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Predicting saturated hydraulic conductivity using soil morphological properties

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Abstract

Many studies have been conducted to predict soil saturated hydraulic conductivity (K_s) by parametric soil properties such as bulk density and particle-size distribution. Although soil morphological properties have a strong effect on K_s, studies predicting K_s by soil morphological properties such as type, size, and strength of soil structure; type, orientation and quantity of soil pores and roots and consistency are rare. This study aimed at evaluating soil morphological properties to predict K_s. Undisturbed soil samples (15 cm length and 8.0 cm id.) were collected from topsoil (0-15 cm) and subsoil (15-30 cm) (120 samples) with a tractor operated soil sampler at sixty randomly selected sampling sites on a paddy field and an adjecent grassland in Central Anatolia (Cankırı), Turkey. Synchronized disturbed soil samples were taken from the same sampling sites and sampling depths for basic soil analyses. Saturated hydraulic conductivity was measured on the soil columns using a constant-head permeameter. Following the K_s measurements, the upper part of soil columns were covered to prevent evaporation and colums were left to drain in the laboratory. When the water flow through the column was stopped, a subsample were taken for bulk density and then soil columns were disturbed for describing the soil morphological properties. In addition, soil texture, bulk density, pH, field capacity, wilting point, cation exchange capacity, specific surface area, aggregate stability, organic matter, and calcium carbonate were measured on the synchronized disturbed soil samples. The data were divided into training (80 data values) and validation (40 data values) sets. Measured values of K_s ranged from 0.0036 to 2.14 cmh^{-1} with a mean of 0.86 cmh^{-1}. The K_s was predicted from the soil morphological and parametric properties by stepwise multiple linear regression analysis. Soil structure class, stickiness, pore-size, root-size, and pore-quantity contributed to the K_s prediction significantly ($P<0.001$, $R^2 = 0.95$). Soil morphological properties can be used along with basic soil properties in predicting K_s.

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Introduction

Soil is a complex system, comprising solid, liquid and gas phases. The liquid and gas phase fill the pores that located between the solid portions. The water in these pores moves continuously by the action of evaporation, precipitation or gravitational forces even though its speed is very slow. The driving force of soil water movement is potential difference exerted from differences in water potential at different regions in

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soil. Hydraulic conductivity is the unique soil property that determines the water flow rate under specified soil water potential gradient (Jurry et al., 1991).

Soil hydraulic properties vary spatially and temporally, and direct measurement of these properties is time consuming and expensive. Therefore, indirect methods such as pedotransfer functions (PTFs) have been used frequently to predict soil hydraulic properties. Hydraulic conductivity is one of the most commonly predicted soil properties by PTFs. Knowing the relationship between hydraulic conductivity and other soil properties are very useful for understanding water flow in soils. Soil physical and chemical properties such as bulk density, organic matter content, porosity, and pore-size distribution are used quite a lot to model saturated and unsaturated hydraulic conductivity of soils (Wösten et al., 2001).

Soil morphologic properties such as soil structural features, soil pores, and roots are expected to affect saturated water flow in soils. Pachepsky et al. (2008) stressed that since soil structural properties are closely related to soil hydraulic parameters, including them in the list of PTF inputs may substantially improve predictions of soil hydraulic parameters. However, use of morphological properties in modeling saturated hydraulic conductivity (K_s) has been ignored for a long time (Lin et al., 1999).

Accoring to Abbaspour and Moon (1992),'Recent trends in PTF's research, however, indicate attempts to expand methods and data collections to better link hydraulic properties to morphological properties. An earlier attempt to bring structural parameters from the horizon/pedon scale to improve predictions of soil hydraulic properties at the aggregate/ped scale was generally unsuccessful'. On the other hand, Lilly et al. (2008) showed that morphological indicators could be used to predict soil hydraulic properties as well as commonly used laboratory data.

Soil morphological features, particularly those pertaining to structure may explain some of the variations in K_s (Sharma and Uehara, 1968; Keng and Lin, 1982; Field et al. 1984; Bouma, 1992). Saturated hydraulic conductivity can also be related to soil morphological criteria based on the expert assessment (McKenzie et al., 2000). The aim of this study was to evaluate potential of some readily avalable soil morphological properties in soil survey reports to predict K_s.

Material and Methods

Material

This study was carried out on paddy and adjacent grassland soils (total 9-ha) in Kızılırmak Township in Cankırı Province in Central Anatolia, Turkey. The study area is located 40º 30' 41º North latitude and 32º 30' 34º East longitudes in the north of Central Anatolia Region of Turkey (Fig. 1). The climate in the region is semi-arid and annual temperature, humidity, evaporation, and rainfall is 11 ºC, 64%, and 418 mm, respectively. Cankırı is surrounded by bare mountains and plateaus (Anonymous, 2011). The parent material within the study area comprises gypsum, andesite, spilite, basalt, marl, clay, and limestone and soils are classified as Gypsic Ustorthends.

Figure 1. Map showing location of the study area (Anonymous, 2014)

Methods

Undisturbed soil samples (15 cm length and 8.0 cm id) were taken from topsoil (0-15 cm) and subsoil (15-30 cm) at randomly selected sixty sampling points) with a tractor mounted sampling apparatus. Saturated hydraulic conductivity (K_s) was measured on the soil columns using a constant-head permeameter (Klute and Dirksen, 1986). After K_s measurement, the soil column was left standing on a desk to dry and when the water flow through the column was stopped (approximately 3 days after the test), a 100 cm^3 sample was taken by a steel cylinder for bulk density measurement and the rest of the column was disturbed and used for diagnosis of morphological properties. Bulk density was measured by the method from Blake and Hartge (1986).

Basic soil properties were measured on disturbed soil samples taken concomitantly with undisturbed samples. Particle–size distribution (Gee and Bauder, 1986), aggregate stability index (Kemper ve Rosenau, 1986), field capacity and wilting point (Klute, 1986), pH and electrical conductivity (Page et al., 1982), specific surface area (Carter et al., 1986), soil organic matter content (Page et al., 1982), cation exchange capacity (Page et al., 1982), $CaCO_3$ (Page et al., 1982), and Coefficient of Linear Extensibility; COLE (Schafer and Singer, 1976) were measured on the disturbed samples.

Soil morphological properties (structure, pores, consistence, stickiness, plasticity, roots, and mottles) were described with standard soil description charts (USDA-NRCS, 2002) used in soil survey studies. The morphological properties and soil colors were converted into numerical values. The strategy "greatest is the best" was applied in coding, depending on the expert idea on relationship between K_s and subjected property (Tables 1-7).

Table 1. Criteria applied to soil color coding in undisturbed soil samples (Munsell Color Scala)

Soil Color	Code	Soil Color	Code	Soil Color	Code	Soil Color	Code
Gley	1	7.5 YR 4/2	3	7.5 YR 5/2	4	7.5 YR 6/2	5
7.5 YR 3/2	2	7.5 YR 4/3	3	7.5 YR 5/3	4	7.5 YR 6/3	5
7.5 YR 3/3	2	7.5 YR 4/4	3	7.5 YR 5/4	4		
7.5 YR 3/4	2						

Soil structure was coded according to type, grade (Table 2), and size (Table 3), and code numbers was attained, accordingly (Table 2).

Table 2. Criteria applied to soil structure coding in undisturbed soil columns(USDA-NRCS, 2002)

Type	Code	Grade	Code
Masive	1	Structureless	1
Platy	2	Weak	2
Prismatic	3	Moderate	3
Blocky/Angular	4	Strong	4
Blocky/Sub-angular	5	Very strong	5
Granular	6		
Single grain	7		

Table 3. Criteria applied to soil structure coding in undisturbed soil columns(USDA-NRCS, 2002)

Size	Granular/Platy (mm)	Block-Angular / Subangular (mm)	Code
Very thin	< 1	< 5	1
Thin	1 – 2	5 – 10	2
Medium	3 – 5	11 – 20	3
Coarse	6 – 10	21 – 50	4
Very coarse	>10	>50	5

Pores in soil samples were classified according to quantity, size, and type and code numbers was given (Table 4).

Table 4. Criteria applied to coding soil pores in undisturbed soil columns (USDA-NRCS, 2002)

Quantity	Code	Size	Size (mm)	Code	Type	Code
Few	1	Micro	< 0,075	1	Irregular	1
Common	2	Very fine	0,075-1	2	Vesicular	2
Many	3	Fine	1-2	3	Dendritic tubular	3
		Medium	2-5	4	Tubular	4
		Coarse	5-10	5	Interstitial	5
		Very coarse	≥ 10	6		

Rupture resistance of soils were determined. Parts of soil samples with size about 3 cm were taken, and strength was evaluated by applying pressure to crash the aggregate and then consistency was evaluated according to Table 5.

Table 5. Consistency Classification Criteria of undisturbed soil columns (USDA-NRCS, 2002)

Consistency	Code	Definition
Loose	5	There is no adhesion between grains.
Soft	4	Adhesion between grains is weak, it becomes powder with light pressure
Slightly hard	3	Soils breakable and disintegrate with light pressure
Hard	2	It is quite resistant to pressure, crushed difficultly between the fingers, and it breakable in the palm.
Very hard	1	It is very durable to pressure, not breakable between the fingers, and hardly breakable in the palm.

Soil stickiness was evaluated at soil moisture slightly above field capacity. Stickiness was observed on the sample squeezed between thumb and forefinger and classified according to degree of adhesion (Table 6). Soil plasticity was determined on the soil yarns at field capacity. The strength of yarns were evaluated according to the state to support when they were standed with approximately 45-degree angle with vertical (Table 7).

Table 6. Criteria applied to stickness coding in undisturbed soil samples (USDA-NRCS, 2002)

Stickiness	Code	Definition
Not sticky	1	Soil does not stick when squeezed between the fingers.
Slightly sticky	2	Soil sticks to one finger
Moderatelystick	3	Soil sticks to two fingers and mud elongate slightly when fingers opened
Very sticky	4	Soil sticks firmly to two fingers and mud extend in certain ways when fingers opened

Table 7. Criteria applied to plasticity coding in undisturbed soil samples (USDA-NRCS, 2002)

Plasticity	Code	Definition
Not plastic	1	Soil does not form yarn.
Slightly plastic	2	Soil forms yarn, but easily breaks
Plastic	3	Soil forms yarn, and it resist somehow against breaking
Very plastic	4	Soil forms yarn and it resists agains breaking

Roots in soil samples were classified according to their quantity and size, and code numbers were given, accordingly (Table 8). Mottles of soil samples were evaluated according to percentage of the soil surface covered and they were coded in three classes (Table 8).

Table 8. Criteria applied to root and mottles coding in undisturbed soil samples (USDA-NRCS, 2002)

Root Quantity		Code	Root Size		Code	Mottle Quantity	Code	Mottle Percentage(%)
Not or few	<1	1	Very thin	<1mm	1	Not or few	3	%2
Common	1-5	2	Thin	1-2mm	2	Common	2	%3 - %20
Many	>5	3	Medium	3-5 mm	3	Many	1	>% 20
			Coarse	6-10 mm	4			
			Very coarse	>10 mm	5			

Of the 120 soil columns, 80 were selected randomly for training and 40 for validation of the predicitons. Saturated hydraulic conductivity (K_s) was predicted by forward stepwise linear regression technique usingcodes of soil morphological properties given in Tables 2-8. Independent variables, which significantly ($P<0.05$) contributed to prediction of K_s were selected as predicting variables.

The accuracy of the developed model was evaluated using validation data set. The predicted K_s were compared with their corresponding measured values. The coefficient of determination (R^2), root mean square error, mean absolute error, and correlation coefficient between measured and predicted K_s-values were used as criteria for sucsess of the developed PTF.

Results and Discussion

Laboratory measured saturated hydraulic conductivity (K_s) values ranged from 2.76 and 0.0036 cmh^{-1} with a mean of 0.82 cmh^{-1} for training and 0.83 cm h^{-1} for validation data sets. Coefficient of variation (CV) was 79.7% for calibration and 80.3% for validation data set, indicating that validation and calibration data sets have similar distributions (Tables 9 and 10).

Greatest variation occurred for K_s and lowest for pH in physical and chemical properties of soils. These results agreed to those reported in literature (Mulla and McBratney 2002). Most of the soil properties exhibited medium variation, and this agreed to those reported by many different authors. Unexpectedly, soil textural components exhibited somehow greater variations than frequently reported values in the literature, and it was attributed that the study area is highly variable in topography and to that soils have been derived from alluvial and colluvial parent materials. Root size have greatest and structure type have lowest variation among soil morphological properties. The soils generally have a high clay content and have angular and subangular bolocky structure.

Table 9. Exploratory statistics of physical, chemical, and morphological properties of the calibration soils (N =80)

Soil properties	Maximum	Minimum	Mean	Std.Deviation	%VC
K_s, cm h^{-1}	2.25	0.0036	0.82	0.65	79.78
Sand, %	74.17	1.49	27.36	17.44	63.74
Silt, %	65.54	4.89	26.83	11.24	41.89
Clay, %	76.8	7.88	45.79	17.06	37.26
BD, gcm^{-3}	1.62	1.08	1.25	0.09	7.89
SSA, m^{2}g^{-1}	284.85	96.75	207.19	48.84	23.57
CEC, meg/100 g	73.85	31.58	55.74	8.07	14.48
COLE, %	9.8	4.5	8.14	1.49	18.30
FC, %	43	21	35.26	6.55	18.57
WP, %	31.0	9.0	22.93	6.32	27.52
pH	9.7	7	8.42	0.46	5.57
EC	0.48	0.01	0.13	0.09	73.1
ASI	0.589	0.19	0.49	0.04	9.05
SOM, %	7.12	0.40	4.09	1.23	30.23
$CaCO_3$, %	24.15	5.11	15.22	4.35	28.63
Structure Grade	4	1	2.03	1.02	50.27
Structure Type	6	2	4.58	0.83	18.25
Structure Size	4	1	2.82	0.95	33.68
Pore Size	5	1	2.43	1.38	56.84
Pore Quantity	3	1	1.85	0.76	41.33
Consistency	6	1	3.63	1.22	33.66
Plasticity	4	1	2.21	0.88	39.84
Stickiness	4	1	2.35	0.76	32.54
Root Size	4	1	1.33	0.70	53.40
Root Quantity	4	1	1.39	0.83	60.12
Mottles	3	1	1.09	0.32	29.96
Color	5	2	3.45	1.00	29.13

K_s: saturated hydraulic conductivity, ρ_b: Bulk Density, SSA: spesific surface area, CEC: cation exchange capasity, COLE:coefficient of linear extensibility, FC: field capacity, WP: wilting point, ASI: agregatte stability index, SOM: soil organic matter

Table 10. Exploratory statistics of physical, chemical, and morphological properties of the validation soils (N =40)

Soil properties	Maximum	Minimum	Mean	Std.Deviation	%VC
K_s, cmh^{-1}	2.71	0.0036	0.84	0.68	80.30
Sand, %	62.75	2.48	29.00	17.0	58.61
Silt, %	52.5	10.09	25.07	8.74	34.86
Clay, %	82.7	2.48	45.91	19.67	42.86
BD, gcm^{-3}	1.51	1.06	1.25	0.094	7.53
SSA, m^2g^{-1}	271.36	82.081	198.45	42.87	21.60
CEC, meg/100 g	70.86	21.8	54.09	8.81	16.29
COLE, %	9.8	4	8.22	1.53	18.62
FC, %	43	20	35.42	6.78	19.15
WP, %	31	8	23.32	6.91	29.61
pH	9.77	6.7	8.36	0.49	5.87
EC	0.47	0.01	0.13	0.08	73.0
ASI	0.57	0.42	0.49	0.02	3.96
SOM, %	7.98	0.94	4.21	1.42	33.45
$CaCO_3$, %	22.69	5.69	15.10	4.05	26.79
Structure Grade	4	1	2.07	1.03	49.83
Structure Type	6	2	4.47	0.92	20.59
Structure Size	4	1	2.85	1.06	37.25
Pore Size	5	1	2.4	1.32	54.96
Pore Quantity	3	1	1.87	0.81	43.31
Consistency	6	1	3.6	1.32	36.64
Plasticity	4	1	2.3	0.93	40.83
Stickiness	4	1	2.42	0.81	33.52
Root Size	4	1	1.15	0.57	49.76
Root Quantity	4	1	1.25	0.80	63.87
Mottles	2	1	1.05	0.22	20.75
Color	5	2	3.5	0.92	26.34

K_s: saturated hydraulic conductivity, ρ_b: bulk density, SSA: spesific surface area, CEC: cation exchange capasity, COLE: coefficient of linear extensibility, FC: field capacity, WP: wilting point, ASI: agregatte stability index, SOM: soil organic matter

The forward stepwise multiple linear regression was performed for developing a PTF that predicts K_s from soil morphological and parametric properties. Soil properties, which significiantly contributed the K_s prediction are shown in Table 11.

Table 11. Soil morphological properties contributed to K_S prediction significantly ($P \leq 0.05$)

Independent Variables					R^2	SSE
Stickiness					90.40	0.206
Stickiness	Structure-grade				93.24	0.174
Stickiness	Structure-grade	Pore-size			93.63	0.170
Stickiness	Structure-grade	Pore-size	Plasticity		93.98	0.167
Stickiness	Structure-grade	Pore-size	Plasticity	Pore-quantity	94.55	0.160

Greatest correlation occurred between K_s and Stickiness (Table 10). Stickness, structure grade, pore size, plasticity, and pore quantity contributed the K_s prediction significantly as shown by Eq (1).

$$K_s = 0.565 - 0.331x(\text{Stickiness}) + 0.184x(\text{Structure Grade}) + 0.0625 \times (\text{Pore Size}) + 0.182x(\text{Plasticity}) + 0.217 \times (\text{Pore Quantity}) \quad (1)$$

The Eq. (1) described 95% of the total variation in K_s. Eq.(1) was used with validation data to evaluate its prediction success using mean error (ME), root mean squared error (RMSE), and mean absolute error (MAE). The results were highly successful (MAE= 0.0042, RMSE = 0.203, MAE = 1.145). In addition, predicted and measured K_s values of validation data set were correlated and related to each other by a 1:1-line (Fig. 2). The results suggested that the Eq (1) was successfully predicted K_s in studied soils.

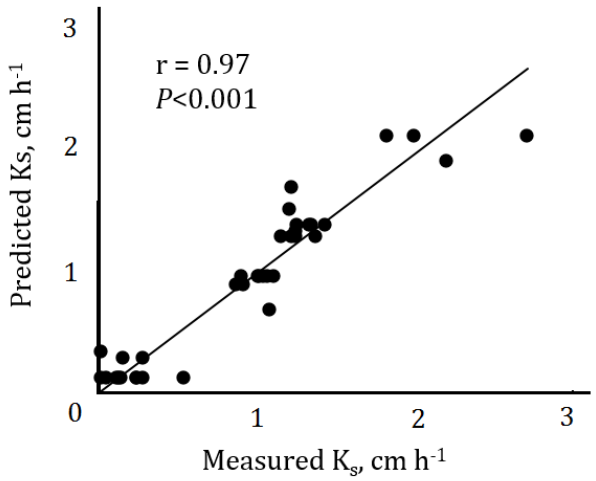

Figure 2. Correlation between measured and calculated K_s-values of validation data set

Effects of clay content on soilphysical and chemical properties have long been known. Besides clay content, clay type is an important factor,controlling many soil properties such as specific surface area, CEC, water hold capacity, COLE index, swelling, shrinking, plasticity, and stickiness. Swelling, stickiness, and plastisity are main soil properties controlled by amount and type of soil clay. Stickiness is greater in soils rich in high activity clays (montmorillonite and vermiculite). These clays are 2:1 type and they have high expansion, adsorptivity, and water retention capacities. When these clays wet, they swell, resulting in decreased soil porosity and decreased water conductivity. In addition, soils rich in these clays can be compacted easily. It was reported in Rahman (2000) that 'The smectite mineral particles have a large specific surface area of up to 800 m^2 g^{-1} and have a high adsorptive capacity and can be compacted to give very low hydraulic conductivity (10^{-11} to 10^{-13} ms^{-1})'. Boivin et al. (2004) reported that swelling capacity of the soil increases with clay content, which is related to clay type, pore size, and moisture content.

Soil clay influence on the soil plasticity and soil stickiness are highly similar since the point of stickiness usually lies above the upper plastic limit on the moisture scale (Baver, 1956). Greater liquid limit, plastic limit, and surface activity are associated with soils having a greater quantity of clay particles (Mitchell, 1976). Soils containing a large quantity of expanding minerals generally have a high plasticity index. The liquid limit and the plastic limit reflect the consistency of the soilstructure. All other factors being equal, more plastic clays should have lower hydraulic conductivity (Day and Daniel, 1985; Mesri and Olson, 1971). The results of this study showed that, expectedly, soil stickiness had a significantly negative correlation with K_s. Soil consistency and structural parameters can serve as predictors of soil water retention because those parameters are related to soil basic properties that affect soil hydraulic properties (Rawls and Pachepsky, 2002).

According to Pachepsky et al. (2006), typical PTF inputs such as soil texture, bulk density, or organic carbon content, are related to the pore structure in a broad sense, but are not sufficient to fully characterize the pore structure of a specific soil. Soil structure type affects the soil structure grade. The absence of large structural units might mean absence of large pores and a wide pore-size distribution that should provide relatively large water retention near field capacity (Pachepsky et al., 2006). Majority of the soil samples (87%) used in this study had medium to strong angular and subangular blocky structure and a significant positive correlation occurred between soil structure type and K_s in our study, agreed to those reported by Mckeagu et al. (1982).

Soil clay content and clay type have a considerable influence on soil structure and pore geometry, which in turn affects K_s. Type, size, spatial orientation, and arrangement of soil pores have significant influence on K_s (Beven and German, 1982). Increased macro porosity in soil structure results in an increased soil hydraulic conductivity (Ahuja et al. 1985). Large and continuous pores have far grater water conductivity than smaller pores. Soils with high clay content generally have lower K_s than sandy soils. Sandy soils generally have greater bulk density and lower total porosity than clayey soils. However, pore-size distribution in sandy soil favors large pores, which promote K_s (Soil Survey Staff, 1993). The results of Keren and Singer (1988) and

Kosmas and Moustakas (1990) suggest that there may be interactions between the dispersion of clays and the swelling processes and their impact on pore size and continuity, and thus on K_s.

Water flow is faster in inter-granular pores in granularly structured soils. In addition, preferential flow is common in saturated structured soils. Presence of root channels and earthworm channels enhances saturated water flow in soils. Water flow in sandy soils is generally higher; however, comparable high K_s values were reported in structured clay soils due to presence of structural features such as cracks, earthworn channels and root channels and large inter-aggregate openings. Anderson and Bouma (1973) reported that excellent estimates of K_s were obtained when void sizes have been measured directly.

A significant positive correlation between observed inter-aggregate pore quantity and K_s was obtained (Eq.1). In this study, amount of the voids (interstitial, tubular, dendritic, irregular, vasicular in shape) between soil aggregates, which detecteable by naked eye, were considered as structural pores.These pores, mainly located between aggregates (inter-aggregate),rapidly conduct waterin saturated soils. However, intra-aggregate pores are not as important as inter-aggregate pores in K_s since water flow very slowly in narrow intra-aggregate pores. In general, total porosity increases with soil clay content as there are many pores between fine soil particles, while most of these pores are small in size and hold water tidily.

Saturated hydraulic conductivity depends on many soils parametric (clay, sand, silt, organic matter contents; specific surface area, cation exchange capacity, soil sodicity and electrolyte concentration of soil solution; and morphological properties such as soil structure, soil porosity and pore geometry, macrospores and roots, and consistency). In K_s modeling studies, soil parametric variables are generally preferred. However, it's well known that a slight change in soil structure has a considerable impact on K_s since K_s is strongly controlled by soil pores and their geometry and their orientations in soils. In this study, significant relations between K_s and soil morphological properties of stickiness, structure grade, structural pore-size, plasticity, and pore quantity were obtained and it was clearly shown that these variables could successfully be used in prediction of K_s in paddy and adjacent grassland soils by forward stepwise multiple regression analysis. The results were highly promising, suggesting that soil morphological properties can be used besides soil parametric variables in K_s modeling studies. Further studies are needed across different soil and management conditions to adapt use of soil morphology in K_s modeling.

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References

Abbaspour, K.C., Moon, D.E., 1992. Relationships between conventional field information and some soil properties measured in the laboratory. *Geoderma* 55(1-2): 119-140.

Ahuja, L. R., Naney, J. W., Williams, R. D.1985. Estimating soil water characteristics from simpler properties or limited data. *Soil Science Society of America Journal* 49: 1100–1105.

Anderson, J.L., Bouma, J., 1973. Relationships between saturated hydraulic conductivity and morphometric data of an argillic horizon. *Soil Science Society of American Proceedings* 37: 408– 413.

Anonymous, 2011. Çankırı İl Çevre Durum Raporu. Çankırı Valiliği Çevre ve Şehircilik İl Müdürlüğü. Available at : http://www.csb.gov.tr/turkce/dosya/ced/icdr2011/cankiri_icdr2011.pdf

Anonymous, 2014. Maps of World. Available at: http://www.mapsofworld.com

Baver, LD. 1956. Soil Physics. Third Edition. John Willey& Sons, Inc., New York.

Beven, K., Germann, P. 1982. Macropores and water flow in soils. *Water Resources Research* 18: 1311-1325.

Blake, G.R., Hartge, K.H., 1986. Bulk density. In: Methods of soil analysis. Klute, A., (Ed.), Part 1, 2nd edition pp. 363-373. American Society of Agronomy, Madison, WI.

Boivin, P., Garnier, P.P., Tessier, D., 2004. Relationship between clay content, clay type and shrinkage properties of soil samples. *Soil Science Society of America Journal* 68(4): 1145-1153.

Bouma, J., 1992. Effect of Soil Structure, Tillage, and Aggregation upon Soil Hydraulic Properties. Book Chapter. Interacting Processes in Soil Science (Ed; RJ Wagenet, P Baveye, BA Stewart).

Carter, D.L., Mortland, M.M., Kemper, W.D.1986. Specific Surface. Book Chapter 16. Eprints.nwisrl.ars.usda.gov.

Day, S. R., Daniel, D. E. 1985. Hydraulic conductivity of two prototype clay liners. *Journal of Geotechnical Engineering* 111: 957-970.

Field, J.A., Parker, J.C., Powell., N.L., 1984. Comparison of field and laboratory-measured and predicted hydraulic properties of soil with macropores. *Soil Science* 138: 385–396.

Gee, G.W., Bauder, J.W., 1986. Particle-size analysis. p. 383–411. In A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Manag. 9. ASA and SSSA, Madison, WI.

Jurry, W.A., Gardner, W.R., Gardner, W.H., 1991. Soil Physics. 5th. Ed. W, NY, 328 p.

Kemper, W. D., Rosenau, R. C., 1986. Aggregate stability and size distribution. In: Methods of soil analysis. Klute, A., (Ed.), Part 1, 2nd edition pp. 425-442. American Society of Agronomy, Madison, WI.

Keng, J.C., Lin, C.S., 1982. A two-line approximation of hydraulic conductivity for structured soils. *Canadian Agricultural Engineering* 24: 77–80.

Keren, R., Singer, M.J., 1988. Effect of low electrolyte concentration on hydraulic conductivity of Na/Ca-montmorillonite-sand system. *Soil Science Society of America Journal* 52: 368-373.

Klute, A. 1986. Methods of soil analysis, Part 1: Physical and mineralogical methods, 2nd edition, American Society of Agronomy, Madison, WI. 1188 p.

Klute, A., Dirksen, C., 1986. Hydraulic conductivity and diffusivity: laboratory methods. In: Methods of soil analysis. Klute, A., (Ed.), Part 1, 2nd edition pp. 687-734. American Society of Agronomy, Madison, WI.

Kosmas, C., Moustakas, N., 1990. Hydraulic conductivity and leaching of an organic saline-sodic soil. *Geoderma* 46: 363-370.

Lilly, A., Nemes, A., Rawls, W.J., Pachepsky, Ya.A., 2008. Probabilistic approach to the identification of input variables to estimate hydraulic conductivity. *Soil Science Society of America Journal* 72: 16–24.

Lin, H.S., McInnes, K.J., Wilding, L.P., Hallmark, C.T., 1999. Effects of soil morphology on hydraulic properties: II. Hydraulic pedotransfer functions. *Soil Science Society of America Journal* 63(4): 955-961.

McKeague, J.A., Wang, C., Topp, G.C., 1982. Estimating saturated hydraulic conductivity from soil morphology. Soil *Science Society of America Journal* 46: 1239–1244.

McKenzie, N.J., Jacquier, D.W., Ashton, L.J., Cresswell, H.P., 2000. Estimation of Soil Properties Using the Atlas of Australian Soils. Technical Report 11/00, CSIRO Land and Water, Canberra ACT.

Mesri, G., Olson, R. E., 1971. Mechanisms controlling the permeability of clays. *Clays and Clay Minerals* 19(3): 151-158.

Mitchell, J. K. 1976. Fundamentals of Soil Behavior. Series in Geotechnical Engineering, John Wiley & Sons, 422.

Mulla, D.J., McBratney, A.B., 2002. Soil spatial variability. In A.W. Warrick (Ed.), Soil Physics Companion (pp. 343-373). CRC Press, Boca Raton, FL.

Pachepsky, Y.A, Rawls, W.J, Lin, H.S., 2006. Hydropedology and pedotransfer functions. *Geoderma* 131(3-4): 308–316.

Pachepsky, Y., Nez, D.G., Lilly, A., Nemes, A., 2008. Promises of hydropedology. *CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources* 3 (040): 1-19.

Page, A.L., Miller, R.H., Keeney, D.R., 1982. Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties Second Edition. SSSA Publisher, Madison, Wisconsin USA.

Rahman, F. 2000. Hydraulic conductivity and chemical compatibility of some Victorian soils used as liners for waste containment. Ph.D Thesis. School of the Built Environment. Victoria University of Technology. Melbourne, Australia.

Rawls, W.J., Pachepsky, Ya. A., 2002. Soil consistence and structure as predictors of water retention. *Soil Science Society of America Journal* 66: 1115–1126.

Schafer, W.M., Singer, M.J., 1976. A new method of measuring shrink -swell potential using soil pastes. *Soil Science Society of America Journal* 40: 805-806.

Sharma, M., Uehara, G., 1968. Influence of soil structure on water relations in low humic latosols: I. Water retention. *Soil Science Society of America Journal* 32: 765-770.

Soil Survey Staff. 1993. Soil Survey Manuel. United States Department of Agriculture Handbook No: 18, USDA, Washington.

USDA-NRCS, 2002. Version 2.0. National Soil Survey Center Natural Resources Conservation Service U.S. Department of Agriculture, Lincoln, Nebraska.

Wösten, J.H.M., Pachepsky, Y.A., Rawls, W.J., 2001. Pedotranfer functions: Bridging the gap between available basic soil data and missing soil hydraulic characteristics. *Journal of Hydrology* 251: 123–150.