Establishing the first database of soil hydraulic properties in tunisia based on pedotransfer functions

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ESTABLISHING THE FIRST DATABASE OF SOIL HYDRAULIC PROPERTIES IN TUNISIA BASED ON PEDOTRANSFER FUNCTIONS

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Abstract: Soil hydraulic properties play a crucial role in the unsaturated soil water supply process. Currently, Tunisia lacks a database containing essential values for soil retention properties and soil saturated hydraulic conductivity. The main objective of this study is to create the inaugural soil hydraulic properties database through the utilization of open-access data and pedotransfer functions (PTFs). To achieve this goal, the harmonized world soil database (FAO) was employed to identify 752 measurement points across Tunisia. Subsequently, the soil texture, organic carbon content, and bulk density were determined at each point. These acquired values were then entered into the CalcPTF software to estimate the van Genuchten soil retention parameters. The calculation of soil saturated hydraulic conductivity was accomplished using two widely recognized pedotransfer functions (Saxton and Rosetta). The outcomes facilitated the creation of a catalog containing soil hydraulic parameter value for each soil texture. Significance of discrepancies between values obtained from the PTFs was assessed using a Tukey test. The spatial variability of each soil hydraulic property was studied using the simple kriging. In conclusion, the establishment of this significant soil hydraulic properties database holds diverse applications in agricultural, hydrological, and environmental studies in Tunisia.

Keywords: Soils; Soil water retention; Saturated hydraulic conductivity; van Genuchten model; Pedotransfer function; Tunisia

1. INTRODUCTION

From the extensive literature within fields like soil sciences (Rousseva et al., 2017), hydrology, agriculture (Ganiyu, 2018), etc., researchers often resort for estimating soil hydraulic properties. Two crucial components of these characteristics are the soil retention curve and the soil hydraulic conductivity curve. Tunisia does not currently have a comprehensive database of soil hydraulic characteristics. Most studies have been conducted on a local scale (Kanzari, 2018).

Methods for measuring these parameters can be broadly categorized into two families: in situ measurement methods and laboratory measurement methods. However, these methods are both time-consuming and resource-intensive (Mbayaki & Karuku, 2022). Consequently, numerous pedotransfer functions (PTFs) have been developed to estimate soil hydrodynamic parameter values based on soil properties. Among the frequently utilized software tools is CalcPTF (Guber et al., 2009), which facilitates the estimation of van Genuchten model parameters using nine distinct PTFs. It is also necessary to determine the saturated hydraulic conductivity, another crucial hydrodynamic parameter. Two pedotransfer functions that are commonly used for evaluating soil saturated hydraulic conductivity are Rosetta (Schaap & Bouten, 1996) and Saxton (Saxton et al., 1986).

For the purpose of creating parameter-specific maps, it is necessary to look into the spatial variability of soil hydraulic properties throughout Tunisia in addition to estimating them. The kriging spatial interpolation method has been employed by various authors to create accurate maps (Honarbakhsh et al., 2022; Steenpass et al., 2010; Dai et al., 2019).

The objectives of this study are as follows: (i) to compile a data catalog containing hydrodynamic parameter values of Tunisian soils; (ii) to map each parameter across the scale of Tunisia; (iii) to analyze the spatial variability of each parameter."

2. MATERIALS AND METHODS

2.1. Methodology and input parameters

The Harmonized World Soil Database (HWSD) (FAO, et al., 2012) served as the starting point for this study. In the case of Tunisia, 752 polygons were identified in the HWSD. Utilizing a Geographic Information System (GIS) tool, 752 points were extracted from each polygon, and key soil properties were delineated, including soil granulometric composition, soil organic matter, soil organic carbon, and soil bulk density. These properties were then input into the CalcPTF software (Guber et al., 2009) to predict soil hydraulic properties using the van Genuchten model through nine common Pedotransfer Functions (PTFs).

The estimation of saturated soil hydraulic conductivity was conducted using the PTFs Rosetta (Schaap & Bouten, 1996) and Saxton (Saxton et al., 1996) functions.

2.2. Pedotranfers functions (PTFs)

Four parameters are needed to calculate the soil hydraulic conductivity from the soil retention curve using the van Genuchten equation: the soil's saturated water content, residual water content, and two shape parameters, α and n. The water retention equation developed by van Genuchten (1980) is:

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

where θr is the soil residual water content (minimum soil water content) in $cm^3.cm^{-3}$; θs is the soil water content in $cm^3.cm^{-3}$; α, m and n are shape parameters.

In the van Genuchten model, the parameter m is defined as follows: m=1-1/n.

The nine used PTFs included in CalcPTf software are as follow:

- Wösten et al., 1999(a) (WS99);
- Varallyay et al., 1982 (VAR82);
- Vereecken et al., 1989 (VEER89);
- Wösten et al., 1999(b) (WoS99);
- Tomasella & Hodnett, 1998 (TH98);
- Rawls et al., 1982 (RAW82);
- Gupta & Larson, 1979 (GL79);
- Rajkai & Varallyay, 1992 (RV92);
- Rawls et al., 1983 (RAW83).

2.3. Mapping of the soil hydraulic properties

The spatial variability of soil hydraulic characteristics was analyzed using the Surfer® software (Golden Software, LLC). This software utilizes the multiple kriging technique and enables the generation of various statistical indices to assess the resultant maps. In this study, a simple linear model was selected. Grid data was generated from the coordinates of the 752 points, and each point was assigned a value for the soil hydraulic parameter.

2.4. Statistical analysis

The acquired results were categorized according to the United States Department of Agriculture (USDA) classification for each soil texture. The significance of differences between the estimated soil hydraulic properties using various PTFs was assessed using ANOVA with a Tukey test at a 5% significance level.

3. RESULTS AND DISCUSSION

3.1. Soil water retention properties

Based on the HWSD (FAO, 2012), the particle-size distribution of each point was determined and subsequently categorized using the USDA soil texture triangle. Approximately 81% of soils in Tunisia fall under four primary texture types: Loam (L), Sandy loam (SL), Clay loam (CL), and Sandy clay loam (SCL), as depicted in Figure 1.

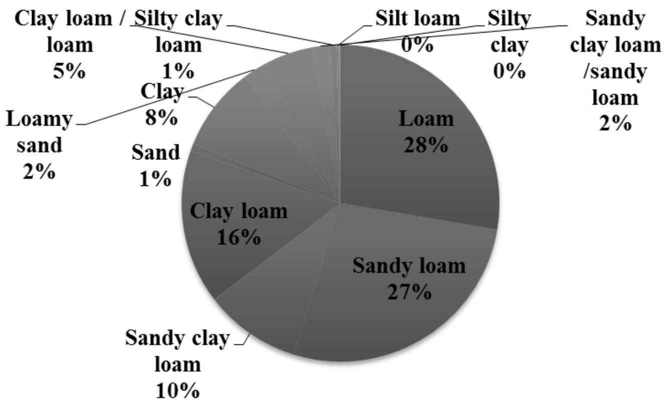

Figure 1. Distribution of soil texture in Tunisia according the HSWD (FAO, 2012).

Figure 2 presents the box plots for the key soil hydraulic properties corresponding to the aforementioned primary soil types. These plots provide a summarized statistical description of each hydraulic property (θr, θs, α, and n) based on van Genuchten model, categorized by the major soil textures.

According to Figure 2, the soil's residual water content (θr) spans between 0 and 0.16 $cm^3.cm^{-3}$ across all soil types. The soil exhibiting the greatest variability in θr values is the sandy clay loam. Seventy-five percent of values for θr fall between 0.01 and 0.1 $cm^3.cm^{-3}$. Concerning the clay loam soil, 25% of its θr values range between 0.1 and 0.16 $cm^3.cm^{-3}$.

Regarding the soil's saturated water content (θs), the range varies between 0.43 and 0.48 $cm^3.cm^{-3}$, with sandy loam soil displaying the widest variation. Seventy-five percent of θs values fall within the 0.43 to 0. $cm^3.cm^{-3}$ range.

In terms of the shape parameter α, values span between 0.02 and 0.06, with sandy loam soil also demonstrating the highest variability. The majority of values lie within the 0.02 to 0.05 range. Loam soil exhibits the least variation. The parameter n ranges between 1 and 1.3, with 75% of values falling within this interval. All soil types exhibit a consistent pattern in their box plots.

The statistical analysis conducted using the ANOVA technique to assess the significance of differences among the employed PTFs (as shown in Table 1) reveals the following results:

- Regarding θr: Most of the disparities among the computed values from each PTF are indeed significant. Consequently, simplification of the obtained values is not feasible. A similar interpretation applies to θs.

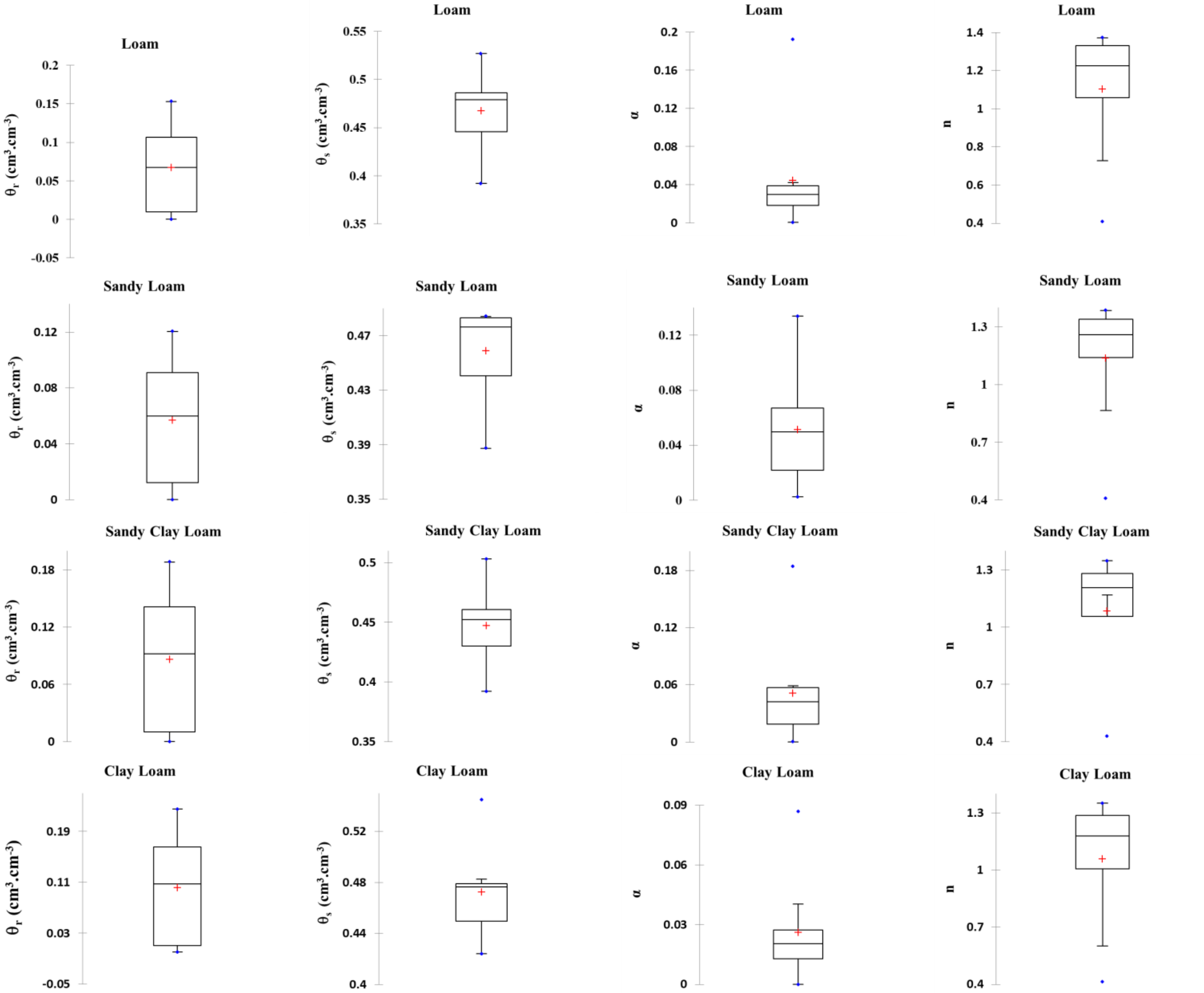

Figure 2. Box plots for loam, sandy loam, sandy clay loam and clay loam soils in Tunisia for the soil. The model uses four parameters: soil residual water content (θr), soil saturated water content (θs) and the two shape parameters α and n. (The red crosses represent the median of each parameter).

Table 1. Database of the soil hydraulic properties for the major texture types in Tunisia.

		θ_r ($cm^3.cm^{-3}$)		θ_s ($cm^3.cm^{-3}$)		α		n	
	PTF	**Value**	**Standard Error**	**Value**	**Standard Error**	**Value**	**Standard Error**	**Value**	**Standard Error**
L	***RV92***	0	±0.0014 a	0.4621	±0.0018 c	0.043	±0.043 ab	1.1509	±0.007 c
	VAR82	0	±0.0014 a	0.4732	±0.0018 d	0.002	±0.043 a	0.4073	±0.007 a
	WS99	0.01	±0.0014 b	0.392	±0.0018 a	0.025	±0.043 ab	1.1689	±0.007 c
	GL79	0.1532	±0.0014 g	0.4868	±0.0018 e	0.024	±0.043 ab	1.373	±0.007 f
	RAW82	0.1	±0.0014 e	0.4859	±0.0018 e	0.034	±0.043 ab	1.3623	±0.007 f
	WoS99	0.01	±0.0014 b	0.4466	±0.0018 b	0.037	±0.043 ab	1.2319	±0.007 d
	VEER89	0.1276	±0.0014 f	0.4429	±0.0018 b	0	±0.043 a	0.7289	±0.007 b
	RAW83	0.0931	±0.0014 d	0.4845	±0.0018 e	0.042	±0.043 ab	1.3216	±0.007 e
	TH98	0.0421	±0.0014 c	0.5268	±0.0018 f	0.192	±0.043 b	1.2222	±0.007 d
SL	***RV92***	0	±0.0006 a	0.4547	±0.0014 c	0.0072	±0.0010 b	1.2391	±0.0042 c
	VAR82	0	±0.0006 a	0.4701	±0.0014 d	0.0027	±0.0010 a	0.4073	±0.0042 a
	WS99	0.0127	±0.0006 b	0.3873	±0.0014 a	0.0282	±0.0010 c	1.233	±0.0042 c
	GL79	0.1204	±0.0006 g	0.4841	±0.0014 e	0.0494	±0.0010 d	1.3495	±0.0042 e
	RAW82	0.0867	±0.0006 e	0.4831	±0.0014 e	0.0622	±0.0010 e	1.3852	±0.0042 f
	WoS99	0.01	±0.0006 b	0.4411	±0.0014 b	0.0504	±0.0010 d	1.2697	±0.0042 d
	VEER89	0.1039	±0.0006 f	0.4388	±0.0014 b	0.0024	±0.0010 a	0.8642	±0.0042 b
	RAW83	0.0799	±0.0006 d	0.4831	±0.0014 e	0.0814	±0.0010 f	1.3362	±0.0042 e
	TH98	0.0397	±0.0006 c	0.4825	±0.0014 e	0.1338	±0.0010 g	1.247	±0.0042 c
CL	***RV92***	0.0263	±0.0037 b	0.4599	±0.0024 c	0.0057	±0.0009 b	1.1286	±0.0037 c
	VAR82	0	±0.0037 a	0.4767	±0.0024 d	0.0002	±0.0009 a	0.4137	±0.0037 a
	WS99	0.01	±0.0037 a	0.4239	±0.0024 a	0.0231	±0.0009 d	1.1392	±0.0037 cd
	GL79	0.2249	±0.0037 g	0.4826	±0.0024 d	0.0183	±0.0009 c	1.3288	±0.0037 g
	RAW82	0.1564	±0.0037 e	0.4779	±0.0024 d	0.017	±0.0009 c	1.3494	±0.0037 h
	WoS99	0.01	±0.0037 a	0.4478	±0.0024 b	0.0405	±0.0009 e	1.1516	±0.0037 d
	VEER89	0.1929	±0.0037 f	0.4503	±0.0024 bc	0	±0.0009 a	0.6017	±0.0037 b
	RAW83	0.1329	±0.0037 d	0.476	±0.0024 d	0.0226	±0.0009 d	1.2731	±0.0037 f
	TH98	0.0811	±0.0037 c	0.5449	±0.0024 e	0.0869	±0.0009 f	1.205	±0.0037 e
SCL	***RV92***	0	±0.0018 a	0.4395	±0.0026 cd	0.0063	±0.0020 a	1.1756	±0.0038 c
	VAR82	0	±0.0018 a	0.4447	±0.0026 d	0.0006	±0.0020 a	0.4278	±0.0038 a
	WS99	0.01	±0.0018 b	0.392	±0.0027 a	0.0249	±0.0020 b	1.1689	±0.0038 c
	GL79	0.1882	±0.0018 g	0.4615	±0.0026 e	0.0474	±0.0020 d	1.3385	±0.0038 f
	RAW82	0.1341	±0.0018 e	0.4605	±0.0026 e	0.0372	±0.0020 c	1.3478	±0.0038 f
	WoS99	0.01	±0.0018 b	0.4246	±0.0026 b	0.0589	±0.0020 e	1.1767	±0.0038 c
	VEER89	0.1625	±0.0018 f	0.4317	±0.0026 bc	0.0001	±0.0020 a	0.7128	±0.0038 b
	RAW83	0.1088	±0.0018 d	0.46	±0.0026 e	0.0563	±0.0020 e	1.2629	±0.0038 e
	TH98	0.0753	±0.0018 c	0.5032	±0.0026 f	0.184	±0.0020 f	1.2361	±0.0038 d

ANOVA was performed using Tukey test at 5% significance level.

- In terms of the shape parameter α: The values exhibit less variability for loam texture. Differences between each PTF are generally not statistically significant for this parameter. However, for the remaining textures (SL, CL, and SCL), the significance level is more pronounced.

Concerning the second shape parameter, n: A similar pattern of significance emerges, with substantial differences observed among the PTFs for the major soil textures.

3.2. Spatial analysis of the soil hydraulic properties

The maps representing each soil hydraulic parameter of the van Genuchten model are depicted in Figures 3, 4, 5, and 6. The spatial distribution of the required soil hydraulic properties was determined using the simple kriging technique, employing a linear model with a ratio of 1 and an angle of 0. This section utilized all 752 data points across all soil texture types.

From the figures mentioned above, the

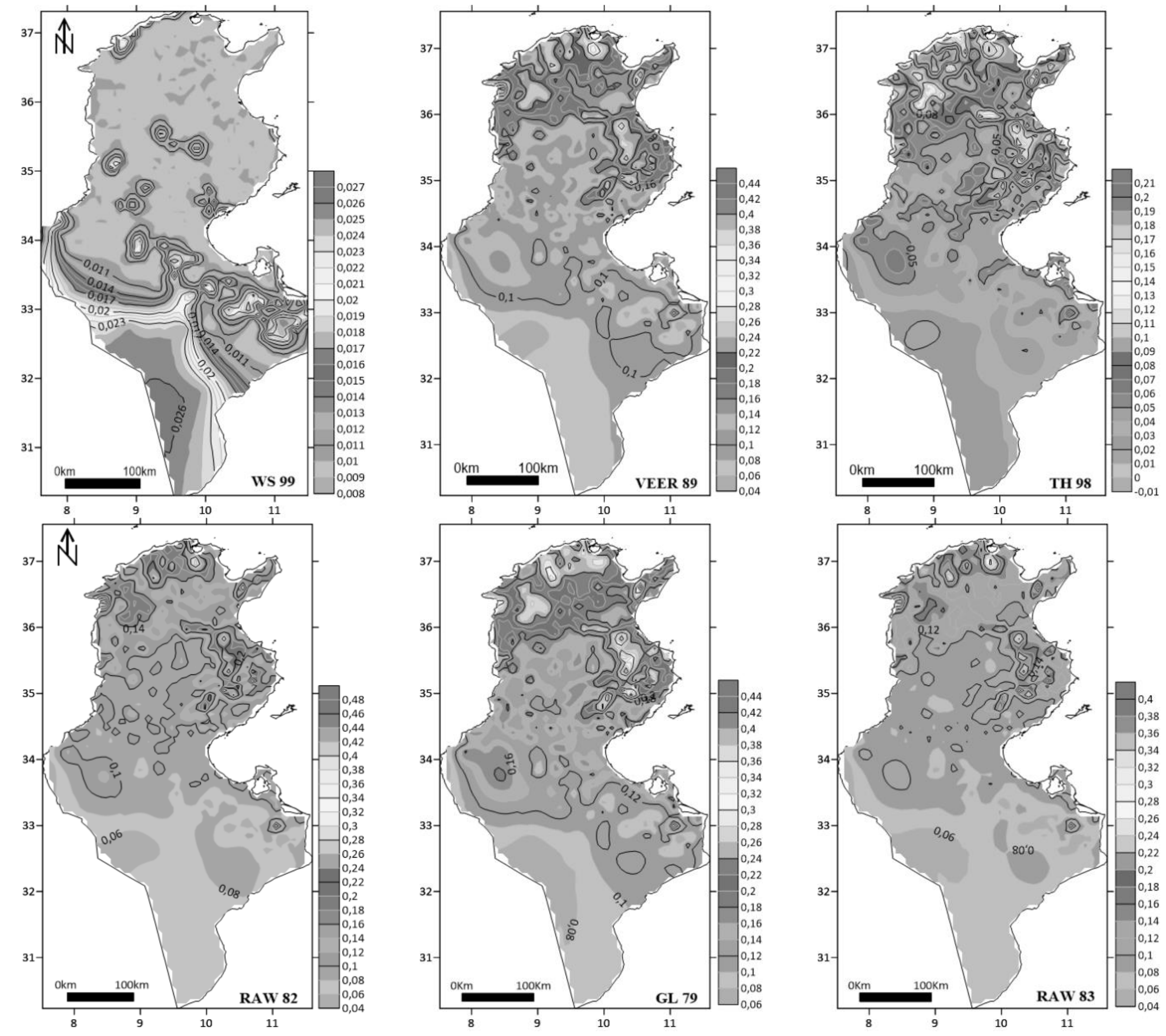

Figure 3. Maps of the soil residual water content in Tunisia estimated by PTFs.

following observations can be made:

- Concerning θr maps: Three of the utilized PTFs (VAR82, WOS99, and RV92) did not yield any values. The remaining PTFs generated six maps. The majority of spatial variability is concentrated in the northern region of the country, while less variation is observed in the south across all PTFs. Notably, PTF WS99 stands as an exception, displaying significant spatial variability in the southern region.
- For θs: Spatial variability is evident across the entire region, with a reduction in variation noted in the southern areas for all PTFs.
- For the two shape parameters, α and n: Similar to the observation for θs, spatial variability is widespread throughout the northern region for most PTFs. However, certain exceptions exist. Specifically, for α, the TH98 and RV92 PTFs exhibit spatial variability solely in the northeastern region, while the VERR99 PTF displays variability exclusively in the southern part of the country. Regarding the parameter n, the GL79 PTF indicates the least spatial variability, with n values varying only within small regions in the central part of the country.

Table 2 provides a comprehensive summary of the key statistical indices — standard error (SE), coefficient of variation (CV), skewness, kurtosis, and the slope of the linear model utilized in the kriging process — for each soil hydraulic property and PTF.

Figure 7 illustrates the univariate statistics of these indexes, revealing both the range and pattern of each value. Notable findings from Figure 7 include:

- Skewness and kurtosis indexes exhibit minimal variation during the Cross Validation process, although exceptions exist for the shape parameter n.
- Considerable variations in range and pattern emerge during the grid generation process for all parameters.

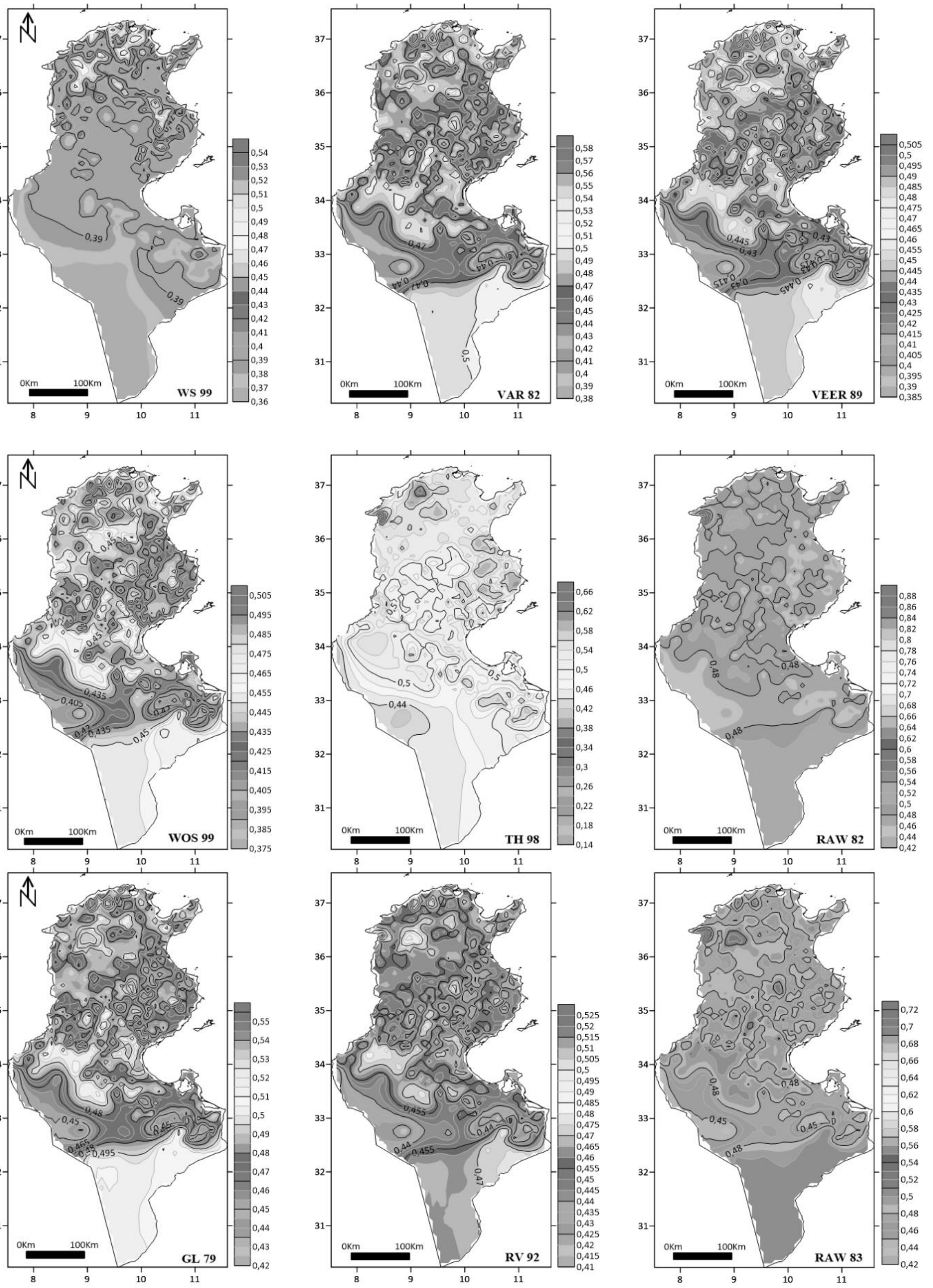

Figure 4. Maps of the soil saturated water content in Tunisia estimated by PTFs.

- The highest variability occurs in SE and CV for θr, θs, and n. Conversely, the shape parameter α experiences the least variation across both processes.

Soil saturated hydraulic conductivity holds significant importance when estimating soil retention properties. The two PTFs, Rosetta and Saxton, appear to yield varying values based on the spatial distribution depicted in Figure 8. Notably, Rosetta

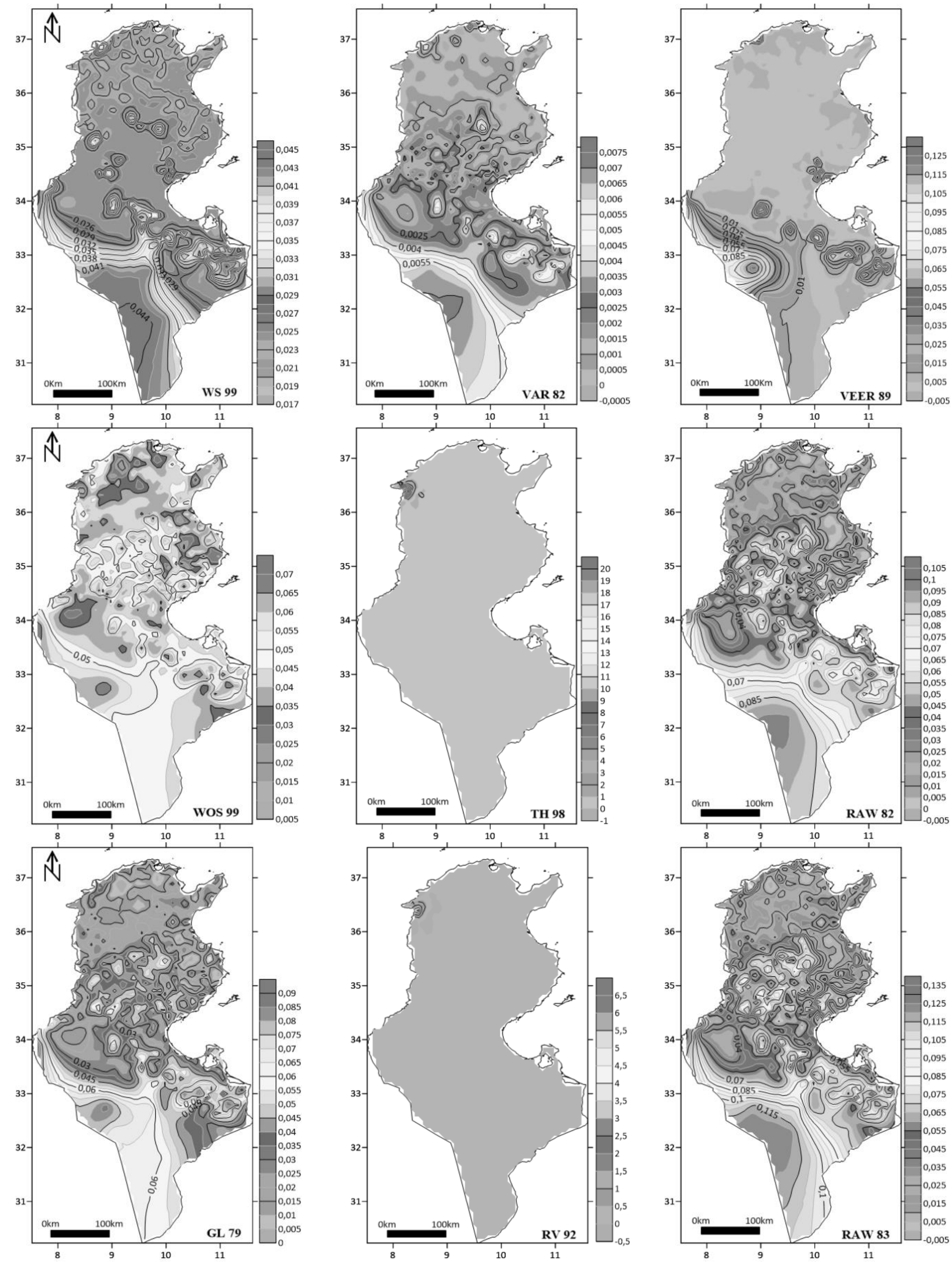

Figure 5. Maps of the soil shape parameter α in Tunisia estimated by PTFs.

exhibits a high degree of variability in Ks across all regions of the country. In contrast, the Saxton equation reveals less variability, primarily concentrated in the northern areas.

4. DISCUSSION

The large-scale characterization of soil hydraulic properties was the focus of this work, which used a technique that provides a thorough understanding of the spatial pattern of each parameter along its range. The regional distribution of soil hydraulic characteristics has not been extensively studied (Popolizio et al., 2022). Soil saturated hydraulic conductivity and other soil hydraulic characteristics show significant regional heterogeneity, as reported by Mohajerani et al., (2021). Researchers often emphasize local scales to optimize irrigation practices (Kumar et al., 2022) or refine input parameters for numerical models (Kanzari, 2018).

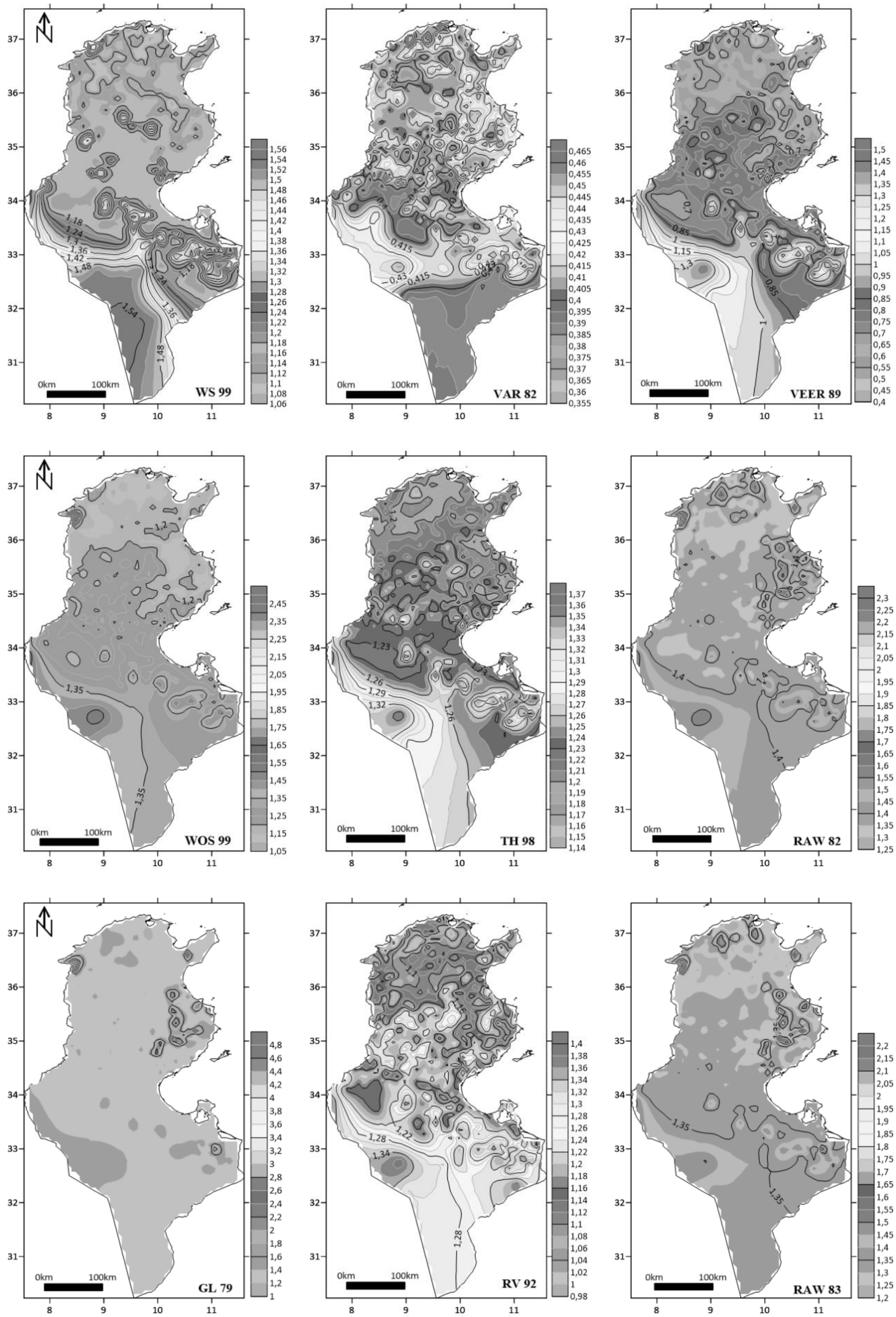

Figure 6. Maps of the soil shape parameter n in Tunisia estimated by PTFs.

Table 2. Geostatistical parameters for the evaluation of data during the grid generation and the cross-validation process for each soil hydraulic parameter map and for each PTFs.

		Slope	Grid Data				CrossValidation			
			Standard Error	***CV***	***Skewness***	***Kurtosis***	**Standard Error**	***CV***	***Skewness***	***Kurtosis***
θ_r	WS99	6E-06	2E-04	0.37	3.00	10.00	3E-04	0.31	4.07	17.69
	GL79	1E-03	2E-03	0.38	1.41	6.13	8E-03	0.43	1.52	5.44
	RAW82	5E-04	2E-03	0.46	2.13	9.70	7E-03	0.50	1.63	5.28
	VEER89	1E-03	2E-03	0.40	0.40	5.66	7E-03	0.42	1.14	4.05
	RAW83	2E-03	2E-03	0.45	2.85	13.59	7E-03	0.53	2.27	7.81
	TH98	9E-04	1E-03	0.64	1.60	6.72	4E-03	0.73	1.49	5.91
θ_s	RV92	5E-04	7E-04	0.04	-0.09	3.54	2E-03	0.04	-0.48	3.16
	VAR82	6E-04	1E-03	0.08	0.13	3.46	4E-03	0.08	0.03	3.04
	WS99	2E-04	1E-03	0.09	2.07	6.32	4E-03	0.11	1.93	5.41
	GL79	2E-04	9E-04	0.05	-0.11	3.53	2E-03	0.05	-0.37	3.24
	RAW82	7E-04	1E-03	0.06	5.33	88.48	2E-03	0.05	-0.21	3.12
	WOS99	3E-04	9E-04	0.05	-0.31	3.27	2E-03	0.05	-0.38	3.03
	VEER89	2E-04	8E-04	0.05	0.05	3.81	2E-03	0.05	0.00	3.50
	RAW83	1E-04	1E-03	0.06	1.53	19.81	2E-03	0.05	-0.20	2.69
	TH98	3E-04	2E-03	0.09	-1.51	17.85	4E-03	0.09	-0.08	2.97
α	RV92	1E-05	1E-02	16.34	27.31	747.78	4E-04	0.61	1.27	7.38
	VAR82	9E-07	6E-05	0.00	1.49	5.06	1E-04	1.08	1.73	6.29
	WS99	1E-04	2E-04	0.22	2.25	7.92	5E-04	0.20	2.30	10.68
	GL79	5E+00	7E-04	0.60	0.80	3.36	2E-03	0.68	0.70	3.19
	RAW82	3E-01	9E-04	0.65	0.33	2.18	2E-03	0.74	0.34	1.85
	WOS99	2E-04	4E-04	0.27	0.14	3.39	1E-03	0.33	-0.03	2.78
	VEER89	2E-04	6E-04	4.49	5.42	31.99	2E-03	5.03	5.46	31.67
	RAW83	3E-02	1E-03	0.65	0.56	2.67	3E-03	0.74	0.62	2.65
	TH98	4E-04	3E-02	6.36	27.20	743.81	5E-03	0.49	0.88	3.55
n	RV92	4E-03	3E-03	0.07	0.05	2.81	8E-03	0.07	-0.01	2.77
	VAR82	2E-04	8E-04	0.05	0.05	2.93	2E-03	0.05	0.05	2.43
	WS99	1E-02	4E-03	0.09	2.54	8.60	9E-03	0.07	3.04	13.18
	GL79	4E-03	1E-02	0.21	7.77	74.85	5E-02	0.31	3.52	13.88
	RAW82	5E-04	4E-03	0.07	4.02	30.33	1E-02	0.09	2.25	7.58
	WOS99	4E-03	4E-03	0.08	6.09	86.46	8E-03	0.07	1.69	7.66
	VEER89	3E-02	7E-03	0.24	1.71	7.89	2E-02	0.25	1.74	8.55
	RAW83	2E-03	4E-03	0.08	4.57	31.71	1E-02	0.11	2.93	10.95
	TH98	4E-03	1E-03	0.03	1.51	7.32	4E-03	0.03	1.45	7.16
K_s	Rosetta	2E-01	2E+00	1.88	5.02	28.32	3E+00	1.91	6.48	45.28
	Saxton	7E+02	1E-01	1.24	4.09	20.99	3E-01	1.33	4.48	24.08

SE : Standard error ; CV : Coefficient of variation.

Conducting statistical analyses on values derived from different PTFs can prove advantageous for streamlining the obtained database (Gupta et al., 2022). Notably, if differences between two PTFs lack significance, averaging their values can simplify the database.

While the PTFs incorporated within the CalcPTFs software rely on only five soil physical and chemical properties, other properties like soil organic matter content and soil cover play pivotal roles in alternative PTFs for estimating soil hydraulic properties (Mohajerani et al., 2021; Mayr & Jarvis, 1999). However, it's essential for each PTF-estimated value to undergo validation against reference measurement methods such as Richards pressure plates (Wassar et al., 2016) or the evaporation method (Singh & Kuriyan, 2003).

Most soils in Tunisia exhibit a soil saturated hydraulic conductivity exceeding 20 $cm.day^{-1}$, primarily resulting from percolation following rainfall events or irrigation (Paltineanu et al., 2022). This heightened conductivity poses an increased risk of groundwater contamination by chemicals (Gobinath & Ramesh, 2023) and fertilizers leaching from the topsoil (Domnariu et al., 2022; Paltineanu et al., 2021).

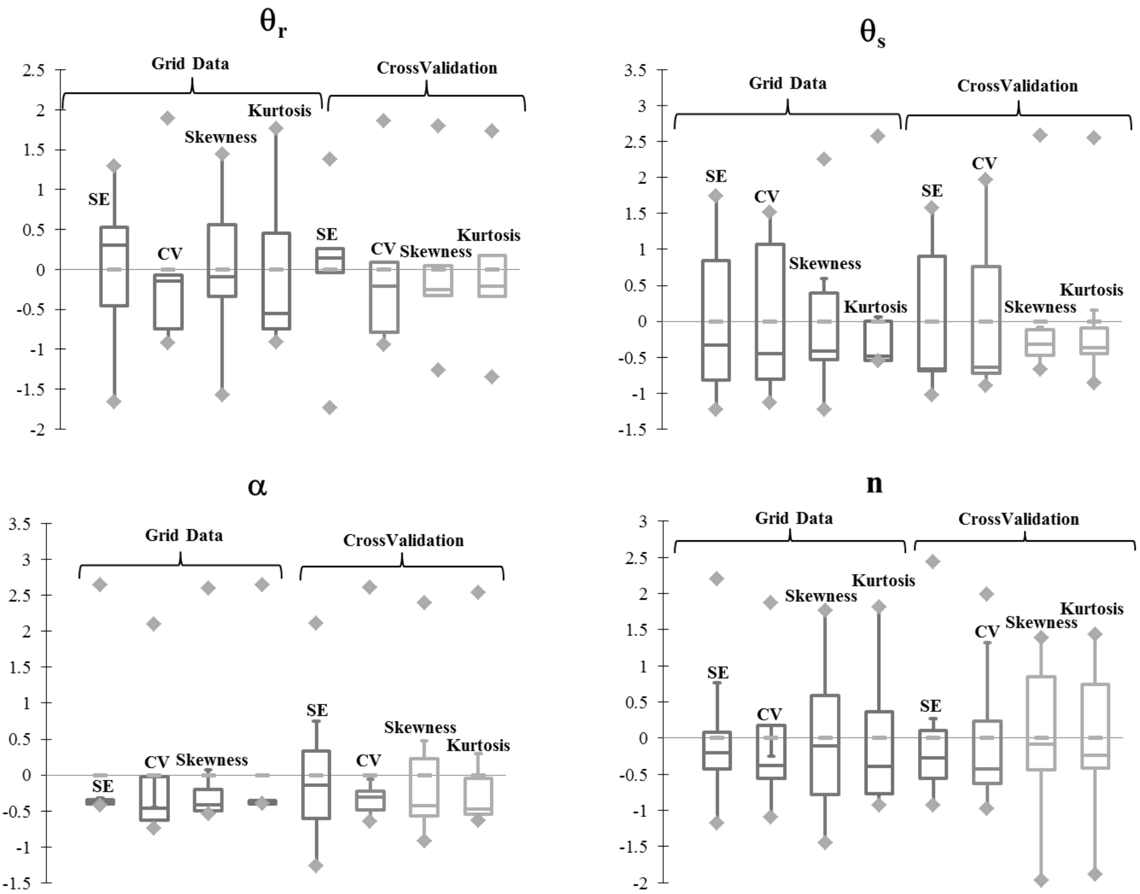

Figure 7. Univariate statistics by box plot for the kriging maps in the generating data (Grid Data) and the CrossValidation processes (100 points).

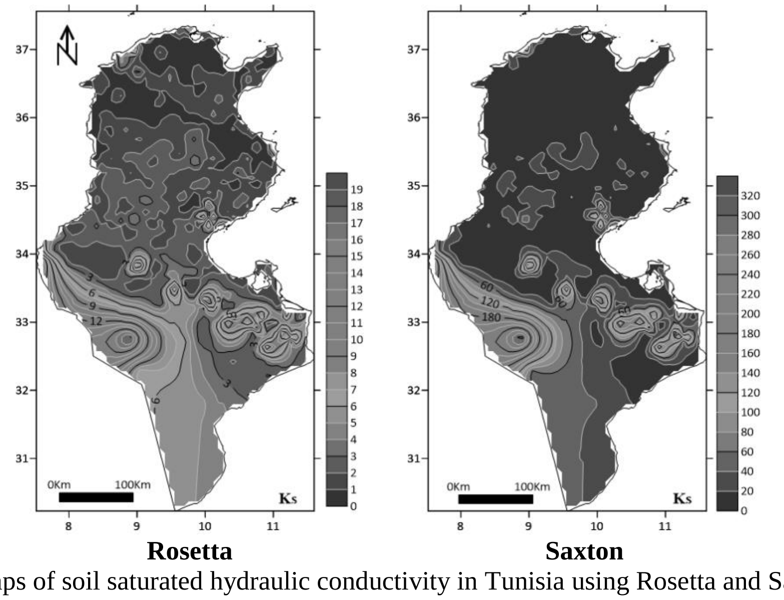

Figure 8. Maps of soil saturated hydraulic conductivity in Tunisia using Rosetta and Saxton PTFs.

Simple kriging stands as a versatile technique for spatial soil property analysis (Gia Pham et al., 2019). External validation (Ma et al., 2010) remains critical for refining model parameters. Additionally, alternative models for mapping soil hydraulic properties can be explored (Mitchell-Fostyk & Haruna, 2021).

5. CONCLUSION

The study focused on investigating soil hydraulic properties using the van Genuchten model, specifically targeting the primary soil texture types found in Tunisia. The HWSD database, being freely accessible and encompassing most requisite input parameters, facilitated the utilization of PTFs, such as those integrated into the CalcPTF software, to derive values for each soil hydraulic parameter, including soil retention and soil saturated hydraulic conductivity. Combining statistical (ANOVA) and geostatistical (kriging) methods seems to provide useful instruments for assessing these attributes' geographical distribution.

The results of the study show that the northern region has the majority of the variability in soil retention and soil saturation hydraulic conductivity. For future endeavors, it is advisable to focus soil sampling efforts primarily in the northern areas to effectively validate the outcomes derived from different PTFs.

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