standard deviation of soil particle diameter)	- Original document link - 234 soil samples of top 30 cm of soil groups from the Karaj and Naghade Plains Iran - Main characteristics of the PTFs developing dataset: Clay (10-50%), Silt (15-55%), Sand (6-71%), BD (1.2-1.83 g cm^{-3}) - The PTFs showed the best performance to predict soil moisture at -10kPa and -1500kPa of United State (Abdelbaki, 2020)

	$\theta_{-30\ kPa}$ (% v) = 14.1 – 0.283*Sa + 17.1*BD (R^2 = 65) $\theta_{-100\ kPa}$ (% v) = 12.2 – 0.31*Sa + 14.3*BD (R^2 = 67.1) $\theta_{-300\ kPa}$ (% v) = 12 – 0.22*Sa + 8.41*BD + 4.3*Cl ⁄ Si (R^2 = 74) $\theta_{-500\ kPa}$ (% v) = 9.4 + 0.32*Cl (R^2 = 65.3) $\theta_{-1500\ kPa}$ (% v) = 6.2 + 0.33*Cl (R^2 = 74.2) PTFs developed based dg, Sg and BD $\theta_{-10\ kPa}$ (% v) = 50.21 – 51.4*dg' (R^2 = 79.0) $\theta_{-30\ kPa}$ (% v) = 25.2 – 67.76*dg' + 13.2*BD (R^2 = 68.3) $\theta_{-100\ kPa}$ (% v) = 17.3 – 49.6*dg' + 11.21*BD (R^2 = 74.4) $\theta_{-300\ kPa}$ (% v) = 16.08 – 39.85*dg' + 8.01*BD (R^2 = 77.7) $\theta_{-500\ kPa}$ (% v) = 14.6 – 42.07*dg' + 3.19* $Sg^{0.5}$ (R^2 = 71.5) $\theta_{-1500\ kPa}$ (% v) = 10.38 – 38.59* dg' + 3.31* $Sg^{0.5}$ (R^2 = 78.0) <u>Converted equations used in LUCI_PTFs:</u> $\theta_{-10\ kPa}$ ($cm^3\ cm^{-3}$) = (34.3 – 0.38*Sa + 12.4*BD)*10^{-2} (R^2 = 80) $\theta_{-30\ kPa}$ ($cm^3\ cm^{-3}$) = (14.1 – 0.283*Sa + 17.1*BD) *10^{-2} (R^2 = 65) $\theta_{-100\ kPa}$ ($cm^3\ cm^{-3}$) = (12.2 – 0.31*Sa + 14.3*BD) *10^{-2} (R^2 = 67.1) $\theta_{-300\ kPa}$ ($cm^3\ cm^{-3}$) = (12 – 0.22*Sa + 8.41*BD + 4.3*Cl ⁄ Si) *10^{-2} (R^2 = 74) $\theta_{-500\ kPa}$ ($cm^3\ cm^{-3}$) = (9.4 + 0.32*Cl) *10^{-2} (R^2 = 65.3) $\theta_{-1500\ kPa}$ ($cm^3\ cm^{-3}$) = (6.2 + 0.33*Cl) *10^{-2} (R^2 = 74.2)	dg' = $dg^{0.6}$	- 64 citations from Google Scholar (accessed on 10 Aug 2020)
Fooladmand (2011)	*Original PTFs:* θ_s ($m^3\ m^{-3}$) = 0.332 - 7.251*10^{-4}*Sa + 0.1276*log(Cl) $\theta_{-3\ kPa}$ ($m^3\ m^{-3}$) = -0.2324 + 0.0606*Cl + 1.0889*θ_s + 0.0867*BD $\theta_{-6\ kPa}$ ($m^3\ m^{-3}$) = -0.3838 + 0.1383*Cl + 1.1503*θ_s + 0.1438*BD $\theta_{-9\ kPa}$ ($m^3\ m^{-3}$) = -0.4977 + 0.2306*Cl + 1.2307*θ_s + 0.1663*BD $\theta_{-12\ kPa}$ ($m^3\ m^{-3}$) = -0.5351 + 0.2857*Cl + 1.2326*θ_s + 0.1706*BD $\theta_{-30\ kPa}$ ($m^3\ m^{-3}$) = -0.4220 + 0.2952*Cl + 0.9693*θ_s + 0.1428*BD $\theta_{-100\ kPa}$ ($m^3\ m^{-3}$) = -0.3786 + 0.3028*Cl + 0.8346*θ_s + 0.1191*BD $\theta_{-500\ kPa}$ ($m^3\ m^{-3}$) = -0.2959 + 0.3306*Cl + 0.5691*θ_s + 0.1043*BD $\theta_{-1000\ kPa}$ ($m^3\ m^{-3}$) = -0.2971 + 0.3459*Cl + 0.5109*θ_s + 0.1090*BD $\theta_{-1500\ kPa}$ ($m^3\ m^{-3}$) = -0.2611 + 0.3178*Cl + 0.4881*θ_s + 0.0877*BD $\theta_{-3\ kPa}$ ($m^3\ m^{-3}$) = 0.2236 - 0.0445*Sa + 1.0664*θ_s + 0.1080*BD $\theta_{-6\ kPa}$ ($m^3\ m^{-3}$) = -0.3614 - 0.0995*Sa + 1.0999*θ_s + 0.1899*BD	*Original PTFs:* Sand: Sa (%) Silt: Silt (%) Clay: Cl (%) Bulk density: BD (g cm^{-3})	- Original document link - 20 soil samples from top-soils (A horizons) in Fars province, South of Iran - Main characteristics of the PTFs developing dataset: Clay (4-46%), Sand (4-80%), dg (0.007-0.431mm), BD (1.16-1.67 g cm^{-3}) - The PTFs showed the best performance in fine/medium fine/medium/coarse soils of United State (Abdelbaki, 2020) - 4 citations from Google Scholar (accessed on 10 Aug 2020)

	$\theta_{-9\ kPa}$ ($m^3\ m^{-3}$) = -0.4616 - 0.1672*Sa + 1.1460*θ_s + 0.2448*BD $\theta_{-12\ kPa}$ ($m^3\ m^{-3}$) = -0.4936 - 0.2098*Sa + 1.1263*θ_s + 0.2712*BD $\theta_{-30\ kPa}$ ($m^3\ m^{-3}$) = -0.3403 - 0.1828*Sa + 0.8757*θ_s + 0.2057*BD $\theta_{-100\ kPa}$ ($m^3\ m^{-3}$) = -0.2938 - 0.1866*Sa + 0.7391*θ_s + 0.1825*BD $\theta_{-500\ kPa}$ ($m^3\ m^{-3}$) = -0.1906 - 0.1926*Sa + 0.4701*θ_s + 0.1601*BD $\theta_{-1000\ kPa}$ ($m^3\ m^{-3}$) = -0.1803 - 0.1956*Sa + 0.4101*θ_s + 0.1603*BD $\theta_{-1500\ kPa}$ ($m^3\ m^{-3}$) = -0.1534 - 0.1795*Sa + 0.3957*θ_s + 0.1345*BD Also include equations that require geometric mean of the soil particle diameter		
(5) Soil texture (Sa, Si, Cl)			
Meng et al. (1987)	*Meng et al. (1987) found in Medeiros et al. (2014):* w_{-33kPa} ($kg\ kg^{-1}$) = -0.0044 + 0.0082*Cl/100 $w_{-1500kPa}$ ($kg\ kg^{-1}$) = -0.0028 + 0.0038*Cl/100	*The PTFs in Medeiros et al. (2014):* Clay: Cl ($g\ kg^{-1}$)	- Original document cannot be accessed - Semiarud sandy soils
Mohamed and Ali (2006)	*Original PTFs:* $\theta_{SAT\ kPa}$ (%) = 0.6658*Si + 0.1567*Sa - 0.0079*Si^2 - 12.31121/(Sa) - 6.4756*Ln(Sa) - 0.0038*Cl*Si + 0.0038*Cl*Sa - 0.0042*Si*Sa + 52.7526 $\theta_{FC\ kPa}$ (%) = 118.932*Cl + 119.0866*Si + 119.1104*Sa + 162.31731/(Cl) - 46.21921/(Si) -5.12991/(Sa) + 18.1733*Ln(Cl) + 0.0013*Cl*Si + 0.0022*Si*Sa - 11939.3493 $\theta_{PWP\ kPa}$ (%) = -1.5722*Si - 0.5423*Sa - 0.0072*Cl^2+ 0.0072*Si^2 - 0.0059*Sa^{*2} + 160.14591/(Cl) + 6.60011/(Sa) + 0.0022*Cl*Si - 0.0039*Cl*Sa + 92.3851	*Original PTFs:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) BD: Bulk density ($Mg\ m^{-3}$)	- Original document link - 147 soil samples containing contains Cambisols, Vertisols, Calcisols and Fluvisols mainly from the Ariana plain with some from Mornag, Tunisia. 109 samples were used to develop PTFs. - Texture fractions defined by USDA system: Sand (0.75-87.51%), Silt (1-68%), Clay (1-68%), OM (0.2-3.2 %), BD (1.23-1.79 g cm^{-3}) - 23 citations from Google Scholar (accessed on 30 Aug 2020)

SMRC parameters – Van Genuchten model
(Jack et al., 2008)

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

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

S_e: the effective saturation
$\theta(h)$: the relationship between volumetric soil moisture content and pressure head
θ_s: the saturated moisture content
θ_r: the residual moisture content
m, n: the empirical shape-defining parameters in the van Genuchten model

(4) Soil texture (Sa, Si, Cl); BD

Dashtaki et al. (2010)	*Original PTFs:* θ_r ($cm^3\ cm^{-3}$) = 0.03 + 0.0032*Cl θ_s ($cm^3\ cm^{-3}$) = 0.85 – 0.00061*Sa – 0.258*BD α* = −476 – 4.1*Sa + 499*BD n = 1.56 – 0.00228*Sa α* = 1/ α Also include equations that require geometric mean and geometric standard deviation of the soil particle diameter	*Original PTFs:* Sand: Sa (%) Clay: Cl (%) Bulk density: BD (g cm^{-3})	- Original document link - 234 soil samples of top 30 cm of soil groups from the Karaj and Naghade Plains Iran - Main characteristics of PTF developing dataset: Clay (10-50%), Silt (15-55%), Sand (6-71%), BD (1.2-1.83 g cm^{-3}) - 64 citations from Google Scholar (accessed on 10 Aug 2020)

Table B1.9 PTFs for estimating saturated hydraulic conductivity and hydraulic conductivity curve developed for temperate climate

Equation name	Equation	Input	Description
Ksat			
(1) Effective porosity			
Forrest et al. (1985)	*Forrest et al. (1985) PTF found in Minasny and McBratney (2000):* ln K_{sat} (mm hr^{-1}) = 10.8731 + 3.914*ln ϕ_e *Forrest et al. (1985) PTF found in M Abdelbaki et al. (2009)* K_{sat} (cm hr^{-1}) = 0.1*Exp (10.8731 + 3.914*ln ϕ_e)	*PTF in Minasny and McBratney (2000) and M Abdelbaki et al. (2009):* ϕ_e: Effective porosity	- Original document link (cannot find equation in the original document) - Soil samples in Australia - 56 citations from Google Scholar (accessed on 10 Aug 2020)
Culley et al. (1987)	*Culley et al. (1987) PTF found in Chen et al. (1998):* K_{sat} (mm hr^{-1}) = 4149*$\phi_e^{2.63}$ (R^2 = 0.52, for mold-board plow) K_{sat} (mm hr^{-1}) = 525*$\phi_e^{1.09}$ (R^2 = 0.52, for mold-board plow)	*PTF in Chen et al. (1998):* ϕ_e: Effective porosity	- Original document link - Clay loam soils in the U.S. Corn Belt - 73 citations from Google Scholar (accessed on 16 Aug 2021)
Ahuja et al. (1989)*	*Original PTF:* K_{sat} (cm hr^{-1}) = 764.5*$\phi_e^{3.288}$ *Ahuja et al. (1989) PTF found in Lebron et al. (1999):* K_{sat} (cm day^{-1}) =B*ϕ_e^m K_{sat} (cm day^{-1}) = 18,350*$\phi_e^{3.288}$ ϕ_e ($cm^3\ cm^{-3}$) = θ_{Sat} – θ_{FC} Converted equations:	*Original PTF:* ϕ_e: Effective porosity B and m are coefficients depending on the calibrwostation data B: depending on soil type	- Original document link (page 410) - 473 soil samples from Southern USA - Modified Kozeny-Carmane equation - The model was applicable to a wide range of soils from the Southern Region of the USA, Hawaii and Arizona (Timlin et al., 1999) - The PTF was used in ROSETTA model - 256 citations from Google Scholar (accessed on 10 Aug 2020)

	K_{sat} (mm hr^{-1}) = 7645*$\phi_e^{3.288}$		
Franzmeier (1991)	*Franzmeier (1991) PTF found in Chen et al. (1998):* K_{sat} (mm hr^{-1}) = 18000*$\phi_e^{3.21}$ (R^2 = 0.86)	*PTF in Chen et al. (1998):* ϕ_e: Effective porosity	- Original document link - Alfisols and Mollisols of Indiana, 14 samples - 91 citations from Google Scholar (accessed on 16 Aug 2021)
Rawls et al. (1998)	*Rawls et al. (1998) PTF found in Timlin et al. (1999):* K_{sat} (cm day^{-1}) =B*$\phi_e^{3-\lambda}$ ϕ_e (cm^3 cm^{-3}) = $\theta_{Sat} - \theta_{FC}$	*The PTF in Timlin et al. (1999):* ϕ_e: Effective porosity λ is the pore-size distribution index from the Brooks-Corey equation	- Original document link - The database includes over 900 measurements - Used USDA soil texture classes - Main characteristics of PTF developing database: Clay (3-50%), Sand (4-92%) - 275 citations from Google Scholar (accessed on 10 Aug 2020)
Timlin et al. (1999)	*Original PTFs:* K_{sat} (m s^{-1}) =C_1*$10^{C_2\lambda}$ K_{sat} (m s^{-1}) =C_3*$10^{C_4\lambda}$ *ϕ_e^n ϕ_e (cm^3 cm^{-3}) = $\theta_{Sat} - \theta_{FC}$	*Original PTFs:* ϕ_e: Effective porosity λ is the pore-size distribution index from the Brooks-Corey equation C_1= 6.94*10^{-7} m s^{-1} C_2 = 1.89 C_3 = 2.59*10^{-4} m s^{-1} C_4 = 0.6 n = 2.54	- Original document link - >500 samples data from the Southern Region database by Ahuja et al. (1989) and 5350 soil horizons database by Rawls et al. (1982) - 76 citations from Google Scholar (accessed on 10 Aug 2020)
Minasny and McBratney (2000)*	*Original PTFs:* The power function model of Ahuja et al. (1984) developed*:* K_{sat} (mm hr^{-1}) = 23,190.55* $\phi_e^{3.66}$ Sandy soils: K_{sat} (mm hr^{-1}) = 21088.86*$\phi_e^{3.34}$ Loamy soils: K_{sat} (mm hr^{-1}) = 15744.27*$\phi_e^{3.34}$ Clayey soils: K_{sat} (mm hr^{-1}) = 4303.27*$\phi_e^{3.34}$	*Original PTFs:* ϕ_e: Effective porosity	- Original document link - 462 soil samples in Australia - Main characteristics of PTFs developing dataset: Clay (5-75%), Silt (1-53%), Sand (11-93%), BD (0.57-1.8 Mg m^{-3}) - 76 citations from Google Scholar (accessed on 10 Aug 2020)
Suleiman and Ritchie (2001b)	*Suleiman and Ritchie (2001b)PTF found in M Abdelbaki et al. (2009):* K_{sat} (µm s^{-1}) = 467.5*$\phi_e^{3.15}$	*The PTF in M Abdelbaki et al. (2009):* ϕ_e: Effective porosity	- Original document link - 5350 horizons of 1323 soils from 32 states in US - Main characteristics of the PTFs developing dataset: 5%$\leq$ Sa $\leq$30% if 8% $\leq$Cl $\leq$ 58% and 30% $\leq$ Sa $\leq$ 95% if 5% $\leq$ Cl $\leq$ 60% (Castellini & Iovino, 2019)

			- International soil dataset was used to evaluate the performance of equation: Belgium (sandy to sandy clay), Brazil (sandy), Chile (silty clay loam), Cyprus (silty loam to clay loam), Japan (sand dunes), Madagascar (sandy), Palestine (sandy to sandy loam), Senegal (sandy), Syria (clay loam), and Thailand (clayey) - 79 citations from Google Scholar (accessed on 10 Aug 2020)
Guarracino (2007)	*Original PTF:* K_{sat} (cm day^{-1}) = $4.65 * 10^4 \phi \alpha^2$	*Original PTF:* ϕ porosity α (cm^{-1}): van Genuchten shape parameter	- Original document link - Thousands of soil samples from 42 USA states - 41 citations from Google Scholar (accessed on 10 Aug 2020)
Spychalski et al. (2007)	*Original PTFs:* K_{sat} (µm s^{-1}) = $4031.57*\phi_e^{3.295}$ Boundary condition: $\phi_e > 0.033$ K_{sat} (µm s^{-1}) = $-2.52 + 581.59*\phi_e^{1.5} - 6966.14*\phi_e^{2.5} + 11693.78*\phi_e^{3}$ Boundary condition: $\phi_e > 0.034$ K_{sat} (µm s^{-1})= $-3.51 – 18154.6*\phi_e^{1.5} – 12213.8*\phi_e^{2}\ln\phi_e – 6925.78*\phi_e/\ln\phi_e$ ϕ_e (m^3 m^{-3}) = $\theta_{Sat} – \theta_{FC}$	Original PTFs: ϕ_e (m^3 m^{-3}): Effective porosity	- Original document link - 35 soil samples from USA, consist mainly of sandy loams and loamy sands - Main characteristics of the PTFs developing dataset: PD (1.64-2.66 Mg m^{-3}), BD (1.49-2.0 Mg m^{-3}), 75% of samples Silt content does not exceed 18% - 12 citations from Google Scholar (accessed on 10 Aug 2020)
(2) Soil texture (Sa, Si, Cl) and porosity			
Brakensiek et al. (1984)*	*Brakensiek et al. (1984) PTF found in Tietje and Hennings (1996); Ghanbarian et al. (2016):* K_{sat} (cm day^{-1}) = $24*\exp(19.52348*\phi_t - 8.96847 - 0.028212*Cl + 0.00018107*Sa^2 – 0.0094125*Cl^2 - 8.395215*\phi_t^2 + 0.077718*Sa*\phi_t - 0.00298*Sa^2*\phi_t^2 - 0.019492*Cl^2*\phi_t^2 + 0.0000173*Sa^2*Cl + 0.02733*Cl^2*\phi_t + 0.001434*Sa^2*\phi_t - 0.0000035*Cl^2*Sa)$ *Brakensiek et al. (1984) PTF found in Sobieraj et al. (2001):* K_{sat} (mm hr^{-1}) = $10*\exp(19.52348*\phi_t - 8.96847 - 0.028212*Cl + 0.00018107*Sa^2 – 0.0094125*Cl^2 - 8.395215*\phi_t^2 + 0.077718*Sa*\phi_t - 0.00298*Sa^2*\phi_t^2$ -	*The PTF in Tietje and Hennings (1996):* ϕ_t : porosity (m^3 m^{-3}) (=θ_s) Sa: Sand (%) Cl: Clay (%)	- The original document cannot be found - 107 citations from Google Scholar (accessed on 24 Aug 2020)

	$0.019492*Cl^2*\phi_t^2 + 0.0000173*Sa^2*Cl + 0.02733*Cl^2*\phi_t + 0.001434*Sa^2*\phi_t - 0.0000035*Cl^2*Sa)$ <u>Converted equation used in LUCI_PTFs:</u> K_{sat} (mm hr^{-1}) = $10*exp(19.52348*\phi_t - 8.96847 - 0.028212*Cl + 0.00018107*Sa^2 – 0.0094125*Cl^2 - 8.395215*\phi_t^2 + 0.077718*Sa*\phi_t - 0.00298*Sa^2*\phi_t^2 - 0.019492*Cl^2*\phi_t^2 + 0.0000173*Sa^2*Cl + 0.02733*Cl^2*\phi_t + 0.001434*Sa^2*\phi_t - 0.0000035*Cl^2*Sa)$		
(3) Soil texture (Sa, Si, Cl)			
Cosby et al. (1984)*	*Original PTFs:* $Log_{10}K_{sat}$ (inch hr^{-1}) = $-0.6 + 0.0126*Sa – 0.0064*Cl$ $Log_{10}K_{sat}$ (inch hr^{-1}) = $- 0.884 + 0.0153*Sa$ *Cosby et al. (1984) PTF found in Sobieraj et al. (2001):* K_{sat} (mm hr^{-1}) = $25.4*10^{-0.6 + 0.0126*Sa – 0.0064*Cl}$ <u>Converted equation used in LUCI_PTFs:</u> K_{sat} (mm hr^{-1}) = $25.4*10^{-0.6 + 0.0126*Sa – 0.0064*Cl}$	*Original PTFs:* Sa: Sand (%) Cl: Clay (%)	- <u>Original document link</u> - Data are from Holtan et al. (1968) and Rawls et al. (1976), 1448 soil samples taken from 35 locations in 23 states from USA - Main characteristics of PTFs developing dataset: Sand (6-92%), Silt (5-70%), Clay (3-58%) - The PTFs were used in ROSETTA model and hydraulic properties maps for China Dai et al. (2013) - 1580 citations from Google Scholar (accessed on 10 Aug 2020)
Campbell (1985)	*Campbell (1985) PTF found in Wagner et al. (2001):* K_{sat} (m s^{-1}) = $4*10^{-5}*exp(-6.88*Cl - 3.63*Si - 0.025)$ *Campbell (1985) PTF found in Chen et al. (1998):* K_{sat} (mm hr^{-1}) = $141*exp(-0.069*Cl – 0.037*Si)$	*The PTFs in Wagner et al. (2001) and Chen et al. (1998):* Si: Silt (%) Cl: Clay (%)	- <u>Original document link</u> (equation 6.12a, Chapter 6) - 2116 citations from Google Scholar (accessed on 24 Aug 2020)
Puckett et al. (1985)*	*Original PTFs:* K_{sat}(m s) =$4.36*10^{-5}*exp(-0.1975*Cl)$ *Puckett et al. (1985) PTF found in M Abdelbaki et al. (2009)* K_{sat}(cm hr^{-1}) =$15.696*exp(-0.1975*Cl)$ *Puckett et al. (1985) PTF found in Ghanbarian et al. (2016):* K_{sat}(cm day^{-1})= $376.7*exp(-0.1975*Cl)$ *Puckett et al. (1985) PTF found in Sobieraj et al. (2001):*	*Original PTFs:* Cl: Clay (%)	- <u>Original document link</u> (Page 835) - Soil samples from USA - The PTF was used in SOILPAR2 - 245 citations from Google Scholar (accessed on 10 Aug 2020)

	K_{sat}(mm hr^{-1}) =156.96*exp(-0.1975*Cl) <u>Converted equation used in LUCI_PTFs:</u> K_{sat}(mm hr^{-1}) =156.96*exp(-0.1975*Cl)		
Saxton et al. (1986)*	*Original PTFs:* K_{sat}(m s^{-1}) = 2.778*10^{-6}*(exp(12.012 – 0.0755*Sa + $\frac{-3.895+0.03671*Sa-0.1103*Cl+8.7546*10^{-4}*Cl^2}{0.332-7.251*10^{-4}*Sa+0.1276*log_{10}(Cl)}$) <u>Converted equation used in LUCI_PTFs:</u> K_{sat}(mm hr^{-1}) = 10.0008*(exp(12.012 – 0.0755*Sa + $\frac{-3.895+0.03671*Sa-0.1103*Cl+8.7546*10^{-4}*Cl^2}{0.332-7.251*10^{-4}*Sa+0.1276*log_{10}(Cl)}$)	*Original PTFs:* Sa: Sand (%) Cl: Clay (%)	- Original document link - Soil samples from USA - Textures defined by the USDA system: Clay < 0.002mm < Silt < 0.05 mm < Sand < 2mm - The equations appear quite valid with 5% ≤ % Sand ≤ 30% with 8% ≤ % clay ≤ 58% and 30% ≤ % sand ≤ 95 with 5% ≤ % clay ≤ 60% (Gijsman et al., 2002) - 2200 citations from Google Scholar (accessed on 24 Aug 2020
Campbell and Shiozawa (1994)*	*Campbell and Shiozawa. (1994) PTFs found in Ghanbarian et al. (2016):* K_{sat}(cm day^{-1}) =129.6*exp(-0.07*Si-0.167*Cl) *Campbell and Shiozawa. (1994) PTFs found in Sobieraj et al. (2001):* K_{sat} (mm hr^{-1}) =54*exp(-0.07*Si-0.167*Cl) <u>Converted equation used in LUCI_PTFs:</u> K_{sat} (mm hr^{-1}) =54*exp(-0.07*Si-0.167*Cl)	*The PTFs in Ghanbarian et al. (2016):* Si: Silt (%) Cl: Clay (%)	- The original document cannot be found - 288 citations from Google Scholar (accessed on 10 Aug 2020)
Dane and Puckett (1994)	*Dane and Puckett (1994) PTF found in M Abdelbaki et al. (2009):* K_{sat}(cm hr^{-1}) = 30.384 exp(-0.144*Cl) *Dane and Puckett (1994) PTF found in Ghanbarian et al. (2016):* K_{sat}(cm day^{-1}) = 729.22 exp(-0.144*Cl) *Dane and Puckett (1994) PTF found in Sobieraj et al. (2001):* K_{sat}(mm hr^{-1}) = 303.84 exp(-0.144*Cl)	*The PTF in M Abdelbaki et al. (2009) and Ghanbarian et al. (2016):* Cl: Clay (%)	- The online version is not available, accessed through the Victoria university library - Soil samples from USA - Dane and Puckett (1994) has the best performance for sandy soils for Australia Soil by Minasny and McBratney (2000) - 81 citations from Google Scholar (accessed on 10 Aug 2020)
Ferrer Julià et al. (2004)*	*Original PTF:* K_{sat} (mm hr^{-1}) = 0.920*exp(0.0491*Sa) (R^{2} = 0.696)	*Original PTF:* Sa: Sand (%)	- Original document link - The paper included equations for different soil types (FAO classification)

			- 3172 soil samples from Spain, the study area covers 500,000 km^2. The database developed by Trueba et al. (2000) - Main characteristics of the PTF developing dataset: Sand (Mean 34.1-88.0%), Clay (Mean 5 – 38.2%), OM (Mean 0.7 – 7.2%) - 87 citations from Google Scholar (accessed on 10 Aug 2020)
(4) Soil texture (Sa, Si, Cl) and BD			
Naney et al. (1983)	*Naney et al. (1983) PTF found in Chen et al. (1998):* K_{sat} (mm hr^{-1}) = 4590*$BD^{-22.27}$	*The PTFs in Chen et al. (1998):* BD: Bulk density (Mg m^{-3})	- 50 data points - 7 citations from Google Scholar (accessed on 16 Aug 2021)
Campbell (1985)	*Campbell (1985) PTF found in Chen et al. (1998):* K_{sat} (mm hr^{-1}) = 141*$(1.3/BD)^{\lambda}$ *exp(-0.069*Cl – 0.037*Si)	*The PTFs in Chen et al. (1998):* Si: Silt (%) Cl: Clay (%) λ: pore size distribution obtained from the soil moisture characteristic curve ranging from 2-24 for typical soils BD: Bulk density (Mg m^{-3})	- Original document link - 2116 citations from Google Scholar (accessed on 24 Aug 2020)
Kenny and Saxton (1988)	*Kenny and Saxton (1988) PTF found in Chen et al. (1998):* K_{sat} (mm hr^{-1}) = 42*$BD^{-10.2}$	*The PTFs in Chen et al. (1998):* BD: Bulk density (Mg m^{-3})	- Original document link - 3 citations from Google Scholar (accessed on 16 Aug 2021)
Chen et al. (1998)	*Original PTF:* K_{sat} (mm hr^{-1}) = 611.27 – 328.15*BD – 2.17*Si (N = 109, R = 0.50) K_{sat} (mm hr^{-1}) = 214.86*$BD^{-5.324}$ (N = 76, R = 0.50)	*Original PTF:* Si: Silt (%) BD: Bulk density (Mg m^{-3})	- Original document link - A databased was compiled from 27 published studies for model development, field measurement were taken in 18 fields on 10 Quebec farms - Main characteristics of the PTF developing dataset: Sand (8 – 83%), Silt (9 – 73%), Clay (6 – 54%), OM (0.2 – 7%), all data were 0 – 300mm depth - 14 citations from Google Scholar (accessed on 16 Aug 2021)
Jabro (1992)*	*Original PTF:* Log(K_{sat}) (cm hr^{-1}) = 9.56-0.81*log(Si) -1.09*log(Cl) – 4.64*BD *Jabro (1992) PTF found in Sobieraj et al. (2001)*	*Original PTF:* Sa: Sand (%) Si: Silt (%) Cl: Clay (%) BD: Bulk density (g cm^{-3})	- The original document cannot be found, accessed through the Victoria university library - 350 samples of varying particle size distribution, BD and saturated hydraulic conductivity from Southern Cooperation Series Bulletins, Alabama, United State.

	$\log(K_{sat})$ (cm hr^{-1}) = 9.56-0.81*log(Si) -1.09*log(Cl) – 4.64*BD <u>Converted equation used in LUCI_PTFs:</u> K_{sat} (mm hr^{-1}) = $10^{(9.56-0.81*\log(Si) -1.09*\log(Cl) – 4.64*BD)}*10$		- Main characteristics of the PTF developing dataset: Sand (17 – 96%), Silt (0.2 – 52%), Clay (1 – 44%), Bulk density (1.26 – 1.97 g cm^{-3}) - The PTF was used in SOILPAR2 - 222 citations from Google Scholar (accessed on 24 Aug 2020)
Qiao et al. (2018)	*Original PTF:* K_{sat} (cm min^{-1}) = −1.523 + 1.685*BD^{-1} + 0.0004*Sa + 0.996*lnBD	*Original PTF:* The paper did not mention unit of Sand, Silt, Clay, BD and OC	- Original equation link - Lack equation for θ_r - 206 soil samples in Loess Plateau, China, continental monsoon climate region - 2 citations from Google Scholar (accessed on 10 Aug 2020)
(5) Soil texture (Sa, Si, Cl) and OC/OM			
Chen et al. (1998)	*Original PTF specific for tillage effect:* No-tillage K_{sat} (mm hr^{-1}) = - 50.85 + 41.79*OM (N = 20, R = 0.56) Moldboard plowing K_{sat} (mm hr^{-1}) = 1020.07 – 5.84*Si – 517.54*BD (N = 40, R = 0.66)	*Original PTF:* OM: Organic matter (%) Si: Silt (%) BD: Bulk density (Mg m^{-3})	- Original document link - A databased was compiled from 27 published studies for model development, field measurement were taken in 18 fields on 10 Quebec farms - Main characteristics of the PTF developing dataset: Sand (8 – 83%), Silt (9 – 73%), Clay (6 – 54%), OM (0.2 – 7%), all data were 0 – 300mm depth - 14 citations from Google Scholar (accessed on 16 Aug 2021)
Ferrer Julià et al. (2004)*	*Original PTF:* K_{sat} (mm hr^{-1})= $0.920*e^{0.0491*Sa}$ K_{sat} (mm hr^{-1})= -4.994 + 0.56728*Sa – 0.131*Cl-0.0127*OM (R^2 = 0.715)	*Original PTF:* Sa: Sand (%) Si: Silt (%) OM: Organic matter (%)	- Original document link - The paper included equations for different soil types (FAO classification) - 3172 soil samples from Spain, the study area covers 500,000 km^2. The database developed by Trueba et al. (2000) - Main characteristics of the PTF developing dataset: Sand (Mean 34.1-88.0%), Clay (Mean 5 – 38.2%), OM (Mean 0.7 – 7.2%) - 87 citations from Google Scholar (accessed on 10 Aug 2020)
Saxton and Rawls (2006)*	*Original PTF:* $K_{sat}(\text{mm h}^{-1}) = 1930(\theta_s - \theta_{33})^{3-\lambda}$ θ_s, θ_{33}, λ and = f (Sa, Cl, OM)	*Original PTF:* Sand: Sa (%w, decimal percent by weight basis) Clay: Cl (%w) Organic matter: OM (%)	- Original document link - Objective: update the Saxton et al. (1986) - Equations are similar to those previously reported by Saxton et al. (1986) but include more variables and application range

	θ_{33} (% v) = θ_{33t} + (1.283 * $(\theta_{33t})^2$ – 0.374*θ_{33t} - 0.015) θ_{33t} (% v) = -0.251*Sa + 0.195*Cl + 0.011*OM + 0.006*(Sa*OM) - 0.027 *(Cl*OM) + 0.452*(Sa*Cl) + 0.299 θ_s (% v) = θ_{33} + θ_{s-33} -0.097*Sa+0.043 θ_{s-33} (% v) = $\theta_{(s-33)t}$ + (0.636*$\theta_{(s-33)t}$ - 0.107) $\theta_{(s-33)t}$ (% v) =0.278*Sa+0.034*Cl+0.022*OM-0.018(Sa*OM)-0.027(Cl*OM) – 0.584(Sa*Cl) + 0.078 θ_{1500} (% v) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (% v) = -0.024*Sa + 0.487*Cl + 0.006*OM + 0.005*(Sa*OM) - 0.013*(Cl*OM) + 0.068*(Sa*Cl) + 0.031 $\lambda = 1/B$ B=[ln(1500)- ln(33)]/[ln(θ_{33}) - ln(θ_{1500}) θ_{1500} (% v) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (% v) = -0.024*Sa + 0.487*Cl + 0.006*OM + 0.005*(Sa*OM) - 0.013*(Cl*OM) + 0.068*(Sa*Cl) + 0.031 Converted equation used in LUCI_PTFs: θ_{33} (cm^3cm^{-3}) = 1.283 * $(\theta_{33t})^2$ + 0.626*θ_{33t} - 0.015 θ_{33t} (cm^3cm^{-3}) = -0.00251*Sa + 0.00195*Cl + 0.00011*OM + 0.0000006*(Sa*OM) - 0.0000027 *(Cl*OM) + 0.0000452*(Sa*Cl) + 0.299 θ_{1500} (cm^3cm^{-3}) = θ_{1500t} + (0.14*θ_{1500t} - 0.02) θ_{1500t} (cm^3cm^{-3}) = -0.00024*Sa + 0.00487*Cl + 0.00006*OM + 0.0000005*(Sa*OM) - 0.0000013*(Cl*OM) + 0.0000068*(Sa*Cl) + 0.031 θ_s (cm^3cm^{-3}) = θ_{33} + θ_{s-33} -0.00097*Sa+0.043 θ_{s-33} (cm^3cm^{-3}) = $\theta_{(s-33)t}$ + (0.636*$\theta_{(s-33)t}$ - 0.107) $\theta_{(s-33)t}$ (cm^3cm^{-3})=0.00278*Sa+0.00034*Cl+0.00022*OM-0.0000018(Sa*OM)-0.0000027(Cl*OM) – 0.0000584(Sa*Cl) + 0.078	θ (% v): decimal percent by volume basis	- 4000 soil water characteristics (2000 A-horizon and 2000 B-C horizon samples) was used to derive the PTFs obtained from the USDA/NRCS National Soil Characterization database - Main characteristics of the PTFs development dataset: Cl<60% (w) and OM < 8% (w), BD (1-1.8 g cm^{-3}) - Equations were used in Soil Water Characteristic tool (SPAW model) - Equations were used in tropical regions: Vietnam by Nguyen et al. (2015) - 1920 citations from Google Scholar (accessed on 10 Aug 2020)
(6) Soil texture (Sa, Si, Cl), BD and OC/OM			
Vereecken et al. (1990)*	*Vereecken et al. (1990) PTF found in Tietje and Hennings (1996)*	Sa: Sand (%) Si: Silt (%) Cl: Clay (%) OM: Organic matter (%) BD: Bulk density (g cm^{-3})	- Original document link (accessed through the Victoria university library) - 127 soil cores from Belgium - The PTF is applicable with Cl < 54.5%, Si <80.7%, 5.6 < Sa < 97.8% OC <6.6% and 1.04 < BD 1.23 g cm^{-3}

	K_{sat} (cm day^{-1}) = exp (20.62 - 0.96*ln(Cl)-0.66*ln(Sa)-0.46*ln(OM)-8.43*BD) *Vereecken et al. (1990) PTF found in Wagner et al. (2001)* K_{sat} (m s^{-1}) = 1.15741*10^{-7}*exp (20.62 - 0.96*ln(Cl)-0.66*ln(Sa)-0.46*ln(OM)-8.43*BD) *Vereecken et al. (1990) PTF found in M Abdelbaki et al. (2009)* K_{sat} (cm hr^{-1}) = 0.04167*exp (20.62 - 0.96*ln(Cl)-0.66*ln(Sa)-0.46*ln(OM)-8.43*BD) <u>Converted equation used in LUCI_PTFs</u>***:*** K_{sat} (mm hr^{-1}) = 10/24*exp(20.62 - 0.96*ln(Cl)-0.66*ln(Sa)-0.46*ln(OM)-8.43*BD)		- 331 citations from Google Scholar (accessed on 24 Aug 2020)
Wösten (1997)	*Wösten (1997) PTFs found in Wagner et al. (2001):* Sandy soil K_{sat} (m s^{-1}) = 1.15741*10^{-7}*exp(9.5 – 1.47*BD^2 – 0.688*OM + 0.0369 *OM^2 – 0.332*ln(Cl*Si)) Loamy and clayey soil: K_{sat} (m s^{-1}) = 1.15741*10^{-7}* exp(-43.1+ 64.8*BD – 22.21*BD^2 +7.02*OM – 0.1562 *OM^2 + 0.985lnOM - 0.01332*Cl*OM – 4.71*BD.OM)	*The PTFs in Wagner et al. (2001):* Sa: Sand (%) Si: Silt (%) Cl: Clay (%) OM: Organic matter (%) BD: Bulk density (g cm^{-3})	- Online version is not available, accessed through VUW library inter-loan service - Data mainly from the Netherlands, also used in Wösten et al. (1990) - 139 citations from Google Scholar (accessed on 24 Aug 2020)
Wösten et al. (1999)*	*Original PTF:* K_{sat} (cm day^{-1}) = exp(7.755 + 0.0352*Si + 0.93*topsoil - 0.976*BD^2- 0.000484*Cl^2 – 0.000322*Si^2 + 0.001*Si^{-1}- 0.0748* OM^{-1} – 0.643*lnSi – 0.0139 *BD*Cl – 0.167*BD*OM + 0.0298*topsoil*Cl-0.03305*topsoil*Si) top soil=1 for top soil, = 0 for subsoil <u>Converted equation used in LUCI_PTFs:</u> K_{sat} (mm hr^{-1}) = 10/24*exp(7.755 + 0.0352*Si + 0.93*1 - 0.976*BD^2- 0.000484*Cl^2 – 0.000322*Si^2 + 0.001*Si^{-1}-	*Original PTF:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (unit is not clear in the original equation)	- Original document link - European soil - Using HYPRES database of 4040 horizons (the Netherlands, Spain, France, England, Scotland, Denmark, Italy, Greece, Portugal, Belgium, Sweden, Northern Ireland, Slovakia) - Texture classes used to classify the available data: Topsoil (Coarse) Clay<18% and Sand> 65%; Topsoil (Medium) 18%<Clay<35% and 15%<Sand or Clay<18% and 15%<sand<65%; Topsoil (Medium fine) Clay <35% and Sand <15%; Topsoil (Fine) 35% <Clay<60%; Topsoil (Very fine) 60%< Clay

	$0.0748*OM^{-1} – 0.643*\ln Si – 0.0139 *BD*Cl – 0.167*BD*OM + 0.0298*1*Cl-0.03305*1*Si)$		- The PTF was used in arid region (Mohawesh, 2013) - 1088 citations from Google Scholar (accessed on 10 Aug 2020)
Wösten et al. (2001)	*Wösten et al. (2001)PTFs found in Nemes et al. (2005):* K_{sat} (cm day^{-1}) $= Exp(45.8-14.34*BD+0.001481*Si^2 – 27.5BD^{-1}-0.891 \ln(Si)-0.34\ln(OM))$ K_{sat} (cm day^{-1}) $= Exp(-42.6 + 8.71*OM + 61.9*BD – 20.79*BD^2 – 0.2107*OM^2-0.0162*Cl*OM-5.382*BD*OM)$	The PTFs in Nemes et al. (2005): Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) BD: Bulk density (g cm^{-3})	- Original document link (in Dutch) - Soil samples from the Netherlands - 172 citations from Google Scholar (accessed on 24 Aug 2020)
Nemes et al. (2005)	*Original PTF:* K_{sat} (cm day^{-1}) $= 10^{0.571+0.956z_4}$ $z_4 = 0.102 + 1.383z_3 + 0.302z_3^2 + 0.103z_3^3 + 0.331x_2 + 0.693z_3x^2 + 0.541z_3^2x_2 + 0.198x_2^2 + 0.429z_3x_2^2 + 0.092x_2^3 + 0.060x_3 + 0.277z_3x_3 + 0.417z_3^2x_3 + 0.242x_2x_3 + 0.929z_3x_2x_3 + 0.319x_2^2x_3 + 0.026x_3^2 + 0.094z_3x_3^2 + 0.116x_2x_3^2$ $x_1 = -3.663 + 0.046*Sa$ $x_2 = -0.887 + 0.083*Cl$ $x_3 = -9.699 + 6.451*BD$ $x_4 = -0.807 + 1.263*OM$ $z_1 = -0.428 + 0.998x_1 + 0.651x_1^2 + 0.130x_1^3$ $z_2 = 0.506x_1 - 0.188x_2 - 0.327x_3 - 0.094x_4$ $z3 = -0.268 + 0.885z_1 + 0.544z_1^2 - 0.682z_1^3 + 0.320z_2 - 0.134z_1z_2 +1.119z_1^2z_2 + 0.050z_2^2 - 0.645z_1z_2^2 + 0.160z_2^3 + 0.126x_4 - 0.144z_1x_4$ _- $0.372z_1^2x_4 + 0.247z_2x_4 + 0.795z_1z_2x_4 - 0.344z_2^2x_4 + 0.038x_4^2 - 0.071z_1x_4^2 + 0.020z_2x_4^2 - 0.015x_4{}^3$	*Original PTF:* Sand: Sa (%) Clay: Cl (%) Organic matter: OM (%) BD: Bulk density (g cm^{-3})	- Original document link - Data originating from the U.S (Rawls et al. (1998), N = 886)., Hungary (HUNSODA, N=131), and the European (HYPRES database, N = 1108) - Main characteristics of PTFs developing datasets: Sand (0.2-100%), Silt (0-82.4%), Clay (0-83.5%), BD (0.15-1.91 g cm^{-3}), OM (0.09-7.89%) - 127 citations from Google Scholar (accessed on 10 Aug 2020)
Li et al. (2007)	*Original PTF:* $\ln(K_s)$ (cm day^{-1}) $= 13.262 − 1.914*\ln(Sa) −0.974*\ln(Si) − 0.058*Cl −1.709*\ln(OM) +2.885*OM− 8.026 *\ln(BD)$	*Original PTF:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk density: BD (g cm^{-3})	- Original documentation link - 64 soil water retention curves from Fengqiu County in the North China Plain. Fengqiu County soils are mainly classified as two types: Ochric Aquic Cambisol and Ustic Sandic Entisol according to the Chinese Soil Taxonomy System - Main characteristics of the PTFs developing dataset: OM (0.13 – 0.96%), BD (1.38 -1.47 g cm^{-3}) - 79 citations from Google Scholar (accessed on 10 Aug 2020)

Weynants et al. (2009)*	*Original PTF:* K_{sat} (cm day^{-1})= Exp(1.9582+0.0308*Sa-0.6142*BD-0.1566*OC)	*Original PTF:* Sa: Sand (%) Si: Silt (%) Cl: Clay (%) OC: Organic carbon (g kg^{-1}) BD: Bulk density (g cm^{-3})	- Original document link - 182 horizons, total 39 soil profiles from Belgium - Main characteristics of the PTFs developing dataset: Sand (7.37-96.1%), Clay (3.9-42.7%), BD (1.28-1.59 g cm^{-3}), OC (1.4 – 60.8 g kg^{-1}) - 141 citations from Google Scholar (accessed on 10 Aug 2020)
Merdun (2010)	*Original PTFs:* Multiple-linear regression K_{sat} (cm day^{-1})= 9509 – 14437*Si – 8169*BD – 860.1*OM + 2332*Si^2 + 1620*BD^2 + 9.113*OM^2 + 7547*Si*BD + 985.1*Si*OM + 985.1*Si*OM + 381.4*BD*OM Seemingly unrelated regression K_{sat} (cm day^{-1})= 8777.937 – 12556.9*Si – 7849.05*BD – 728.977*OM + 2100.454*Si^2 + 1666.815*BD^2 + 6.799714*OM^2 + 6597.45*Si*BD + 736.1490*Si*OM + 371.5434*BD*OM	*Original PTFs:* Sand: Sa, fraction (kg kg^{-1}) Silt: Si, fraction (kg kg^{-1}) Clay: Cl, fraction (kg kg^{-1}) Bulk density: BD (g cm^{-3}) OM	- Original equation link - 135 samples from UNSODA database for PTFs development - Main characteristics of the PTFs developing dataset: 0.019 kg kg^{-1} <Sand < 0.958 kg kg^{-1}; 0.024 kg kg^{-1} <Silt< 0.799 kg kg^{-1}; 0.01 kg kg^{-1} <Clay< 0.581 kg kg^{-1}; BD (0.71 – 1.73 g cm^{-3}) - 13 citations from Google Scholar (accessed on 10 Aug 2020)
(7) Soil texture (Sa, Si, Cl); BD; OM/OC and other properties			
Rawls and Brakensiek (1985)	*Rawls and Brakensiek (1985) found in Carsel and Parrish* (1988) ln (K_{sat}) (cm hr^{-1})= - 8.96847 – 0.028212*Cl + 19.52348*θ_s + 0.00018107*Sa^2 – 0.0094125*Cl^2 – 8.395215*θ_s^2 + 0.077718*Sa*θ_s + 0.0000173*Sa^2*Cl + 0.02733*Cl^2*θ_s + 0.001432*Sa^2*θ_s -0.0000035*Sa*Cl^2 – 0.00298*Sa^2*θ_s^2 – 0.019492*Cl^2*θ_s^2	*Original equations:* Sand: Sa (%) Clay: Cl (%) θ_s: total saturated water content (cm^3 cm^{-3})	- Original document link - PTFs was tested with 95 soil samples (51 silt loams, 10 loams, 12 silty clay, and 22 loamy sands and sands. The PTFs performed well with silt loams agriculture soil - Main characteristics of the PTFs developing dataset: Clay (5-60%); Sand (5-70%) - 640 citations from Google Scholar (accessed on 22 Sep 2020)
Wösten et al. (1995)	*Original PTF for sandy siliceous, mesic soils :* K_s* (cm d^{-1}) =9.5 - 1.471*BD^2 - 0.688*OM + 0.0369*OM^2 - 0.332*In(Cl + Si) (R^2=32%) α* = 146.9 - 0.0832*OM - 0.395*topsoil - 102.1*BD + 22.61*BD^2 - 70.6*BD^{-1} - 1.872 *(Cl+Si)$^{-1}$ - 0.3931*ln(Cl + Si)	*Original PTF:* Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) M50: median sand particle size Bulk Density: BD (unit is not clear in the original equation)	- Original document link - 88 soil profiles (sandy, siliceous, mesic Typic Haplaquod) from the Netherlands - 277 citations from Google Scholar (accessed on 30 Aug 2020)

(8) Particle size distribution information			
Bloemen (1980)	*Original PTF:* K_{sat} (cm day^{-1}) = $0.02*M_d^{1.93}*GSDI^{-0.74}$	*Original PTF:* Md: median particle size distribution (µm), GSDI: grain size distribution index (dimensionless)	- Original document link - Soil data from the Netherlands obtained from literature and from the archives of the Institute for Land and Water Management Research at Wageningen (the Netherlands) - Main characteristics of the PTF developing dataset: Clay (0-57.9%) - 169 citations from Google Scholar (accessed on 24 Aug 2020)
(9) Particle size distribution information and van Genuchten parameters			
Mishra et al. (1989)	*Original PTF:* K_{sat} (cm hr^{-1}) = $\alpha*\theta_s(d_{50})^2$	*Original PTF:* α and θ_s : van Genuchten parameter d_{50} : median particle diameter	- Original document link (equation 8a) - 250 soil samples from Virginia, USA - Main characteristics of PTF developing dataset: Clay (1.9-29/7%), Silt (0.5-54.5%), Sand (2.0-40.3%), BD (1.11 – 1.65 g cm^{-3}) - 182 citations from Google Scholar (accessed on 10 Aug 2020)
(10) van Genuchten parameters			
Mishra and Parker (1990)	*Original PTF:* K_{sat} (cm s^{-1}) = $108*(\theta_s - \theta_r)^{2.5}\alpha^2$	*Original PTF:* θ_r; θ_s, α : van Genuchten parameter	- Original document link (equation 6) - 41 citations from Google Scholar (accessed on 24 Aug 2020)

<table>
<tr><td colspan="4">HCC - Mualem van Genuchten
$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} = \frac{1}{[1 + (\alpha h)^n]^m}$$
$$m = 1 - \frac{1}{n}$$
$$K(S_e) = K_{sat} * S_e^l * \left[1 - \left(1 - S_e^{\frac{1}{m}}\right)^m\right]^2$$
$$K(h) = K_{sat} * \frac{\left[((1 + (\alpha h)^n)^m - (\alpha h)^{(n-1)}\right]^2}{((1 + (\alpha h)^n)^{m*(l+2)}}$$
$$K(\theta) = K_{sat} * \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right)^l * \left[1 - \left(1 - \left(\frac{\theta(h) - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m}}\right)^m\right]^2$$
$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha * h)^n]^m}$$
S_e: relative saturation
$\theta(h)$: the relationship between volumetric soil moisture content and pressure head
θ_s: the saturated moisture content
θ_r: the residual moisture content
m, n: the empirical shape-defining parameters in the van Genuchten model</td></tr>
<tr><td colspan="4">(6) Soil texture (Sa, Si, Cl), BD and OC/OM</td></tr>
<tr><td>Wösten et al. (1999) *</td>
<td>Original PTFs:
K_{sat} (cm day^{-1}) = exp(7.755 + 0.0352*Si + 0.93*topsoil - 0.976*BD^2- 0.000484*Cl^2 – 0.000322*Si^2 + 0.001*Si^{-1}- 0.0748* OM^{-1} – 0.643*lnSi – 0.0139 *BD*Cl – 0.167*BD*OM + 0.0298*topsoil*Cl-0.03305*topsoil*Si)

top soil=1 for top soil, = 0 for subsoil

<u>Converted equation used in LUCI_PTFs:</u>
K_{sat} (mm hr^{-1}) = 10/24*exp(7.755 + 0.0352*Si + 0.93*1 - 0.976*BD^2- 0.000484*Cl^2 – 0.000322*Si^2 + 0.001*Si^{-1}-</td>
<td>Original PTFs:
Sand: Sa (%)
Silt: Si (%)
Clay: Cl (%)
Organic matter: OM (%)
Bulk Density: BD (unit is not clear in the original equation)</td>
<td>- Original document link
- European soil
- Using HYPRES database of 4030 horizons (the Netherlands, Spain, France, England, Scotland, Denmark, Italy, Greece, Portugal, Belgium, Sweden, Northern Ireland, Slovakia)
- Texture classes used to classify the available data: Topsoil (Coarse) Clay<18% and Sand> 65%; Topsoil (Medium) 18%<Clay<35% and 15%<Sand or Clay<18% and 15%<sand<65%; Topsoil (Medium fine) Clay <35% and Sand <15%; Topsoil (Fine) 35% <Clay<60%; Topsoil (Very fine) 60%< Clay</td></tr>
</table>

	0.0748* OM^{-1} – 0.643*lnSi – 0.0139 *BD*Cl – 0.167*BD*OM + 0.0298*1*Cl-0.03305*1*Si) θ_s(cm^3cm^{-3}) = 0.7919 + 0.001691*Cl – 0.29619*BD – 0.000001491*Si^2 + 0.0000821*OM^2 + 0.02427*Cl^{-1} + 0.01113*Si^{-1} + 0.01472*ln(Si) – 0.0000733*OM*Cl-0.000619*BD*Cl – 0.001183*BD*OM-0.0001664*topsoil*Si $\theta_r(cm^3cm^{-3}) = \begin{cases} 0.025, & Cl < 18\% \text{ and } Sa > 65\% \\ 0.01 & otherwise \end{cases}$ (Information in Table 4) α= exp (-14.96 + 0.03135*Cl + 0.0351*Si + 0.646*OM + 15.29*BD – 0.192*top soil – 4.671*BD^2 – 0.000781*Cl^2 – 0.00687*OM^2 + 0.0449*OM^{-1} + 0.0663*ln(Si) + 0.1482*ln(OM) – 0.04546*BD*Si – 0.4852*BD*OM + 0.00673*topsoil*Cl) n = exp (-25.23 – 0.02195*Cl + 0.0074*Si – 0.1940*OM + 45.5*BD – 7.24*BD^2 + 0.0003658*Cl^2 + 0.002885*OM^2 - 12.81*BD^{-1}- 0.1524*Si^{-1}- 0.01958*OM^{-1} – 0.2876*ln(Si) – 0.0709*ln(OM) – 44.6*ln(BD) – 0.02264*BD*Cl + 0.0896*BD*OM + 0.00718*topsoil*Cl) + 1 m = 1 – 1/n l* = 0.0202 + 0.0006193*Cl^2 – 0.001136*OM^2 – 0.2316*ln(OM) – 0.03544*BD*Cl + 0.00283*BD*Si + 0.0488*BD*OM l* = ln((l+10)/(10-l)) top soil=1 for top soil, = 0 for subsoil		- The equations were used in semi-arid region (Wösten et al., 2013) - 1088 citations from Google Scholar (accessed on 10 Aug 2020)
Weynants et al. (2009)*	*Original PTFs:* K_{sat} (cm day^{-1}) = 10/24*exp(1.9582+0.0308*Sa-0.6142*BD-0.1566*OC) <u>Converted equation used in LUCI_PTFs:</u> K_{sat} (mm hr^{-1}) = exp(1.9582+0.0308*Sa-0.6142*BD-0.1566*OC)	Sa: Sand (%) Si: Silt (%) Cl: Clay (%) OC: Organic carbon (g kg^{-1}) BD: Bulk density (g cm^{-3})	- Original document link - 182 horizons, total 39 soil profiles from Belgium - Main characteristics of the PTFs developing dataset: Sand (7.37-96.1%), Clay (3.9-42.7%), BD (1.28-1.59 g cm^{-3}), OC (1.4 – 60.8 g kg^{-1}) - 141 citations from Google Scholar (accessed on 10 Aug 2020)

	θ_r (m^3 m^{-3}) = 0 θ_s (m^3 m^{-3}) = 0.6355 + 0.0013*Cl – 0.1631*BD α* = -4.3003 – 0.0097*Cl + 0.0138*Sa – 0.0992*OC n* = -1.0846-0.0236*Cl-0.0085*Sa+0.0001*Sa^2 α* = lnα, n* = ln(n – 1) l = - 1.8642 – 0.1317*Cl + 0.0067*Sa		
Merdun (2010)	*Original PTFs:* Multiple-linear regression: K_{sat} (cm day^{-1})= 9509 – 14437*Si – 8169*BD – 860.1*OM + 2332*Si^2 + 1620*BD^2 + 9.113*OM^2 + 7547*Si*BD + 985.1*Si*OM + 985.1*Si*OM + 381.4*BD*OM -ln(θ_r) (cm^3cm^{-3}) = - 31.61 +40.78*Si + 53.34*Cl + 36.52*BD – 15.66*Si^2 – 30.20*Cl^2 – 8.92*BD^2 + 0.843*Si*Cl – 17.83*Si*BD – 24.50*Cl*BD θ_s (cm^3cm^{-3}) = 1.391 – 0.289*Cl – 1.007*BD – 0.026*OM – 0.096*Cl^2 + 0.22*BD^2 – 0.00039*OM^2 + 0.3*Cl*BD + 0.0233*Cl*OM + 0.0229*BD*OM -ln (α) = 4.647 – 6.425*Sa + 0.795*BD – 0.427*OM + 2.567*Sa^2 – 0.057*BD^2 + 0.0024*OM^2 + 0.943*Sa*BD + 0.456*Sa*OM + 0.0914*BD*OM ln(n) = 0.710 – 1.413*Sa – 2.533*Si – 0.068*BD + 2.263*Sa^2 + 2.807*Si^2 + 0.124*BD^2 + 3.268*Sa*Si – 0.624*Sa*BD – 0.219*Si*BD Seemingly unrelated regression K_{sat} (cm day^{-1})= 8777.937 – 12556.9*Si – 7849.05*BD – 728.977*OM + 2100.454*Si^2 + 1666.815*BD^2 +	*Original PTFs:* Sand: Sa, fraction (kg kg^{-1}) Silt: Si, fraction (kg kg^{-1}) Clay: Cl, fraction (kg kg^{-1}) Bulk density: BD (g cm^{-3}) OM	- Original equation link - 135 samples from UNSODA database for PTFs development - Main characteristics of the PTFs developing dataset: 0.019 kg kg^{-1} <Sand < 0.958 kg kg^{-1}; 0.024 kg kg^{-1} <Silt< 0.799 kg kg^{-1}; 0.01 kg kg^{-1} <Clay< 0.581 kg kg^{-1}; BD (0.71 – 1.73 g cm^{-3}) - 13 citations from Google Scholar (accessed on 10 Aug 2020)

	$6.799714*OM^2 + 6597.45*Si*BD + 736.1490*Si*OM + 371.5434*BD*OM$ $-\ln(\theta_r)$ (cm^3cm^{-3}) $= -33.3305 + 40.28644*Si + 58.57803*Cl + 38.36318*BD – 15.9138*Si^2 – 30.5357*Cl^2 – 90.34917*BD^2 + 1.810918*Si*Cl – 17.4892*Si*BD – 28.3829*Cl*BD$ θ_s (cm^3cm^{-3}) $= 1.419680 – 0.37696*Cl – 1.04082*BD – 0.02362*OM + 0.085484*Cl^2\ 0.230911*BD^2 + 0.000020*OM^2 + 0.322291*Cl*BD + 0.004189*Cl*OM + 0.022525*BD*OM$ $-\ln(\alpha) = -2.03482 – 2.70633*Sa + 8.547309*BD + 0.365279*OM + 2.439804*Sa^2 – 2.28273*BD^2 – 0.00292*OM^2 – 1.115*Sa*BD – 0.06837*Sa*OM – 0.37115*BD*OM$ $\ln(n) = 0.028513 – 0.30159*Sa – 1.52086*Si + 0.433897*BD + 1.699044*Sa^2 + 2.775716*Si^2 + 0.068137*BD^2 + 2.472513*Sa*BD – 0.95821*Sa*BD – 0.83048*Si*BD$		
(7) Soil texture (Sa, Si, Cl); BD; OM/OC and other properties			
Wösten et al. (1995)	*Original PTFs for sandy siliceous, mesic soils:* K_s* ($cm\ d^{-1}$) $=9.5 - 1.471*BD^2 - 0.688*OM + 0.0369*OM^2 - 0.332*In(Cl + Si)$ (R^2=32%) $\alpha^* = 146.9 - 0.0832*OM - 0.395*topsoil - 102.1*BD + 22.61*BD^2 - 70.6*BD^{-1} - 1.872*(Cl+Si)^{-1} - 0.3931*\ln(Cl + Si)$ $n^* = 1092 + 0.0957*(Cl + Si) + 1.336*M50 - 13{,}229*M50^{-1} - 0.001203*M50^2 - 234.6*\ln(M50) - 2.67*BD^{-1} - 0.115*OM^{-1} - 0.4129*\ln(OM) - 0.0721*BD*(Cl + Si)$ $l^* = 0.797 - 0.591*OM + 0.0677*OM^2 + 0.573*subsoil$ θ_s(cm^3cm^{-3}) $= - 13.6- 0.01533*(Cl + Si) + 0.0000836*(Cl + Si)^2 - 0.0973*(Cl + Si)^{-1} + 0.708*BD^{-1} - 0.00703*M50 + 225.3*M50^{-1} + 2.614*\ln(M50) + 0.0084*OM^{-1} +0.02256*1n(OM) +0.00718*BD*(Cl + Si)$	*Original PTFs:* Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) M50: median sand particle size Bulk Density: BD (unit is not clear in the original equation)	- Original document link - 88 soil profiles (sandy, siliceous, mesic Typic Haplaquod) from the Netherlands - 277 citations from Google Scholar (accessed on 30 Aug 2020)

Table B1.10 PTFs for estimating saturated hydraulic conductivity developed for tropical climate

Equation name	Equation	Input	Description
(1) Effective porosity			
Ahuja et al. (1989)*	*Original PTF:* K_{sat} (cm hr^{-1}) = 764.5*$\phi_e^{3.29}$ *Ahuja et al. (1989) PTF found in Lebron et al. (1999):* K_{sat} (cm day^{-1}) =B*ϕ_e^{m} K_{sat} (cm day^{-1}) = 18,350*$\phi_e^{3.288}$ ϕ_e (cm^3 cm^{-3}) = $\theta_s - \theta_{-33kPa}$ Converted equations to use in LUCI_PTFs: K_{sat} (mm hr^{-1}) = 7645*$\phi_e^{3.29}$	*Original PTF:* ϕ_e: Effective porosity B and m are coefficients depending on the calibration data B: depending on soil type,	- Original document link (Page 410) - 473 soil samples from Southern USA - Modified Kozeny-Carmane equation - The model was applicable to a wide range of soils from the Southern Region of the USA, Hawaii and Arizona (Timlin et al., 1999) - The equation was used in ROSETTA model - 256 citations from Google Scholar (accessed on 10 Aug 2020)
Mbagwu (1995)	*Original PTF:* K_{sat} (cm min^{-1}) = 0.07*$e^{0.08*Pe}$ (R^2 = 0.95)	*Original PTF:* Pe: macro-porosity (%)	- Original document link - 18 sites in watershed in a part of the University of Nigeria, Nsukka, Teaching and Research Farm - 54 citations from Google Scholar (accessed on 16 Aug 2021)
Tomasella and Hodnett (1997)	*Original PTF:* K_{sat} (mm hr^{-1}) = 56540*$\phi_e^{4.5359}$	*Original PTF:* ϕ_e.: Effiective porosity (m^3 m^{-3})	- Original document link (Fig.1) - 124 soil samples from 13 sites in Brazil - 61 citations from Google Scholar (accessed on 24 Aug 2020)
Suleiman and Ritchie (2001b)	*Original PTF:* K_{sat} (cm day^{-1}) = 4.09*$\phi_e^{3.63}$	*Original PTF:* ϕ_e: Effective porosity	- Original document link - 5350 horizons of 1323 soils from 32 states in US - Main characteristics of the PTFs developing dataset: 5%≤ Sa ≤30% if 8% ≤Cl ≤ 58% and 30% ≤ Sa ≤ 95% if 5% ≤ Cl ≤ 60% (Castellini & Iovino, 2019) - International soil dataset was used to evaluate the performance of equation: Belgium (sandy to sandy clay), Brazil (sandy), Chile (silty clay loam), Cyprus (silty loam to clay loam), Japan (sand dunes), Madagascar (sandy), Palestine (sandy to sandy loam), Senegal (sandy), Syria (clay loam), and Thailand (clayey)

			- 79 citations from Google Scholar (accessed on 10 Aug 2020)
Ottoni et al. (2019)	*Original PTF:* K_{sat} (cm day^{-1}) = 1,931*$\phi_e^{1.948}$	*Original PTF:* ϕ_e: Effective porosity	- Original document link - 425 soil samples from Brazil and Europe - Main characteristics of the PTFs development dataset: Sand (0.4-100%), Silt (0-81.7%), Clay (0-96%); BD (0.52-1.97 g cm^{-3}) - 9 citations from Google Scholar (accessed on 16 Oct 2020)
(3) Soil texture (Sa, Si, Cl)			
Ottoni et al. (2019)	*Original PTF:* K_{sat} (cm day^{-1}) = $10^{(2.039 - 0.00874*Si - 0.00723*Cl)}$	*Original PTF:* Silt: Si (%) Clay: Cl (%)	- Original document link - 425 soil samples from Brazil and Europe - Main characteristics of the PTFs development dataset: Sand (0.4-100%), Silt (0-81.7%), Clay (0-96%); BD (0.52-1.97 g cm^{-3}) - 9 citations from Google Scholar (accessed on 16 Oct 2020)
(4) Soil texture (Sa, Si, Cl) and BD			
Mbagwu (1995)	*Original PTF:* K_{sat} (cm min^{-1}) = 3.12*BD$^{-6.28}$ (R^2 = -0.884) K_{sat} (cm min^{-1}) = 4.47 – 2.76*BD (R^2 = -0.73)	*Original PTF:* Bulk density: BD (Mg m^{-3})	- Original document link - 18 sites in watershed in a part of the University of Nigeria, Nsukka, Teaching and Research Farm - 54 citations from Google Scholar (accessed on 16 Aug 2021)
Ottoni et al. (2019)	*Original PTF:* K_{sat} (cm day^{-1}) = $10^{(3.998 - 0.0101*Si - 0.0152*Cl - 1.163*BD)}$ K_{sat} (cm day^{-1}) = 1,266 $(0.582 – 0.00216*Si - 0.00232*Cl - 0.203*BD)^{1.853}$	*Original PTF:* Silt: Si (%) Clay: Cl (%) Bulk density: BD (g cm^{-3})	- Original document link - 425 soil samples from Brazil and Europe - Main characteristics of the PTFs development dataset: Sand (0.4-100%), Silt (0-81.7%), Clay (0-96%); BD (0.52-1.97 g cm^{-3}) - 9 citations from Google Scholar (accessed on 16 Oct 2020)
(7) Soil texture (Sa, Si, Cl); BD; OM/OC and other properties			
Shwetha and Prasanna (2018)	*Original PTF:* Sandy loam-agriculture	*Original PTF:* ϕ_t: porosity (cm^3 cm^{-3}) Sand: Sa (%) Silt: Si (%)	- Original document link - Soil samples from the Pavanje River basin in Dakshina Kannada district of coastal Karnataka, India

	K_{sat} (cm hr^{-1}) = 80.16 + 0.81*Sa – 143.57*BD + 21.99*OM + 0.002*Sa^2 – 0.687*Sa*BD – 0.0022*Sa*OM + 63.33*BD^2 – 13.63*BD*OM – 0.219*OM^2 Loamy sand-agriculure K_{sat} (cm hr^{-1}) = – 238.90 – 3.248*Sa – 5.468*Si + 502.7*BD + 0.0042*Sa^2 – 0.0166*S*Si + 1.589*S*BD + 0.0362*Si^2 + 2.057*Si*BD – 206.43*BD^2 Sandy loam-forest K_{sat} (cm hr^{-1}) = – 1.272 – 0.0433*Si + 0.693*OM + 13.04*ϕ_t + 0.0009*Si^2 – 0.0074*Si*OM – 0.091*Si* ϕ_t – 0.0036*OM^2 – 1.128*OM* ϕ_t – 3.204*ϕ_t^2 Loamy sand-forest K_{sat} (cm hr^{-1}) = 271.11 – 9.116*Si + 45.38*OM – 289.13*BD + 0.0809*Si^2 – 0.695*Si*OM + 4.681*Si*BD + 1.991*OM^2 – 25.74*OM*BD + 80.04*BD^2	Clay: Cl (%) Organic matter: OM (%) Bulk density: BD (g cm^{-3})	- Main characteristics of soil samples: Sand (32-89%), Silt (10-52%), Clay - (1-5%), BD (1.22-1.81 g cm^{-3}), OM (0.24 – 7.5%) - 1 citation from Google Scholar (accessed on 24 Aug 2020)

Table B1.11 PTFs for estimating saturated hydraulic conductivity developed for arid climate

Equation name	Equation	Input	Description
(6) Soil texture (Sa, Si, Cl), BD and OC/OM			
Wösten et al. (1999)*	*Original PTF:* K_{sat} (cm day^{-1}) = exp(7.755 + 0.0352*Si + 0.93*topsoil -0.976*BD^2-0.000484*Cl^2 – 0.000322*Si^2 + 0.001*Si^{-1}- 0.0748* OM^{-1} – 0.643*lnSi – 0.0139 *BD*Cl – 0.167*BD*OM + 0.0298*topsoil*Cl-0.03305*topsoil*Si) top soil=1 for top soil, = 0 for subsoil Converted equation used in LUCI_PTFs: K_{sat} (mm hr^{-1}) = 10/24*exp(7.755 + 0.0352*Si + 0.93*1 -0.976*BD^2-0.000484*Cl^2 – 0.000322*Si^2 + 0.001*Si^{-1}- 0.0748* OM^{-1} – 0.643*lnSi – 0.0139 *BD*Cl – 0.167*BD*OM + 0.0298*1*Cl-0.03305*1*Si)	*Original PTF:* Sand: Sa (%) Silt: Si (%) Clay: Cl (%) Organic matter: OM (%) Bulk Density: BD (unit is not clear in the original equation)	- Original document link - European soil - Using HYPRES database of 4040 horizons (the Netherlands, Spain, France, England, Scotland, Denmark, Italy, Greece, Portugal, Belgium, Sweden, Northern Ireland, Slovakia) - Texture classes used to classify the available data: Topsoil (Coarse) Clay<18% and Sand> 65%; Topsoil (Medium) 18%<Clay<35% and 15%<Sand or Clay<18% and 15%<sand<65%; Topsoil (Medium fine) Clay <35% and Sand <15%; Topsoil (Fine) 35% <Clay<60%; Topsoil (Very fine) 60%< Clay - Equations were used in arid region

			- 1088 citations from Google Scholar (accessed on 10 Aug 2020)
(7) Soil texture (Sa, Si, Cl); BD; OM/OC and other properties			
Gamie and De Smedt (2018)	*Original PTF:* $\log_{10} K_{sat}$ (m day^{-1}) = 0.838 − 7.58*θ_{WP} − 0.0124*SAR − 0.0202*Si	*Original PTF:* θ_{WP}: soil moisture at wilting point (m^3 m^{-3}) SAR: sodium adsorption ratio Si: Silt (%)	- Original document link - 144 soil samples from Kharga Oasis, Egypt - Main characteristics of PTF developing dataset: Silt (1.04-45.35%), Clay (1.59-28.65%), OM (0-0.5%), BD (1.138-1.728 g cm^{-3}) - 14 citations from Google Scholar (accessed on 24 Aug 2020)

Infiltration and how infiltration links with hydraulic conductivity

Infiltration is defined as "the flow of water from aboveground into the subsurface" (Ferré & Warrick, 2005). Infiltration rate is defined as "the meters per unit time of water entering into the soil regardless of the types or values of forces" (Kirkham, 2014). Infiltration is a key process in various environmental models including hydrology models, crop models, climate models etc. The infiltration of rain and surface water into soil is influenced by many factors, including soil depth, geomorphology, rainfall intensity etc. (Morbidelli et al., 2018). Infiltration rate therefore varies both spatially and temporally. Therefore, it is difficult and expensive to directly measure infiltration rates at all scales of interest in hydrological models. Infiltration modelling using measurable soil hydraulic parameters is essential for obtaining these infiltration rates. A number of predictive infiltration models were developed to estimate infiltration rates (Tuffour et al., 2018). The four most commonly adopted models in applied hydrology are the Philip model, the Green–Ampt model, the Smith model and the Parlange model (Morbidelli et al., 2018; Tuffour et al., 2019).

In many infiltration models, infiltration rate I(t) is a function of soil hydraulic conductivity (K_{sat}) (Canarache et al., 1968; Komatsu, 2018 ; Tuffour et al., 2018). K_{sat} reflects the soil's ability to transmit water through soil pore spaces, which is closely connected with hydrologic infiltration processes and land cover's properties (Bormann & Klaassen, 2008; Gonzalez-Sosa et al., 2010; Trinh et al., 2018). Infiltration rates plotted over time show that the infiltration curve will eventually flatten and become constant when the soil has reached full saturation (Upstream Technologies, 2021). This constant is $K_{sat.}$ In other word, K_{sat} is the infiltration rate once the ground has reached fully saturation and the infiltration rate has become constant. At saturation, the steady state infiltration capacity I_o controls the infiltration process. Thus, saturated hydraulic conductivity K_{sat} and steady state infiltrability I_o are closely related. In other words, K_{sat} represents the limiting value of infiltration if the soil is saturated and homogenous (Arrington et al., 2013). In fact, K_{sat} can be substituted for I_o in equations for infiltration estimates in Ghana (Tuffour et al., 2018). Similarly, soil water infiltration modelled by I = K_{sat} were close to those modelled by Parlange model under ponding conditions (Dejun & Zhengfu, 2011). Inversely, the steady infiltration rate could sometimes be used to approximate K_{sat} of soil (Bayabil et al., 2019).

Parameters needed for infiltration models can be estimated from readily available and easily measurable soil properties. The following table (Table B1.12) presents how parameters of Green-Ampt and Parlange models can be estimated using soil properties.

Table B1.12 Estimating parameters of Green-Ampt model and Parlange model

Green-Ampt model (Chen et al., 2015; Gillies, 2008)	**Parlange model**
$I(t) = K_{sat}\left[1 + \frac{(\theta_s - \theta_i) * G}{I}\right]$ I(t): infiltrability or infiltration rate K_{sat}: saturated hydraulic conductivity I: infiltrated depth G: net capillary drive parameter θ_s: soil water content at saturation θ_i: initial soil water content	$I(t) = K_{sat}\left[1 + \frac{\sigma}{\exp\left(\frac{\sigma I}{B}\right) - 1}\right]$ $B = (G + h_w)(\theta_s - \theta_i)$ I(t): infiltrability or infiltration rate K_{sat}: saturated hydraulic conductivity I: infiltrated depth σ: Parlange parameter, represents soil type; B: combining the effects of net capillary drive G: net capillary drive parameter h_w: surface water depth θ_s: soil water content at saturation θ_i: initial soil water content

Parameter	**Estimation method**
K_{sat}	Can be estimated using the guidelines tables B1.3, B1.5, B1.9, B1.10 and B1.11
G (cm)	For Brook-Corey model (Talbot & Ogden, 2008; USDA, 2010): $G = h_b \frac{2 + 3\lambda}{1 + 3\lambda}$ λ: Books-Corey pore size distribution index can be estimated using the guidelines in previous sections h_b: Brooks-Cory air entry pressure or bubbling pressure can be estimated using the guidelines in previous sections For van Genuchten model: $G = \frac{0.046m + 2.07m^2 + 19.5\,m^3}{\alpha(1 + 4.7m + 16m^2)}$ m: van Genuchten fitting parameter can be estimated using the guidelines in previous sections
I (cm)	The infiltration process into two stages: (1) the first stage occurs when the rainfall intensity is less than the infiltration capacity of the soil. (2) The second stage when the soil rate is greater than the infiltration capacity of the soil (Bharali, 2019)

	• If $K_{sat} > P$ The *Topo flow model*, *Van den Putte et al. (2013), Walter (2011) and Brevnova (2001)* gave the following guideline: I = P (t) P = precipitation rate (cm/day) • If P >K_{sat} (infiltration depth before water begins to pond at the surface) *Walter (2011)* gave the following guideline: $I = \frac{\lvert G \rvert K_{sat}(\theta_s - \theta_i)}{P - K_{sat}}$ *Xiang et al. (2016)* gave the following guideline: $I = \frac{\lvert G \rvert K_e(\theta_s - \theta_i)}{P/K_e}$ K_e: effective hydraulic conductivity (cm/day) $K_e = \frac{1}{2} K_{sat}$
h_w (cm)	KINEROS set I as 0 however, in VMD water-based crop should have different value based on land use (KINEROS model)
θ_s (cm^3/cm^3)	Can be estimated using the guidelines in previous sections
θ_i (cm^3/cm^3)	• *Mayr and Jarvis (1999) equation:* $\theta_i = \frac{2b\theta_s}{1 + 2b}$ Log (1/b)= -0.8466880654-0.0046806123*%sand+0.0092463819*%silt-0.4542769707BD-0.0497915563*OC+ 0.0003294687*%sand^2 + 0.000001689056*sand^2 + 0.0011225373*OC^2 Mayr and Jarvis (1999) also suggested an equation to estimate pressure head of initial water content $hi = a \left(\frac{2b}{1+2b}\right)^{-b}$ log (a) = -4.9840297533+0.0509226283*%sand + 0.1575152771*%silt+0.1240901644*BD-0.1640033143*OC-0.0021767278*%silt^2+0.0000143822*%silt^3 + 0.000804040715%clay^2 + 0.0044067117*OC^2 • θ_i *can be obtained from the the Soil Water Infiltration Global database (SWIG)* https://doi.pangaea.de/10.1594/PANGAEA.885492
σ (dimension less)	• KINEROS model: σ is near 0 for sand, in which Parlange model approach the Green-Ampt relation σ is near 1 for well-mixed loam, in which Parlange model represent the Smith-Parlange infiltration equation

	σ is near 0.85 for most soils In KINEROS model, value 0.85 is fixed

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Appendix B2

LUCI_PTFs v1.0 help document

1. Purpose of this document

This document combines the information from the LUCI_PTFs v1.0's help text, found within the tool, and step-by-step instructions on how to use the toolbox.

2. Overview

LUCI_PTFs is the open source ArcGIS toolbox associated with the guidelines given in the paper *"Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling"* (Dang et al., 2021). The toolbox provides a wide range of pedotransfer functions (PTFs) options to obtain information on key soil hydraulic properties, e.g. soil moisture content at certain pressures, soil moisture-pressure relationships, saturated hydraulic conductivity, hydraulic conductivity-pressure relationship and water content held between key thresholds. The PTFs included in the toolbox can be used for different climatic regions i.e. temperate, tropical, and arid regions with different level of data availability (some PTFs only require sand/silt/clay or some PTFs require more inputs, e.g. OC/OM, BD, pH). Selected PTFs were based on the number of citations from Google Scholar.

3. Summary of included tools

- 01 Calculate van Genuchten parameters and plot SMRC
- 02 Calculate Brook-Corey parameters and plot SMRC
- 03 Calculate water content using point PTFs
- 04 Calculate saturated hydraulic conductivity (K_{sat})

4. Requirement for application

LUCI_PTFs requires ESRI's ArcGIS 10.4.1 or above to run. The required input file for LUCI_PTFs is a soil map in shapefile format. The attribute table of the input soil map must contain required soil properties for selected PTFs, and a required field named *"LUCIname"* which contains the soils' name/identifier. Required soil properties for different PTFs can be checked using this help document or the supplementary material of the associated paper. It is very important to have the field names and unit of soil properties of the input data correct, as per the instructions given in Table B2.1. For example, if the selected PTFs require bulk density and clay, the attribute table should include the required fields: 'BD' and 'Clay' and the values filled in these fields should be converted to percentage (%).

Table B2.1 Instructions for creating attribute fields for input soil maps

Input	Field name	Unit
Sand content	Sand	%
Silt content	Silt	%
Clay content	Clay	%
Organic matter content	OM	%
Organic carbon content	OC	%
Bulk density	BD	g cm^{-3}
CEC	CEC	cmol kg^{-1}
pH	pH	

<u>*Note for pressure unit:*</u> The word "pressure" used in the toolbox is referring to "matric pressure" therefore a seemingly positive "pressure" in the tool is actually a suction/negative pressure.

5. Setting up LUCI_PTFs on ArcMap

The toolbox has been developed as part of the Land Utilisation and Capability Indicator (LUCI) framework but can also be accessed as a stand-alone toolbox. Installing LUCI_PTFs can be done through LUCItools GitHub or download at https://github.com/lucitools/LUCI_PTFs.

6. '01 Calculate van Genuchten parameters and plot SMRC' tool

6.1 Summary

This tool provides 7 PTFs to estimate van Genuchten model parameters and the soil moisture-pressure relationship. Among the PTFs, Wösten et al., (1999) (topsoil and subsoil) and Weynants et al. (2009) can be used to obtain Mualem van Genuchten model parameters and hydraulic conductivity pressure relationships. To select the PTFs of interest, the user can use the guidelines given in the paper "Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling" (Dang et al., 2021).

6.2 Input

Output folder: Specify the path and folder name where output from this tool should be stored.

Input soil shapefile: Soil shapefile can be polygon or point vector which includes required soil properties of the selected PTFs and a required field named *"LUCIname"* which contains the soils' name/identifier.

PTFs of choice: Select the PTFs of interest from the dropdown list. Details of required input parameters for each PTFs for van Genuchten model is presented in Table B2.2.

Table B2.2 PTFs for van Genuchten model supported in LUCI_PTFs and required soil properties input

PTFs	Original pressure unit	Input
Temperate climate		
Wösten et al., (1999) topsoil and subsoil	cm	Sand, Silt, Clay, Organic Matter, Bulk Density
Vereecken et al., (1989)	cm*	Sand, Silt, Clay, Organic Carbon, Bulk Density
Zacharias and Wessolek (2007)	kPa	Sand, Clay, Bulk Density
Weynants et al. (2009)	cm	Sand, Silt, Clay, Organic Carbon, Bulk Density
Tropical climate		
Hodnett and Tomasella (2002)	kPa	Sand, Silt, Clay, Organic Carbon, Bulk Density; CEC
Arid climate		
Dashtaki et al. (2010)	cm	Sand, Silt, Clay, Bulk Density

cm*: converted from pF (pressure in cm = $10^{\wedge pF}$, or pF = $\log_{10}$(pressure in cm))

Specify pressures to calculate water content using van Genuchten and hydraulic conductivity using Mualem van Genuchten model (space delimited) (optional): By default, the output shapefile will contain soil moisture retention/hydraulic conductivity at -1kPa, -3kPa, -10kPa, -33kPa, -100kPa, -200kPa, -1000kPa and -1500kPa**.** Using this option, the user can customise the output to get soil moisture/hydraulic conductivity at the pressure of interest, in addition to the default pressures. This information will get written to a CSV file (WaterContent.csv) within the output folder.

Value of pressure (kPa) at field capacity: Specify pressure for field capacity. Field capacity is commonly between -10kPa to -100kPa. The default value is -33kPa.

Value of pressure (kPa) at water stress-induced stomata closure: Specify pressure for water stress-induced stomata closure. The default value is -100kPa.

Value of pressure (kPa) at permanent wilting point: Specify pressure for permanent wilting point. The default value is -1500kPa.

If the selected PTF requires OC or OM, select which type is present in your dataset: Specifying soil carbon information in the input data.

If the selected PTF requires OC or OM, enter the appropriate conversion factor to change OM to OC (or vice-versa): You do not need to use this function if your dataset has the same type of soil carbon as required by the PTFs. If the selected PTFs require organic matter (OM) but the input data only has organic carbon (OC) or inversely, this function can be used to convert OM to OC and inversely. LUCI_PTFs gives default conversion factors (the Van Bemmelen factors): 1.724 to convert OC to OM and 0.58 to convert OM to OC. However, the user can customise the factor by typing a conversion factor into this field.

Pressure units for plotting purposes: Selecting the pressure unit for plotting soil moisture results. LUCI_PTFs has three pressure unit options: kPa, cm and m.

Create water content and pressure plots with water content and hydraulic conductivity on the X-axis or Y-axis: Choose which axis water content (when using van Genuchten model) and hydraulic conductivity (when using Mualem-van Genuchten model) will be plotted on.

Estimate unsaturated hydraulic conductivity and generate hydraulic conductivity curve using PTFs for Mualem van Genuchten model: Tick this box if you would like to obtain Mualem van Genuchten model parameters and hydraulic conductivity pressure relationship. You must select either Wösten et al., 1999 or Weynants et al. (2009) PTFs.

7.2 Output

Output folder include: (1) a shapefile output, (2) plots of soil moisture retention curve (SMRC)/Hydraulic conductivity curve (HCC) for each soil type as well as a plot combining SMRCs/HCCs of all soil types and (3) a folder 'VG_WaterContents' storing csv files containing estimated water content from -1500 kPa to 0 kPa for each soil type.

The output shapefile (soil_vg.shp) is a copy of the input shapefile with new fields added. The new fields added contain the information of van Genuchten parameters and soil moisture content at 0kPa (saturation), -1kPa, -3kPa, -10kPa, -33kPa, -100kPa, -200kPa, -1000kPa and -1500kPa by default. In addition, the output shapefile includes information on soil moisture held between key thresholds. If the Mualem van Genuchten option is selected, the output shapefile ('K_MVG.shp') will contain all the fields of the soil_vg.shp and information on hydraulic conductivity. If users select "Specify pressures to calculate water content using van Genuchten and hydraulic conductivity using Mualem van Genuchten model (space delimited) (optional)" option, the water content at pressures of interest will be added to a csv file (WaterContents.csv file.) within the output folder. Table B2.3 presents the details of the output attribute table.

Table B2.3 Output of ‘Calculate van Genuchten parameters and plot SMRC’ tool

Output	Output Field name	Unit
PTFs for van Genuchten model		
Volumetric water content	WC_pressure potential e.g. WC_10kPa	v/v, cm^3 cm^{-3}
van Genuchten α parameter	alpha_VG	cm^{-1}
van Genuchten n parameter	n_VG	dimensionless
van Genuchten m parameter	m_VG	dimensionless
Saturated moisture content	WC_sat	v/v, cm^3 cm^{-3}
Residual moisture conten	WC_res	v/v, cm^3 cm^{-3}
PTFs for Mualem van Genuchten model		
Volumetric water content	WC_pressure potential e.g. WC_10kPa	v/v, cm^3 cm^{-3}
Unsaturated hydraulic conductivity	K_pressure potential e.g. K_10kPa	mm hr^{-1}
van Genuchten α parameter	Alpha_VG	kPa^{-1}
van Genuchten n parameter	n_VG	dimensionless
van Genuchten m parameter	m_VG	dimensionless
Saturated moisture content	WC_sat	v/v, cm^3 cm^{-3}
Residual moisture conten	WC_res	v/v, cm^3 cm^{-3}
Soil water held between key thresholds		
Soil moisture content at saturation	wc_satCalc	v/v, cm^3 cm^{-3}
Soil moisture content at field capacity	wc_fcCalc	v/v, cm^3 cm^{-3}
Soil moisture content at stomata closure point	wc_sicCalc	v/v, cm^3 cm^{-3}
Soil moisture content at permanent wilting point	wc_pwpCalc	v/v, cm^3 cm^{-3}
Drainable water	wc_DW	v/v, cm^3 cm^{-3}
Plant available water	wc_PAW	v/v, cm^3 cm^{-3}
Readily available water	wc_RAW	v/v, cm^3 cm^{-3}
Not readily available water	wc_NRAW	v/v, cm^3 cm^{-3}

7. ‘02 Calculate Brooks-Corey parameters and plot soil moisture retention curve (SMRC)’ tool

7.1 Summary

This tool provides 6 PTFs to estimate Brooks and Corey model parameters and the soil moisture-pressure relationship. To select the PTFs of interest, the user can use the guidelines given in the paper "Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling" (Dang et al., 2021).

7.2 Input

Output folder: Specify the path and folder name where output from this tool should be stored.

Input soil shapefile: Soil shapefile can be polygon or point vector which includes required soil properties of the selected PTFs and a required field named *"LUCIname"* which contains the soils' name/identifier.

PTFs of choice: Select the PTFs of interest from the dropdown list. Details of required input parameters for each PTFs for Brooks and Corey model is presented in Table B2.4.

Table B2.4 PTFs for Brooks and Corey model supported in LUCI_PTFs and required soil properties input

PTFs	Original pressure unit	Input
Temperate climate		
Cosby et al. (1984) (Equation with Sand, Silt, Clay)	cm	Sand, Silt, Clay
Cosby et al. (1984) (Equation with Silt, Clay)	cm	Silt, Clay
Rawls and Brakensiek (1985)*	cm	Sand, Clay, θ_s
Campbell and Shiozava (1992)*	cm	Silt, Clay, BD, θ_s
Saxton et al. (1986) *	kPa	Sand, Clay, θ_s
Saxton and Rawls (2006)	kPa	Sand, Clay, Organic Matter

(*) These PTFs require θ_s.

Specify pressures to calculate water content using Brooks-Corey model (space delimited) (optional): In the default, the output will contain soil moisture retention/hydraulic conductivity at -1kPa, -3kPa, -10kPa, -33kPa, -100kPa, -200kPa, -1000kPa and -1500kPa**.** Using this option, the user can customise the output to get soil moisture/hydraulic conductivity at the pressure of interest, in addition to the default pressures. This information will get written to a csv file (WaterContent.csv) within the output folder.

Value of pressure (kPa) at field capacity: Specify pressure for field capacity. Field capacity is commonly between -10kPa to -100kPa. The default value is -33kPa.

Value of pressure (kPa) at water stress-induced stomata closure: Specify pressure for water stress-induced stomata closure. The default value is -100kPa.

Value of pressure (kPa) at permanent wilting point: Specify pressure for permanent wilting point. The default value is -1500kPa.

If the selected PTF requires OC or OM, select which type is present in your dataset: Specifying soil carbon information in the input data.

If the selected PTF requires OC or OM, enter the appropriate conversion factor to change OM to OC (or vice-versa): You do not need to use this function if your dataset has the same type of soil carbon as required by the PTFs. If the selected PTFs require organic matter (OM) but the input data only has organic carbon (OC) or inversely, this function can be used to convert OM to OC and inversely. LUCI_PTFs gives default conversion factors (the Van Bemmelen factors): 1.724 to convert OC to OM and 0.58 to convert OM to OC. However, the user can customise the factor by typing a conversion factor into this field.

Pressure units for plotting purposes: Select the pressure unit for plotting soil moisture results. LUCI_PTFs has thee pressure unit options: kPa, cm and m.

Create water content and pressure plots with water content on the X-axis or Y-axis: Choose which axis water content will be plotted on.

7.2 Output

Output folder includes: (1) a shapefile output; (2) plots of the soil moisture retention curve (SMRC) for each soil type as well as a plot combining SMRCs of all soil types and (3) a folder 'BG_WaterContents' storing csv files containing estimated water content from -1500 kPa to 0 kPa.

The output shapefile (BrooksCorey.shp) is a copy of input shapefile with new fields added. The new fields added contain information on Brooks and Corey parameters and soil moisture content at 0kPa (saturation), -1kPa, -3kPa, -10kPa, -33kPa, -100kPa, -200kPa, -1000kPa and -1500kPa as default. In addition, the output shapefile includes information on soil moisture held between key thresholds. If users select "Specify pressures to calculate water content using Brooks-Corey model (space delimited) (optional)" option, the water content at pressures of interest will be added to a csv file (WaterContents.csv file.) within the output folder. Table B2.5 presents the details of the output attribute table.

Table B2.5 The output of 'Calculate Brooks and Corey parameters and plot SMRC' tool

Output	Output Field name	Unit
PTFs for Brooks and Corey model		
Volumetric water content	WC_pressure potential e.g. WC_10kPa	v/v, cm^3 cm^{-3}
Saturated moisture content	WC_sat_BC	v/v, cm^3 cm^{-3}
Residual moisture conten	WC_res	v/v, cm^3 cm^{-3}
Air-entry pressure	BC_hb	kPa
Pore size distribution index	Lamda_BC	dimensionless
Soil water held between key thresholds		
Soil moisture content at saturation	wc_satCalc	v/v, cm^3 cm^{-3}
Soil moisture content at field capacity	wc_fcCalc	v/v, cm^3 cm^{-3}
Soil moisture content at stomata closure point	wc_sicCalc	v/v, cm^3 cm^{-3}
Soil moisture content at permanent wilting point	wc_pwpCalc	v/v, cm^3 cm^{-3}
Drainable water	wc_DW	v/v, cm^3 cm^{-3}

Output	Output Field name	Unit
Plant available water	wc_PAW	v/v, cm^3 cm^{-3}
Readily available water	wc_RAW	v/v, cm^3 cm^{-3}
Not readily available water	wc_NRAW	v/v, cm^3 cm^{-3}

* if the Saxton and Rawls (2006) PTF is selected, information of K_{sat} will be exported in the output.

8. '03 Calculate water content using point PTFs' tool

8.1 Summary

This tool provides 21 options to estimate soil moisture content at certain pressures using point-PTFs. When a point PTFs is selected, the tool also estimates soil water held between key thresholds including drainable water, plant available water, readily available water, and total water content. To select the PTFs of interest, the user can use the guidelines given in the paper "Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling" (Dang et al., 2021).

8.2 Input

Output folder: Specify the path and folder name where output from this tool should be stored.

Input soil shapefile: Soil shapefile can be polygon or point vector which includes required soil properties of the selected PTFs and a required field named *"LUCIname"* which contains the soils' name/identifier

PTFs of choice: Select the PTFs of interest from the dropdown list. Details of required input soil properties for each point PTF are presented in Table B2.6.

Table B2.6 Point PTFs supported in LUCI_PTFs and required soil properties input

PTFs	Original pressure unit	Input
Hall et al. (1977) topsoil and subsoil	kPa	Silt, Clay, Organic Carbon, Bulk Density
Gupta and Larson (1979)	Bars (10^{-2} kPa)	Sand, Silt, Clay, Organic Matter, Bulk Density
Rawls et al. (1982)	Bars (10^{-2} kPa)	Sand, Silt, Clay, Organic Matter, Bulk Density
Batjes (1996)	pF (log10 (-head cm of water))	Silt, Clay, Organic Carbon
Van Den Berg et al. (1997)	kPa	Sand, Silt, Clay, Organic Carbon, Bulk Density
Pidgeon (1972)	Bars (10^{-2} kPa)	Silt, Clay, Organic Matter
Lal (1978) (Group I)	Bars (10^{-2} kPa)	Clay, Bulk Density
Lal (1978) (Group II)	Bars (10^{-2} kPa)	Clay, Bulk Density
Aina and Periaswamy (1985)	kPa	Sand, Clay, Bulk Density
Manrique and Jones (1991)	kPa	Sand, Clay, Bulk Density
Tomasella and Hodnett (1998)	kPa	Silt, Clay, Organic Carbon
Adhikary et al. (2008)	kPa	Sand, Silt, Clay
Reichert et al. (2009) (1)	kPa	Sand, Silt, Clay, Organic Matter, Bulk Density
Reichert et al. (2009) (2)	kPa	Sand, Silt, Clay, Bulk Density

PTFs	Original pressure unit	Input
Botula et al. (2013)	kPa	Sand, Clay, Bulk Density
Shwetha and Varija (2013)	kPa	Sand, Silt, Clay, Bulk Density
Nguyen et al. (2014)	cm	Sand, Silt, Clay, Organic Carbon, Bulk Density
Santra et al. (2018) (1)	Bars (10^{-2} kPa)	Sand, Clay, Organic Carbon, Bulk Density
Santra et al. (2018) (2)	Bars (10^{-2} kPa)	Sand, Clay, Bulk Density
Dashtaki et al. (2010)	kPa	Sand, Silt, Clay, Bulk Density

Value of pressure (kPa) at field capacity: Specify pressure for field capacity from the dropdown list. There are three options, -10kPa, -20kPa or -33kPa for field capacity when using point-PTFs.

Value of pressure (kPa) at water stress-induced stomata closure: The default value is -100kPa. However, the user can type in the pressure of interest to define water stress-induced stomata closure point. Please check whether the selected point-PTFs can give soil moisture at the pressure of interest. If point-PTFs stomata closure point is not available, a fraction of 0.5 is used to estimate RAW from PAW, RAW = PAW*0.5.

Value of pressure (kPa) at permanent wilting point: The default value is -1500kPa. However, the user can type in the pressure of interest to define permanent wilting point. Please check whether the selected point-PTFs can give soil moisture at the pressure of interest.

If the selected PTF requires OC or OM, select which type is present in your dataset: Specifying soil carbon information in the input data.

If the selected PTF requires OC or OM, enter the appropriate conversion factor to change OM to OC (or vice-versa): You do not need to use this function if your dataset has the same type of soil carbon as required by the PTFs. If the selected PTFs require organic matter (OM) but the input data only has organic carbon (OC) or inversely, this function can be used to convert OM to OC and inversely. LUCI_PTFs gives default conversion factors (the Van Bemmelen factors): 1.724 to convert OC to OM and 0.58 to convert OM to OC. However, the user can customise the factor by typing a conversion factor into this field.

Pressure unit for plotting purposes: Selecting the pressure unit for plotting soil moisture result. LUCI_PTFs has thee pressure unit options: kPa, cm and m.

8.3 Output

The output folder includes a shapefile output and plots of soil moisture content at certain pressure for each soil type.

The output (soil_point_ptf.shp) is a copy of the input shapefile with new fields added which contain information on volumetric soil moisture content at certain pressures. New fields added is depended on the selected PTFs. Table B2.7 lists the soil moisture content at certain pressure which can be obtained from each PTFs in the toolbox. The format of added field name is WC_pressure potential e.g. WC_10kPa means volumetric moisture content at -10kPa.

Table B2.7 Soil moisture at certain pressures estimated using point-PTFs

PTFs	Estimated soil moisture content (v/v, cm^3 cm^{-3})
Hall et al. (1977)	θ_{-5kPa}; θ_{-10kPa}; $\theta_{-33\ kPa}$; $\theta_{-200\ kPa}$; $\theta_{-1500\ kPa}$
Gupta and Larson (1979)	$\theta_{-4\ kPa}$; $\theta_{-7\ kPa}$; $\theta_{-10\ kPa}$; $\theta_{-20\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-60\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-200\ kPa}$; $\theta_{-400\ kPa}$; $\theta_{-700\ kPa}$; $\theta_{-1000\ kPa}$; $\theta_{-1500\ kPa}$
Rawls et al. (1982)	$\theta_{-10\ kPa}$; $\theta_{-20\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-60\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-200\ kPa}$; $\theta_{-400\ kPa}$; $\theta_{-700\ kPa}$; $\theta_{-1000\ kPa}$; $\theta_{-1500\ kPa}$
Batjes (1996)	θ_{0cm}; $\theta_{-10cm\ (pF1)}$; $\theta_{-32cm\ (pF1.5)}$; $\theta_{-50cm\ (pF1.7)}$; $\theta_{-100cm\ (pF2.0)}$; $\theta_{-200cm\ (pF2.3)}$; $\theta_{-316cm\ (pF2.5)}$; $\theta_{-501cm\ (pF2.7)}$; $\theta_{-2511cm\ (pF3.4)}$; $\theta_{-15849cm(pF4.2)}$
Van Den Berg et al. (1997)	θ_{-10kPa}; $\theta_{-1500\ kPa}$
Pidgeon (1972)	$\theta_{-10\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-1500\ kPa}$
Lal (1978)	$\theta_{0\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-1500\ kPa}$
Aina and Periaswamy (1985)	$\theta_{-33\ kPa}$; $\theta_{-1500\ kPa}$
Manrique and Jones (1991)	θ_{-33kPa}; $\theta_{-1500kPa}$
Tomasella and Hodnett (1998)	θ_{0kPa}; θ_{-1kPa}; θ_{-3kPa}; θ_{-6kPa}; θ_{-10kPa}; θ_{-33kPa}; $\theta_{-100kPa}$; $\theta_{-500kPa}$; $\theta_{-1500kPa}$
Adhikary et al. (2008)	$\theta_{-10\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-300\ kPa}$; $\theta_{-500\ kPa}$; $\theta_{-1000\ kPa}$; $\theta_{-1500\ kPa}$
Reichert et al. (2009)	$\theta_{-6\ kPa}$; $\theta_{-10\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-500\ kPa}$; $\theta_{-1500\ kPa}$
Botula et al. (2013)	$\theta_{-1\ kPa}$; $\theta_{-3\ kPa}$; $\theta_{-6\ kPa}$; $\theta_{-10\ kPa}$; $\theta_{-20\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-1500\ kPa}$
Shwetha and Varija (2013)	$\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-300\ kPa}$; $\theta_{-500\ kPa}$; $\theta_{-1000\ kPa}$; $\theta_{-1500\ kPa}$
Nguyen et al. (2014)	$\theta_{-1\ kPa}$; $\theta_{-3\ kPa}$; $\theta_{-6\ kPa}$; $\theta_{-10\ kPa}$; $\theta_{-20\ kPa}$; $\theta_{-33\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-1500\ kPa}$
Santra et al. (2018)	$\theta_{-33\ kPa}$; $\theta_{-1500\ kPa}$
Dashtaki et al. (2010)	$\theta_{-10\ kPa}$; $\theta_{-30\ kPa}$; $\theta_{-100\ kPa}$; $\theta_{-300\ kPa}$; $\theta_{-500\ kPa}$; $\theta_{-1500\ kPa}$

The output also contains the information of soil moisture content at saturation (wc_satCalc), field capacity (wc_fcCalc), stomata closure point (wc_sicCalc), permanent wilting point (wc_pwpCalc) as well as soil water held between these key thresholds including drainable water (wc_DW), plant available water (wc_PAW), readily available water (wc_RAW), and not readily available water (wc_NRAW)

9. '04 Calculate saturated hydraulic conductivity' tool

9.1 Summary

This tool provides various options to estimate soil saturated hydraulic conductivity via PTFs developed in temperate, tropical, and arid regions. To select the PTFs of interest, the user can use the guidelines given in the paper "Guidelines and a supporting toolbox for parameterising key soil hydraulic properties in hydrological studies and broader integrated modelling" (Dang et al., 2021).

9.2 Input

Output folder: Specify the path and folder name where output from this tool should be stored.

Input folder: results from calculation using point-PTF or vg-PTFs or bc-PTFs: The user should run 'Calculate van Genuchten parameters and plot SMRC', 'Calculate Brooks-Corey parameters and plot SMRC' or 'Calculate water content using point PTFs' first. Then specify the path of folder where the output shapefile is stored from running 'Calculate van Genuchten parameters and plot SMRC', 'Calculate Brooks-Corey parameters and plot SMRC' or 'Calculate water content using point PTFs'.

Select PTF to estimate K_{sat}:

Select the PTFs of interest from the dropdown list. Details of required input parameters for each PTF is presented in Table B2.8.

Table B2.8 PTFs for K_{sat} estimation supported in LUCI_PTFs and required soil properties input

PTFs	Input
Temperate climates	
Cosby et al. (1984)	Sand, Clay
Brakensiek et al. (1984) *	θ_s, Sand, Clay
Puckett et al. (1985)	Clay
Jabro (1992)	Sand, Silt, Clay, Bulk Density
Campbell and Shiozawa (1994)	Silt, Clay
Minasny and McBratney (2000)	Effective porosity
Ferrer Julia et al. (2004)	Sand
Ferrer Julia et al. (2004)	Sand, Clay, Organic Matter
Tropical climates	
Ahuja et al. (1989)	Effective porosity

(*) PTF require θ_s

If the selected PTF requires OC or OM, select which type is present in your dataset: Specifying soil carbon information in the input data.

If the selected PTF requires OC or OM, enter the appropriate conversion factor to change OM to OC (or vice-versa): You do not need to use this function if your dataset has the same type of soil carbon as required by the PTFs. If the selected PTFs require organic matter (OM) but the input data only has organic carbon (OC) or inversely, this function can be used to convert OM to OC and inversely. LUCI_PTFs gives default conversion factors (the Van Bemmelen factors): 1.724 to convert OC to OM and 0.58 to convert OM to OC. However, the user can customise the factor by typing a conversion factor into this field.

9.3 Output

The output is a shapefile which copies the input soil shapefile with new a field added containing the estimated K_{sat} using the selected PTFs. The unit of K_{sat} is in mm hr^{-1}

10. Using LUCI_PTFs for soil parameterisation for the Vietnamese Mekong Delta case study step by step

10.1 Input example

Example of the attribute table of Vietnamese Mekong Delta's local soil map.

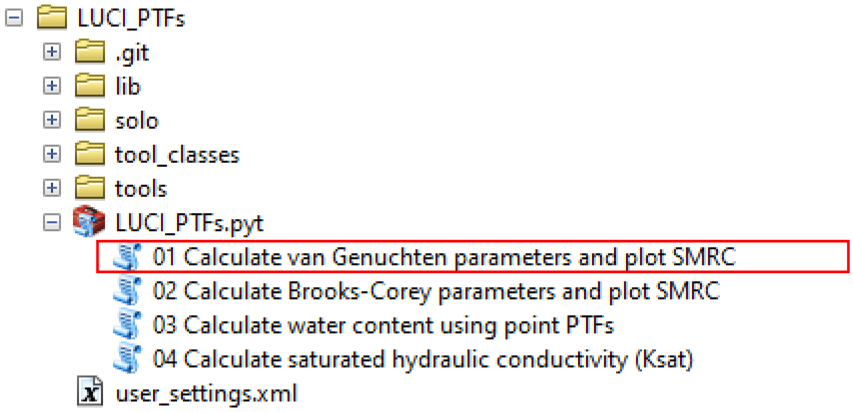
Table

VNsoil_FAOclasses_FAO90_dissolve_value

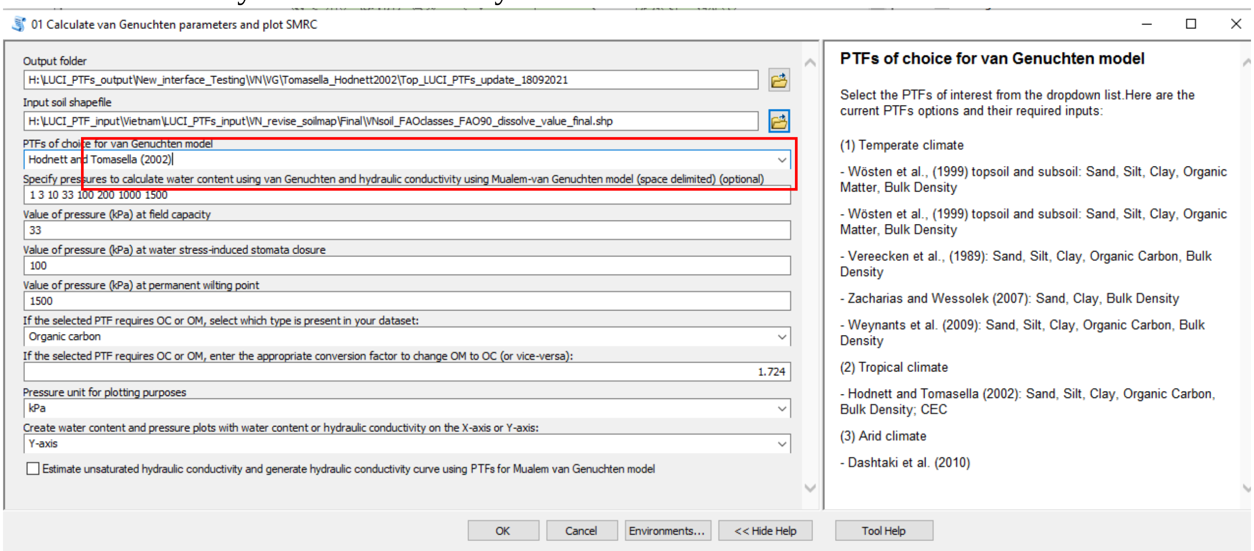
FID	Shape *	FAO90	Sand	Silt	Clay	OC	BD	OCg_kg	CEC	pH	LUCIname	OBJECTID	Texture
0	Polygon	Acf	53.454992	19.220949	27.332242	1.164144	1.385962	11.6414	7.78541	5.28006	Acf	1	Sandy Clay Loam
1	Polygon	Acg	47.678571	30.553571	21.741071	1.311441	1.357179	13.1144	7.43652	4.86174	Acg	2	Sandy Clay Loam
2	Polygon	Ach	56.515247	18.141956	25.341746	1.113691	1.395702	11.1369	6.96894	5.06622	Ach	3	Sandy Clay Loam
3	Polygon	Acu	35.17931	23.868966	40.944828	3.031579	1.30641	30.3158	13.8797	4.95864	Acu	4	Clay
4	Polygon	Arh	89.121359	6.150485	4.737864	0.65769	1.603818	6.5769	6.375	5.97879	Arh	5	Sand
5	Polygon	Fle	40.272436	32.557692	27.160256	1.090476	1.441139	10.9048	17.2565	6.48168	Fle	6	Loam
6	Polygon	FLm	38.031746	28.904762	33.063492	2.124762	1.474667	21.2476	22.7927	6.55763	FLm	7	Clay Loam
7	Polygon	FLs	37.586957	28.673913	33.717391	2.6325	1.3	26.325	26.5121	8.87609	FLs	8	Clay
8	Polygon	FLt	29.505263	27.894737	42.6	3.676452	1.005	36.7645	20.2632	4.6445	FLt	9	Clay
9	Polygon	GLd	40.868132	29.956044	29.175824	1.458774	1.271636	14.5877	12.9137	5.01914	GLd	10	Clay Loam
10	Polygon	GLm	31.560606	32.469697	35.969697	2.020238	1.370435	20.2024	28.9402	6.35925	GLm	11	Clay Loam
11	Polygon	HSt	24.8	26.2	49	24.795	1.165	247.95	41.8214	5.02	HSt	12	Clay
12	Polygon	LPq	50.818182	26.090909	23.090909	3.623636	1.26	36.2364	15.685	6.75	LPq	13	Sandy Clay Loam
13	Polygon	SCg	37.586957	28.673913	33.717391	1.086822	1.3	10.8682	26.5121	8.87609	SCg	14	Clay Loam

10.2 Step by step using LUCI_PTFs to estimate soil moisture content and create van Genuchten soil moisture retention curves

- Open LUCI_PTFs
- Select '01 Calculate van Genucten parameters and plots SMRC
- The tool is opened as below



- Add 'Output folder', 'Input soil shapefile'
- Select PTF of choice from the dropdown list. In the example, 'Hodnett and Tomasella (2002)' was selected
- Specify pressures to calculate water content using van Genuchten model for the shapefile output in 'Specify pressures to calculate water content using van Genuchten and hydraulic conductivity using Mualem-van Genuchten model (space delimited) (optional)'
- Specify pressure for field capacity in 'Value of pressure (kPa) at field capacity'
- Specify pressure for water stress-induced stomata closure in 'Value of pressure (kPa) at water stress-induced stomata closure'
- Specify pressure for permanent wilting point in 'Value of pressure (kPa) at permanent wilting point'
- As the 'Hodnett and Tomasella (2002)' PTFs require OC as the input, specify soil carbon type in the input dataset in 'If the selected PTF requires OC or OM, select which type is present in your dataset'. The VMD soil data has OC, then OC is selected
- As the VMD soil data has OC which is required by the 'Hodnett and Tomasella (2002)' PTFs, we do not need to specify OC/OM conversion factor.
- Select 'Pressure unit for plotting purposes'
- Select axis to plot water content in 'Create water content and pressure plots with water content or hydraulic conductivity on the X-axis or Y-axis:'



Screenshot of the inputs and dialogue box

- Click OK
- Output shapefile named 'soil_vg.shp' can be found in the output folder. The shapefile contains information of soil moisture content at different pressure heads as well as values of van Genuchten model's parameters. Example of the attribute table of output file is as below:

Table

soil_vg

WC_res	WC_sat	alpha_VG	n_VG	m_VG	WC_1kPa	WC_3kPa	WC_10kPa	WC_33kPa	WC_100kPa	WC_200kPa	WC_1000kPa	WC_1500kPa	wc_satCalc	wc_fcCalc	wc_sicCalc	wc_pwpCalc
0.165516	0.427489	0.299172	1.399038	0.285223	0.415118	0.385004	0.325522	0.26939	0.232852	0.216659	0.192446	0.188424	0.427489	0.26939	0.232852	0.188424
0.161671	0.43117	0.235051	1.349577	0.259027	0.422077	0.399357	0.34786	0.291292	0.250725	0.231716	0.201627	0.196349	0.43117	0.291292	0.250725	0.196349
0.157718	0.421491	0.315779	1.41104	0.291303	0.408053	0.375627	0.313735	0.257324	0.221392	0.205672	0.182484	0.178683	0.421491	0.257324	0.221392	0.178683
0.228674	0.465711	0.284801	1.352499	0.260628	0.455557	0.431799	0.383552	0.33496	0.301264	0.285625	0.260999	0.256696	0.465711	0.33496	0.301264	0.256696
0.057851	0.344761	0.406921	1.728407	0.421433	0.322487	0.255833	0.157453	0.100908	0.077129	0.069492	0.061456	0.060534	0.344761	0.100908	0.077129	0.060534
0.189691	0.418942	0.184352	1.355751	0.262401	0.413226	0.397722	0.357394	0.307694	0.270579	0.253094	0.225517	0.220708	0.418942	0.307694	0.270579	0.220708
0.216398	0.414773	0.203365	1.356231	0.262663	0.409167	0.394371	0.357904	0.315172	0.283934	0.269298	0.246261	0.242246	0.414773	0.315172	0.283934	0.242246
0.207645	0.481377	0.158741	1.372174	0.27123	0.475721	0.459407	0.413001	0.351558	0.304883	0.283051	0.249157	0.243346	0.481377	0.351558	0.304883	0.243346
0.25331	0.562702	0.269254	1.342996	0.255396	0.550433	0.521469	0.460774	0.397644	0.352999	0.33205	0.298695	0.292805	0.562702	0.397644	0.352999	0.292805
0.195268	0.466325	0.234052	1.345901	0.257003	0.457253	0.434668	0.383401	0.326807	0.286013	0.266826	0.23633	0.230959	0.466325	0.326807	0.286013	0.230959
0.243539	0.451223	0.189838	1.355752	0.262402	0.445847	0.431383	0.394359	0.349418	0.316071	0.300386	0.275659	0.271347	0.451223	0.349418	0.316071	0.271347
0.318035	0.524549	0.439618	1.218227	0.179135	0.513291	0.494561	0.463499	0.432461	0.40832	0.395724	0.372751	0.36812	0.524549	0.432461	0.40832	0.36812
0.164862	0.472357	0.222381	1.36352	0.266604	0.462586	0.437244	0.377722	0.311338	0.264052	0.24214	0.207969	0.202064	0.472357	0.311338	0.264052	0.202064
0.207645	0.481377	0.15296	1.38344	0.277164	0.475982	0.460029	0.413412	0.350716	0.303227	0.281203	0.247415	0.241692	0.481377	0.350716	0.303227	0.241692

1 (0 out of 14 Selected)

Table

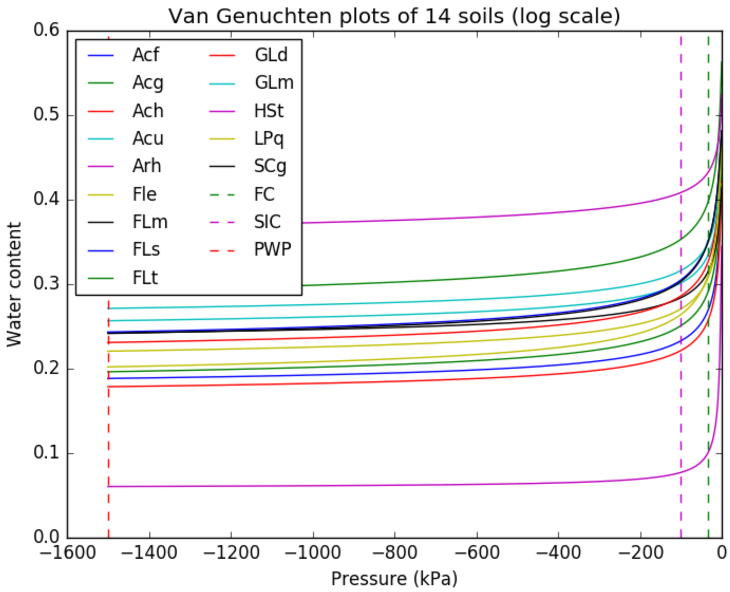
soil_vg

n_VG	m_VG	WC_1kPa	WC_3kPa	WC_10kPa	WC_33kPa	WC_100kPa	WC_200kPa	WC_1000kPa	WC_1500kPa	wc_satCalc	wc_fcCalc	wc_sicCalc	wc_pwpCalc	wc_DW	wc_RAW	wc_NRAW	wc_PAW
1.399038	0.285223	0.415118	0.385004	0.325522	0.26939	0.232852	0.216659	0.192446	0.188424	0.427489	0.26939	0.232852	0.188424	0.158099	0.036538	0.044428	0.080966
1.349577	0.259027	0.422077	0.399357	0.34786	0.291292	0.250725	0.231716	0.201627	0.196349	0.43117	0.291292	0.250725	0.196349	0.139878	0.040567	0.054376	0.094942
1.41104	0.291303	0.408053	0.375627	0.313735	0.257324	0.221392	0.205672	0.182484	0.178683	0.421491	0.257324	0.221392	0.178683	0.164167	0.035932	0.042709	0.078641
1.352499	0.260628	0.455557	0.431799	0.383552	0.33496	0.301264	0.285625	0.260999	0.256696	0.465711	0.33496	0.301264	0.256696	0.130751	0.033696	0.044569	0.078265
1.728407	0.421433	0.322487	0.255833	0.157453	0.100908	0.077129	0.069492	0.061456	0.060534	0.344761	0.100908	0.077129	0.060534	0.243854	0.023779	0.016595	0.040373
1.355751	0.262401	0.413226	0.397722	0.357394	0.307694	0.270579	0.253094	0.225517	0.220708	0.418942	0.307694	0.270579	0.220708	0.111248	0.037115	0.049871	0.086986
1.356231	0.262663	0.409167	0.394371	0.357904	0.315172	0.283934	0.269298	0.246261	0.242246	0.414773	0.315172	0.283934	0.242246	0.099601	0.031238	0.041688	0.072926
1.372174	0.27123	0.475721	0.459407	0.413001	0.351558	0.304883	0.283051	0.249157	0.243346	0.481377	0.351558	0.304883	0.243346	0.129818	0.046675	0.061537	0.108212
1.342996	0.255396	0.550433	0.521469	0.460774	0.397644	0.352999	0.33205	0.298695	0.292805	0.562702	0.397644	0.352999	0.292805	0.165059	0.044645	0.060194	0.104839
1.345901	0.257003	0.457253	0.434668	0.383401	0.326807	0.286013	0.266826	0.23633	0.230959	0.466325	0.326807	0.286013	0.230959	0.139518	0.040794	0.055054	0.095848
1.355752	0.262402	0.445847	0.431383	0.394359	0.349418	0.316071	0.300386	0.275659	0.271347	0.451223	0.349418	0.316071	0.271347	0.101805	0.033347	0.044724	0.078071
1.218227	0.179135	0.513291	0.494561	0.463499	0.432461	0.40832	0.395724	0.372751	0.36812	0.524549	0.432461	0.40832	0.36812	0.092088	0.024141	0.0402	0.064341
1.36352	0.266604	0.462586	0.437244	0.377722	0.311338	0.264052	0.24214	0.207969	0.202064	0.472357	0.311338	0.264052	0.202064	0.161018	0.047286	0.061988	0.109274
1.38344	0.277164	0.475982	0.460029	0.413412	0.350716	0.303227	0.281203	0.247415	0.241692	0.481377	0.350716	0.303227	0.241692	0.130661	0.047489	0.061535	0.109023

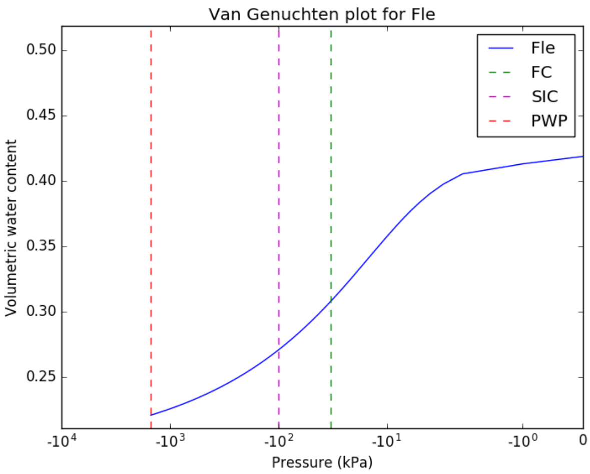
1 (0 out of 14 Selected)

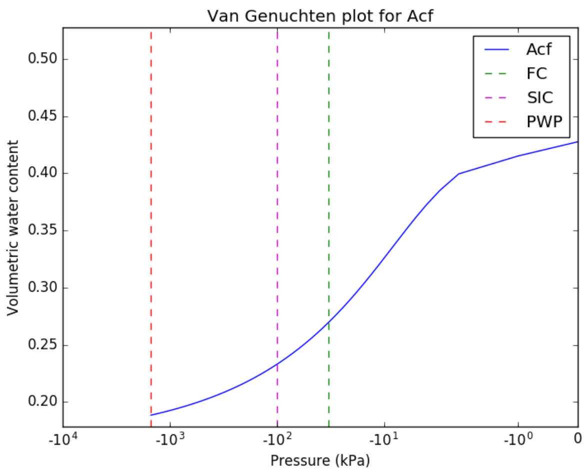
soil_vg

- LUCI_PTFs also provide graphs of Soil Moisture Retention Curves of for all soil types, examples as below:

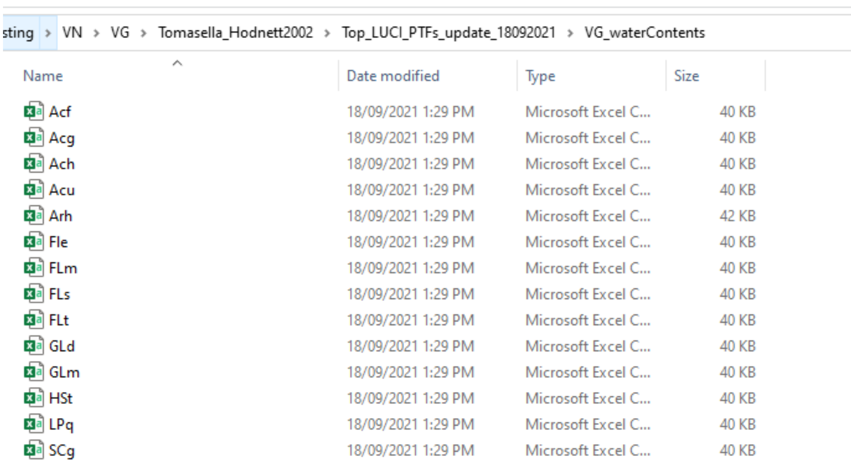


- LUCI_PTFs also provide graphs of Soil Moisture Retention Curves of for individual soil types, examples as below:



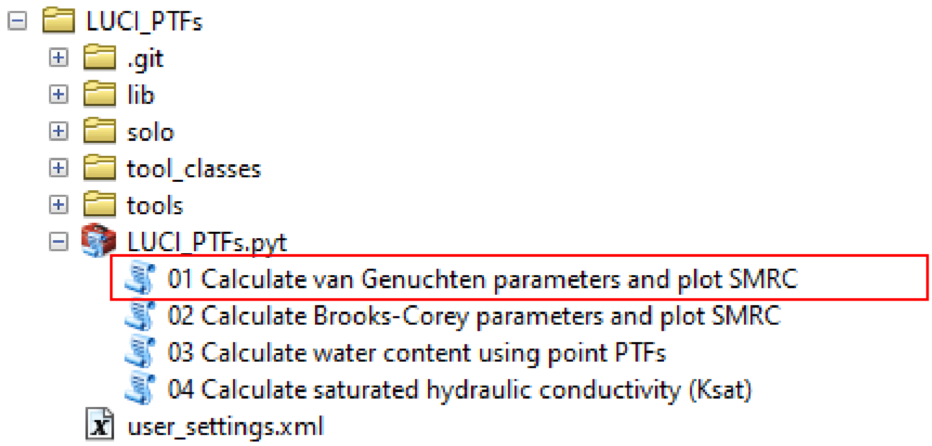


- csv files contain water content value from -1500kpa to 0 kPa can be found in the folder

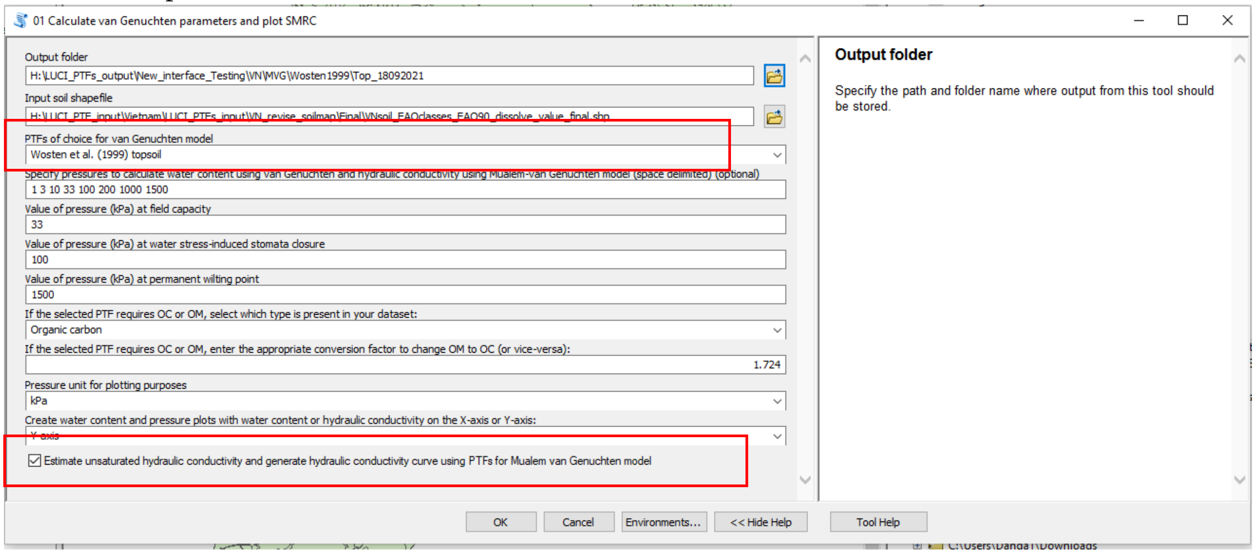


10.3 Step by step using LUCI_PTFs to estimate hydraulic conductivity and create hydraulic conductivity curves using Mualem van Genuchten model

- Open LUCI_PTFs



- Select ‘01 Calculate van Genucten parameters and plots SMRC’
- The tool is opened as below



-

- Add ‘Output folder’, ‘Input soil shapefile’
- Select PTFs of choice from the dropdown list. In the example, ‘Wosten et al. (2009) topsoil’ was selected
- Specify pressures to calculate water content and hydraulic conductivity for the shapefile output in ‘Specify pressures to calculate water content using van Genuchten and hydraulic conductivity using Mualem-van Genuchten model (space delimited) (optional)’
- Specify pressure for field capacity in ‘Value of pressure (kPa) at field capacity’
- Specify pressure for water stress-induced stomata closure in ‘Value of pressure (kPa) at water stress-induced stomata closure’
- Specify pressure for permanent wilting point in ‘Value of pressure (kPa) at permanent wilting point’
- As the ‘Wosten et al. (2009) topsoil’ PTFs require OM as the input, specify soil carbon type in the input dataset in ‘If the selected PTF requires OC or OM, select which type is present in your dataset’. The VMD soil data has OC, then OC is selected
- As the VMD soil data has OC which is not the soil carbon type required by ‘Wosten et al. (2009) topsoil’ PTFs, we need specify OC/OM conversion factor. The default factor to convert OC to OM is 1.724. You can type in your conversation factor of interest.
- Select ‘Pressure unit for plotting purposes’
- Select axis to plot water content in ‘Create water content and pressure plots with water content or hydraulic conductivity on the X-axis or Y-axis:’

- Tick ‘Estimate unsaturated hydraulic conductivity and generate hydraulic conductivity curve using PTFs for Mualem van Genuchten model’
- Click OK
- Output shapefile named ‘K_MVG.shp’ can be found in the output folder. The shapefile contains information of soil water content, hydraulic conductivity at different pressure heads as well as values of Mualem van Genuchten model’s parameters. An example of the attribute table of output file is as below:
- LUCI_PTFs also provide graphs of Soil Moisture Retention Curves of for all soil types, examples as below:

Table

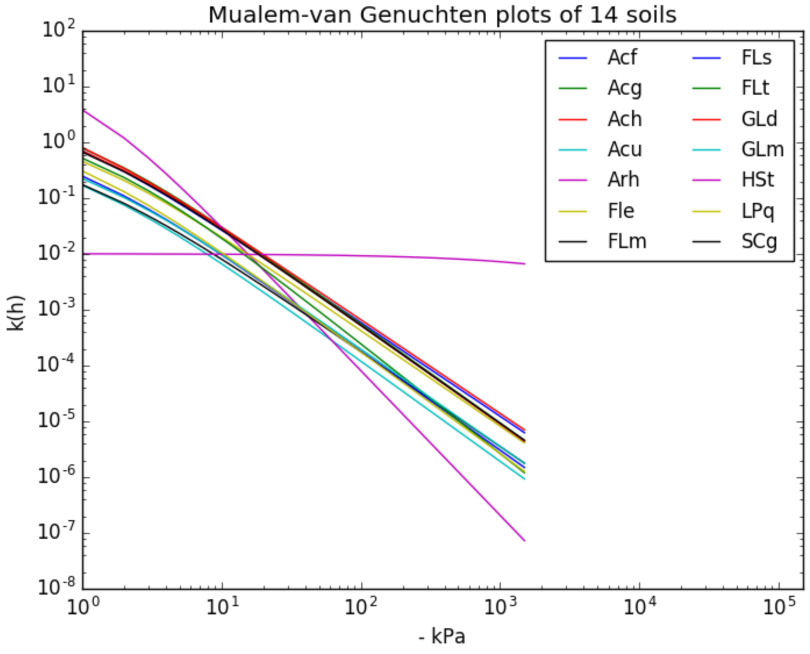
soil_vg

K_sat	WC_res	WC_sat	alpha_VG	n_VG	m_VG	WC_1kPa	WC_3kPa	WC_10kPa	WC_33kPa	WC_100kPa	WC_200kPa	WC_1000kPa	WC_1500kPa
29.40101	0.01	0.438412	0.625786	1.170776	0.145866	0.410847	0.373397	0.318213	0.264388	0.221143	0.197691	0.152647	0.143108
20.939823	0.01	0.446943	0.471589	1.188647	0.158707	0.423789	0.387555	0.32859	0.268793	0.220867	0.195188	0.146779	0.136712
31.313949	0.01	0.433756	0.649197	1.182194	0.154115	0.404144	0.364228	0.306584	0.251474	0.207893	0.184523	0.140222	0.130952
11.969663	0.01	0.462499	0.433183	1.104321	0.094466	0.448432	0.427654	0.391754	0.351184	0.31496	0.293908	0.250163	0.240226
44.13491	0.025	0.350325	0.675948	1.472418	0.320845	0.306966	0.236413	0.15446	0.099793	0.069417	0.057027	0.039976	0.037366
14.69711	0.01	0.425598	0.438846	1.16012	0.13802	0.407344	0.378811	0.330564	0.279255	0.236447	0.212849	0.166869	0.157014
8.785536	0.01	0.411263	0.407992	1.119509	0.106751	0.398107	0.37792	0.342446	0.302433	0.267169	0.246936	0.205604	0.19636
14.049933	0.01	0.464742	0.461058	1.121521	0.108354	0.4478	0.42287	0.380946	0.33503	0.295067	0.272246	0.225781	0.215415
24.865444	0.01	0.559897	0.345765	1.116283	0.10417	0.544832	0.520492	0.475074	0.421569	0.373487	0.345695	0.288611	0.275794
24.499729	0.01	0.477907	0.45657	1.15783	0.136316	0.456782	0.424349	0.370293	0.313197	0.265584	0.239303	0.187975	0.17695
11.144642	0.01	0.447742	0.401451	1.119889	0.107054	0.433572	0.411697	0.373039	0.329285	0.290687	0.268541	0.223312	0.2132
0.010119	0.01	0.475544	0.000038	1.565126	0.361074	0.475544	0.475544	0.475543	0.475539	0.475517	0.475463	0.474547	0.47367
14.863411	0.01	0.467188	0.510578	1.142118	0.124434	0.446007	0.415407	0.366174	0.314558	0.271063	0.246751	0.198446	0.1879
24.476038	0.01	0.474024	0.442863	1.150498	0.130812	0.454385	0.424115	0.372953	0.318108	0.271854	0.246129	0.195451	0.18448

1 (0 out of 14 Selected)

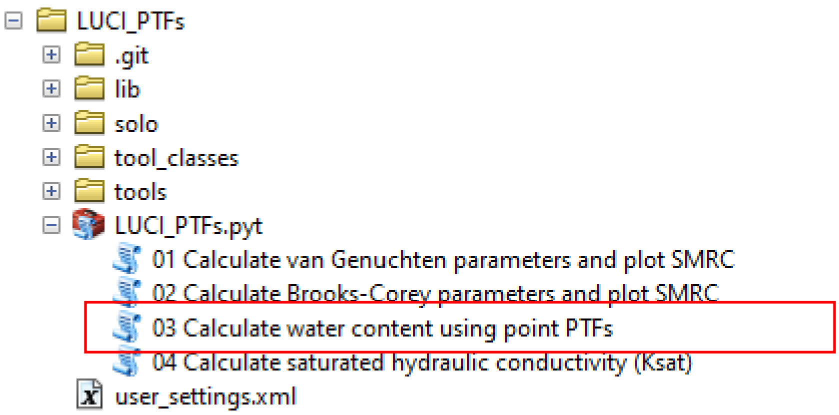
soil_vg

wc_DW	wc_RAW	wc_NRAW	wc_PAW	l_MvG	K_1kPa	K_3kPa	K_10kPa	K_33kPa	K_100kPa	K_200kPa	K_1000kPa	K_1500kPa
0.174023	0.043245	0.078035	0.12128	-3.861153	0.706348	0.170528	0.026802	0.003777	0.000592	0.000185	0.000012	0.000006
0.178149	0.047926	0.084155	0.132081	-3.187149	0.790825	0.200172	0.030442	0.003929	0.000558	0.000164	0.000009	0.000005
0.182281	0.043581	0.076941	0.120522	-3.749821	0.808567	0.193184	0.030149	0.00424	0.000665	0.000208	0.000014	0.000007
0.111315	0.036223	0.074734	0.110958	-3.926489	0.170165	0.043363	0.006688	0.000859	0.00012	0.000035	0.000002	0.000001
0.250532	0.030376	0.032052	0.062428	-0.744082	3.839922	0.520055	0.030037	0.001431	0.000081	0.000014	0	0
0.146343	0.042808	0.079432	0.12224	-3.779595	0.457333	0.121753	0.019966	0.002782	0.000424	0.00013	0.000008	0.000004
0.10883	0.035264	0.070809	0.106073	-4.472233	0.17516	0.047683	0.00807	0.001151	0.000178	0.000055	0.000004	0.000002
0.129712	0.039963	0.079652	0.119615	-3.839939	0.24876	0.062881	0.009716	0.001268	0.000181	0.000053	0.000003	0.000001
0.138328	0.048082	0.097693	0.145775	-2.242873	0.521547	0.134638	0.019164	0.002099	0.000245	0.000063	0.000003	0.000001
0.16471	0.047613	0.088635	0.136248	-3.471512	0.702509	0.179868	0.027907	0.003661	0.000526	0.000155	0.000009	0.000004
0.118456	0.038599	0.077487	0.116085	-4.092636	0.224405	0.060219	0.009853	0.001342	0.000198	0.000059	0.000004	0.000002
0.000005	0.000022	0.001847	0.001869	-4.401559	0.010055	0.01	0.009885	0.009662	0.009274	0.008885	0.007261	0.006642
0.15263	0.043495	0.083163	0.126658	-3.239917	0.307609	0.073461	0.010584	0.001296	0.000175	0.00005	0.000003	0.000001
0.155915	0.046255	0.087373	0.133628	-3.601959	0.667819	0.173373	0.027339	0.003634	0.000528	0.000157	0.000009	0.000005

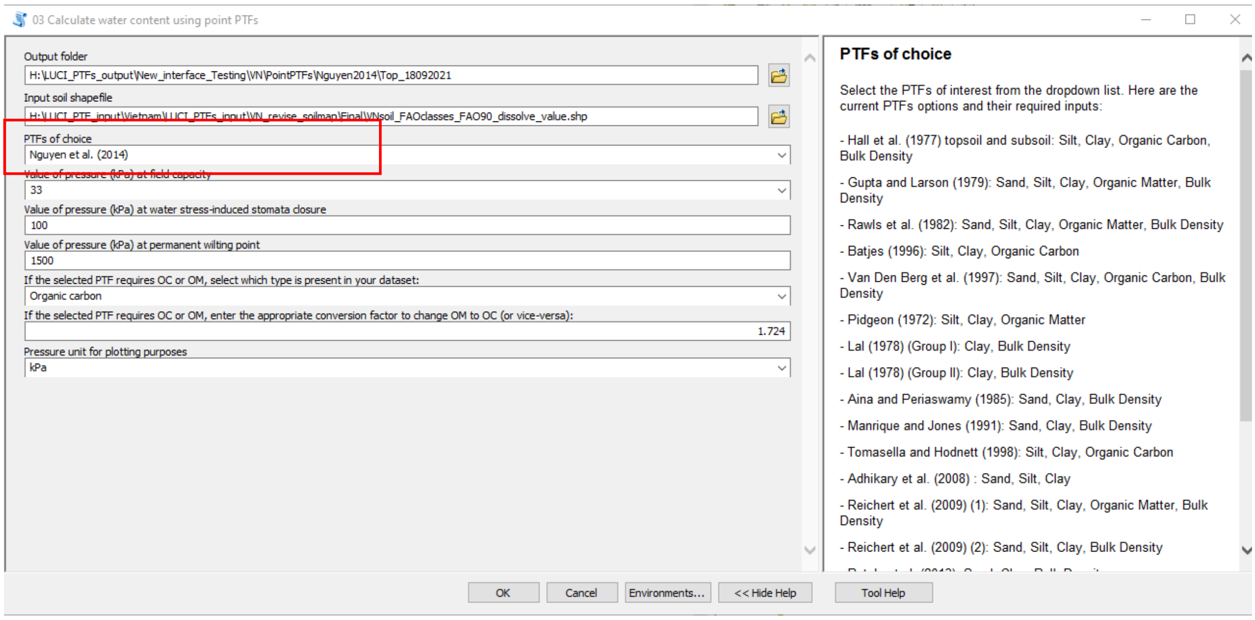


10.4 Step by step using LUCI_PTFs to estimate soil moisture content with point-PTFs

- Open LUCI_PTFs



- Select '03 Calculate water content using point PTFs'
- The tool is opened as below



- Add ‘Output folder’, ‘Input soil shapefile’
- Select PTFs of choice from the dropdown list. In the example, ‘Nguyen et al. (2014)’ was selected
- Specify pressure for field capacity in ‘Value of pressure (kPa) at field capacity’
- Specify pressure for water stress-induced stomata closure in ‘Value of pressure (kPa) at water stress-induced stomata closure’
- Specify pressure for permanent wilting point in ‘Value of pressure (kPa) at permanent wilting point’
- As the ‘Nguyen et al. (2014)’ PTFs require OC as the input, specify soil carbon type in the input dataset in ‘If the selected PTF requires OC or OM, select which type is present in your dataset’. The VMD soil data has OC, then OC is selected
- As the VMD soil data has OC which is required by the ‘Nguyen et al. (2014)’ PTFs, we do not need to specify OC/OM conversion factor.
- Select ‘Pressure unit for plotting purposes’
- Click OK
- Output shapefile named ‘soil_point_ptf.shp’ can be found in the output folder. The shapefile contains information of soil moisture content at different pressure heads. Example of the attribute table of output file is as below:

Table

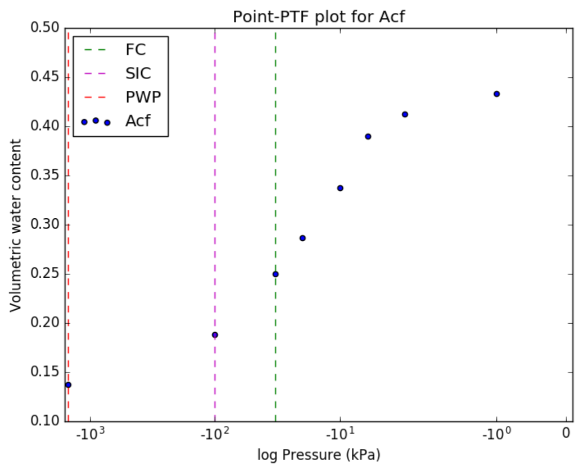
soil_point_ptf

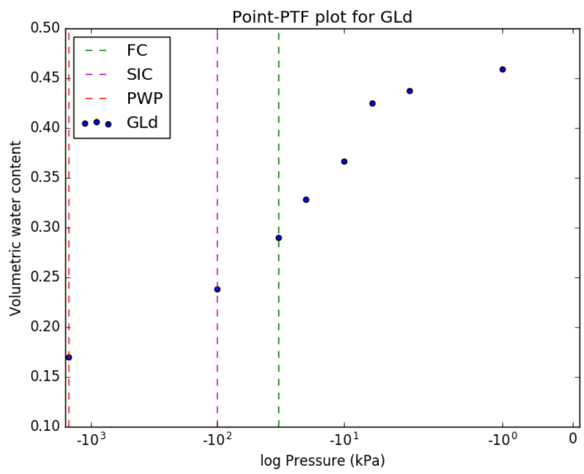
OBJECTID	Texture	warning	WC_1kPa	WC_3kPa	WC_6kPa	WC_10kPa	WC_20kPa	WC_33kPa	WC_100kPa	WC_1500kPa	wc_fcCalc	wc_sicCalc	wc_pwpCalc	wc_RAW	wc_NRAW	wc_PAW
1	Sandy Clay Loam		0.433716	0.412842	0.390209	0.337601	0.286725	0.249879	0.188337	0.137404	0.249879	0.188337	0.137404	0.061542	0.050933	0.112475
2	Sandy Clay Loam		0.429524	0.408724	0.392762	0.338731	0.29218	0.259237	0.208746	0.138695	0.259237	0.208746	0.138695	0.050491	0.070051	0.120541
3	Sandy Clay Loam		0.427275	0.406354	0.380245	0.328106	0.274789	0.240618	0.178114	0.126991	0.240618	0.178114	0.126991	0.062504	0.051124	0.113628
4	Clay		0.495258	0.47786	0.490506	0.435875	0.382549	0.30943	0.251676	0.203726	0.30943	0.251676	0.203726	0.057754	0.04795	0.105704
5	Sand		0.343517	0.323806	0.26609	0.225253	0.141201	0.130245	0.058027	0.013911	0.130245	0.058027	0.013911	0.072217	0.044117	0.116334
6	Loam		0.423865	0.403698	0.396202	0.346816	0.307672	0.269561	0.221981	0.161659	0.269561	0.221981	0.161659	0.04758	0.060322	0.107902
7	Clay Loam		0.446777	0.430723	0.442943	0.397664	0.341135	0.275989	0.225115	0.176874	0.275989	0.225115	0.176874	0.050874	0.048241	0.099115
8	Clay		0.478355	0.460099	0.46667	0.411213	0.359605	0.298143	0.245139	0.184661	0.298143	0.245139	0.184661	0.053004	0.060478	0.113483
9	Clay		0.546579	0.524459	0.528236	0.455504	0.420218	0.357999	0.300949	0.228029	0.357999	0.300949	0.228029	0.05705	0.07292	0.12997
10	Clay Loam		0.459255	0.437384	0.425321	0.36631	0.328684	0.290386	0.238331	0.169923	0.290386	0.238331	0.169923	0.052056	0.068407	0.120463
11	Clay Loam		0.466394	0.448097	0.45906	0.407165	0.36449	0.304137	0.255682	0.198964	0.304137	0.255682	0.198964	0.048456	0.056717	0.105173
12	Clay		0.58193	0.572797	0.635294	0.578284	0.487858	0.35493	0.297945	0.24512	0.35493	0.297945	0.24512	0.056985	0.052825	0.10981
13	Sandy Clay Loam		0.470495	0.453145	0.451341	0.394375	0.323369	0.265775	0.209725	0.138225	0.265775	0.209725	0.138225	0.056049	0.0715	0.127549
14	Clay Loam		0.457224	0.434357	0.420565	0.362418	0.334247	0.298143	0.245139	0.184661	0.298143	0.245139	0.184661	0.053004	0.060478	0.113483

1 (0 out of 14 Selected)

soil_point_ptf

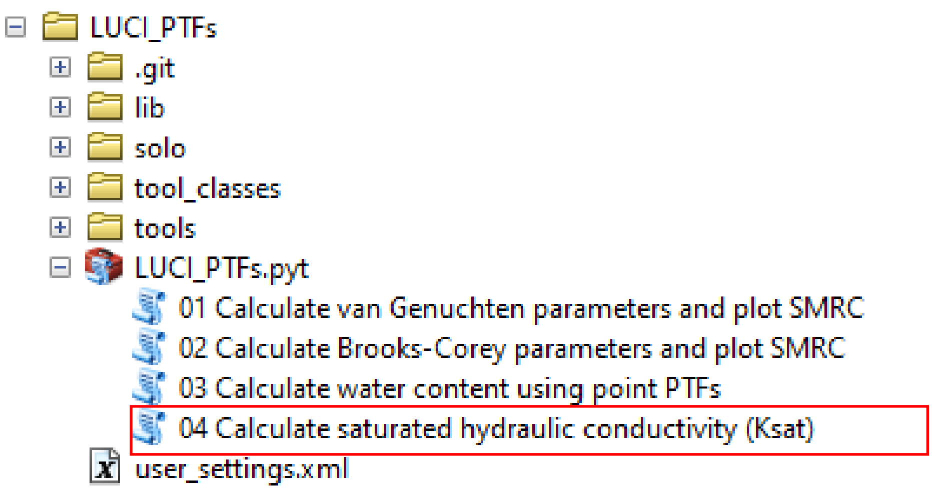
Plotting graphs can also be found in the output folder



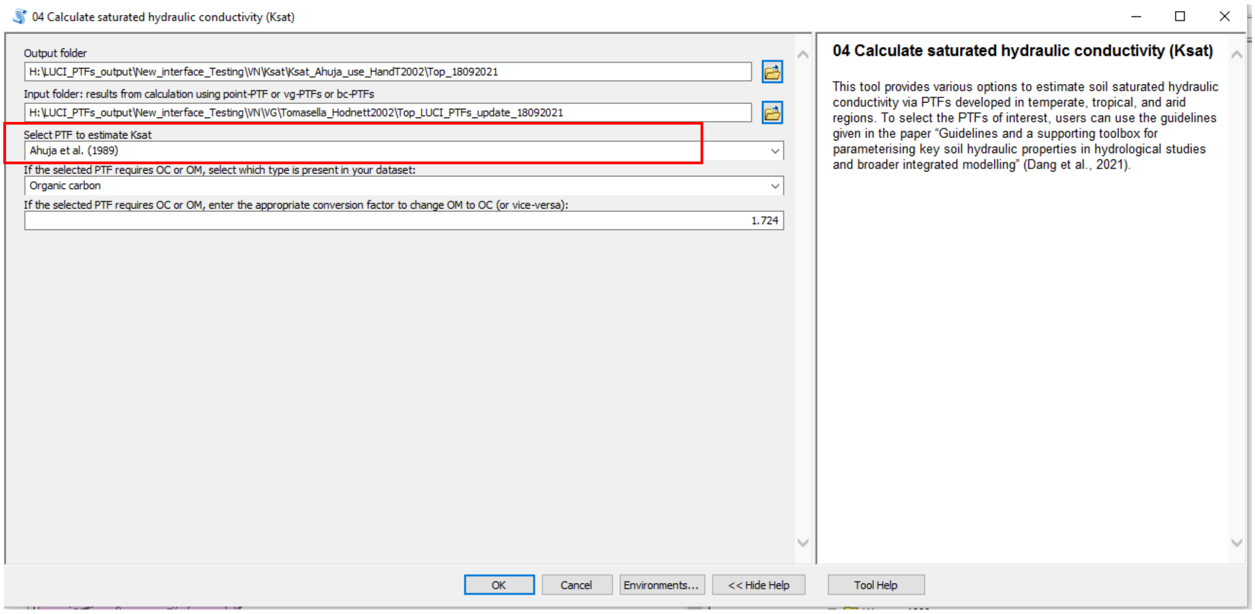


10.5 Step by step using LUCI_PTFs to estimate saturated hydraulic conductivity

- Open LUCI_PTFs



- Select '04 Calculate saturated hydraulic conductivity (Ksat)'



- Add ‘Output folder’
- Add ‘Input folder’ which is the output folder obtained from of either ‘01 Calculate van Genuchten parameters and plot SMRC’, ‘02 Calculate Brooks-Corey parameters and plot SMRC’ or ‘03 Calculate water content using point PTFs’ tool. In the example, result folder of ‘Hodnett and Tomasella (2002)’ was selected
- Select PTF to estimate K_{sat} from the dropdown list. In the example, ‘Ahuja et al. (1989)’ was selected
- As ‘Ahuja et al. (1989)’ does not require soil carbon as input so you do not need to select soil carbon type in your dataset.
- Click OK
- Output shapefile named ‘Ksat.shp’ can be found in the output folder. The shapefile contains information of saturated hydraulic conductivity. Example of the attribute table of output file is as below:

1500kPa	wc_satCalc	wc_fcCalc	wc_sicCalc	wc_pwpCalc	wc_DW	wc_RAW	wc_NRAW	wc_PAW	K_sat
0.188424	0.427489	0.26939	0.232852	0.188424	0.158099	0.036538	0.044428	0.080966	17.695041
0.196349	0.43117	0.291292	0.250725	0.196349	0.139878	0.040567	0.054376	0.094942	11.827603
0.178683	0.421491	0.257324	0.221392	0.178683	0.164167	0.035932	0.042709	0.078641	20.029447
0.256696	0.465711	0.33496	0.301264	0.256696	0.130751	0.033696	0.044569	0.078265	9.472815
0.060534	0.344761	0.100908	0.077129	0.060534	0.243854	0.023779	0.016595	0.040373	73.626351
0.220708	0.418942	0.307694	0.270579	0.220708	0.111248	0.037115	0.049871	0.086986	5.567779
0.242246	0.414773	0.315172	0.283934	0.242246	0.099601	0.031238	0.041688	0.072926	3.869574
0.243346	0.481377	0.351558	0.304883	0.243346	0.129818	0.046675	0.061537	0.108212	9.252399
0.292805	0.562702	0.397644	0.352999	0.292805	0.165059	0.044645	0.060194	0.104839	20.389557
0.230959	0.466325	0.326807	0.286013	0.230959	0.139518	0.040794	0.055054	0.095848	11.727671
0.271347	0.451223	0.349418	0.316071	0.271347	0.101805	0.033347	0.044724	0.078071	4.158527
0.36812	0.524549	0.432461	0.40832	0.36812	0.092088	0.024141	0.0402	0.064341	2.989564
0.202064	0.472357	0.311338	0.264052	0.202064	0.161018	0.047286	0.061988	0.109274	18.79303
0.241692	0.481377	0.350716	0.303227	0.241692	0.130661	0.047489	0.061535	0.109023	9.451475