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Developing Mathematical Models of Saturated Hydraulic Conductivity in Iraqi Soils

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Abstract

Saturated hydraulic conductivity (Ksat) is a fundamental parameter in hydrology and modeling surface and groundwater flow, as well as the transport of dissolved materials within the soil. Estimating saturated conductivity by field or laboratory methods is often expensive and time-consuming. The hydraulic conductivity parameter is the most important parameter in modeling the hydraulic properties of soils in saturated and unsaturated soils and is subject to high variability and spatial differences across spatial scales. The study aims to develop a mathematical model for estimating the saturated hydraulic conductivity (ks) in Iraqi soils using basic physical properties. A theoretical model was initially proposed based on effective relative porosity (φer). However, regression analysis performed on empirical data collected from multiple soil samples across Iraq indicated that proposed theoretical relationship (ks = 75. φer) did not hold under actual conditions. Instead, an empirical model was derived using linear regression Ks= 12.29 φer+ 24.5, with a coefficient of determination (R2) of 0.443. This model suggests a moderate inverse correlation between φer and ks, likely due to textural and structural characteristics specific to the studied soils. The findings emphasize the need for localized calibration of hydraulic models to ensure accuracy in soil-water management practices.

Keywords:

Saturated hydraulic conductivity, soil physical and chemical properties.

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Introduction

Water conductivity is one of the most important properties that must be considered in irrigation and drainage, and to obtain accurate values for managing all natural or artificial processes that include water flow into the soil (Khudhur, 2024). It depends on studying the physicochemical (Sengupta & Deshmukh, 2024) composition of both water and soil and the composition of exchangeable positive ions. Many studies have agreed that saturated conductivity (Ksat) decreases because of the decrease in the total concentration of salt in the soil and the increase in the percentage of adsorbed sodium (SAR) in the soil solution (West et al., 2008). Water conductivity also decreases with an increase in ESP and a decrease in the electrolytic concentration of the soil solution. Water conductivity also decreases because of the sodic effects that depend on the concentration of the electrolytic soil solution. Saturated water conductivity also decreases with a decrease in the quality of irrigation water when SAR increases. On the other hand, saturated water conductivity increases when using saline water compared to distilled water and decreases with an increase in sodium in both (Khayyun and Mahdi, 2019; Naji and Ati, 2019; Keïta et al., 2019).

Saturated conductivity expresses the movement of water in saturated soils and the soil's ability to transmit water. It depends on the hydraulic properties and pore geometry. Water viscosity and density are the most important hydraulic properties affecting the saturated conductivity values of soils and are inversely proportional to them, while soil texture and structure primarily influence the geometry of pore spaces (Naji and Ati, 2019; Nasr and Ati, 2023). Several methods exist for measuring saturated conductivity, including field methods such as the constant water column method and the variable water column method. Laboratory methods rely on collecting soil samples, either stirred (placed in columns of known cross-section) or unstirred, using a cylinder of known dimensions (Madesh et al., 2018). Water movement through the soil is then regulated, the amount of water passing through the soil column per unit time is calculated, and the pore space geometry is then calculated according to Darcy's law (Hillel, 2004). Several physical, chemical and biological factors affect the water conductivity values, including: water stagnating due to air trapped in the soil, water seepage through cracks in the soil, blockage of soil pores due to the growth of microorganisms, salt concentration in the soil solution and the interaction between the soil solution and solid particles, (Gandhi et al., 2024) movement of soil particles and their deposition in the pore spaces and increased pore tortuosity (Mahdee et al., 2023).

Soil hydraulic properties, such as saturated hydraulic conductivity (Ksat), are critical for infiltration mass transfer, irrigation and drainage practices, and control of many soils hydrological processes. Their impact is evident at all stages before and after soil development. Direct measurement of soil hydraulic properties is difficult, expensive, and requires long time and sophisticated measuring equipment, making it impractical in practice, especially when preparing hydrological forecasts for large areas of land due to spatial and temporal variations. To overcome this problem, find alternative solutions and achieve convergence of hydraulic properties from some basic and easy-to-measure soil properties (such as clay, sand and silt content and bulk density), soil transport functions (PTFs) have been used to relate water and solutes transport parameters to basic soil properties available in soil surveys. The use of these functions has been widely accepted when they were first applied in empirical regression equations (Pedregosa et al., 2011; Naji and Ati, 2019).

Estimating a reliable value of hydraulic conductivity is a fundamental challenge in building mathematical models of saturated water conductivity and water modeling applications in saturated and unsaturated soils. High variations in hydraulic conductivity parameters often occur, with spatial differences appearing across the spatial scales. This is the most important factor in modeling the hydraulic properties of soils in saturated and unsaturated soils (Ismail, 2024). The basic hydraulic properties in the equations describing unsaturated flow include permeability, absorptivity and diffusivity (Udayakumar et.al., 2023). The importance of mathematical models that use these functions is evident in their ability to describe the movement and distribution of water during horizontal and vertical flow, as well as in unsaturated soils and to relate this to changes in the draft column and the volumetric moisture content, this enables these functions to be used as functions of the rate of structural collapse and the pore sizes that occur during water movement in the soil. Various indirect analytical and numerical methods, in addition to advanced computer programs, have been used to solve the mathematical models and obtain the values of these functions (Naji and Ati, 2019; Masood and Salim,2022; Al-Hassan et al., 2023). Despite these advancements, such models remain largely untested in Iraqi soils. This study therefore seeks not only to propose a theoretically justified model, but also to empirically validate it using actual field measurements across various regions and soil types in Iraq (Razvanchy & Fayyadh, 2023).

Materials and Methods

The study area was represented by the Iraqi region, which is in the Middle East at the far north of the Arabian Gulf. It is bordered to the east by Iran, to the west by Syria, to the north by Turkey, and to the south by Kuwait and Saudi Arabia. Iraq extends between longitudes (40.28586 - 48.47309) and latitudes (29.97421 - 37.14871), as shown in Figure (1). The area of Iraq is 438,314 km2 and includes four main topographical regions: the alluvial plain “the Mesopotamian region”, the highlands region, the desert region and the northern highlands. Soil samples were obtained for chemical and physical analysis from sites representing the diverse types of Iraqi soil (Black et al., 1965). The number of samples was 100, one sample for each site. The sample sites were distributed over 18 governorates located in central, northern, southern, western and eastern Iraq. The number of sites representing sample sources in those areas ranged from (4-8) sites for each governorate. They were distributed as follows: Baghdad (8), Babylon (5), Anbar (6), Wasit (5), Diyala (6), Karbala (5), Najaf (4), Maysan (5), Dhi Qar (5), Muthanna (5), Basra (6), Diwaniyah (5), Nineveh (6), Salah al-Din (6), Kirkuk (6), Sulaymaniyah (5), Erbil (6), Dohuk (5).

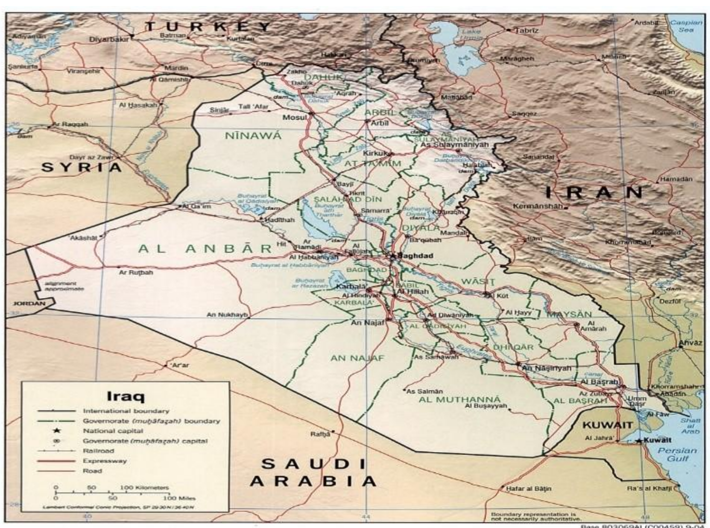

Figure 1. Geographical location of the Iraqi region

These methods involves Disturbed soil samples placed in columns of known cross-section, or Undisturbed soil samples taken using a cylinder of known dimensions using a core sample device, regulating the movement of water through the soil, calculating the amount of water passing through the soil column per unit time and then calculating the value of water conductivity according to Darcy's law, which states that the density of water flow (q) is proportional to the driving force of water (f) and that the constant of proportionality represents the value of the soil's water conductivity (Ks), then, q = Q/At. The driving force of water (f) is equal to the hydraulic gradient, which is the change in water potential ΔH between two points in the soil divided by the distance between them (L), then: F = ΔH/ L, Thus, Darcy's law is in the following form:

$$\frac{Q}{At} = -K \frac{\Delta H}{L}$$

Where: (q) flux density, (Q) amount of water passing through the cross-sectional area of the flow, (A) cross-sectional area of the flow, (t) time.

Then, q = Q/At.

To formulate a simplified, physically interpretable model for estimating saturated hydraulic conductivity (ks), we began with the classical kozeny-Carman (KC) equation:

$$Ks= \frac{C.n^3}{(1-n)^2}$$

Where:

Ks: saturated hydraulic conductivity (cm/day), C: empirical constant dependent on soil texture and fluid properties, n: total porosity (cm3/ cm3).

The KC equation, while foundational, tends to overestimate ks real soils due to ignoring the effect of water retention and pore blockage. To address this, we define the effective relative porosity (φer) as:

$$\varphi er= \frac{(n-FC)^2}{FC^2}$$

Where:

FC: filed capacity (cm3/ cm3)

This expression captures the portion of the pore space most likely to transmit water under near-saturated conditions. It incorporates not just the size of the pores (via n) but also the soil`s ability to retain moisture (via FC).

We then hypothesize a linear proportionality:

Ks= A. φer

To determine A, preliminary local data and published ranges (Hillel, 2004; Dane, 2002; Dowad and Jasim, 2023) suggest A≈75 cm/day for Iraqi loamy soils, giving the theoretical model:

Ks= 75 φer

This model is subjected to empirical validation and regression analysis in the next section.

To extend the theoretical modeling framework beyond traditional approaches such as the Kozeny-Carman equation, this study introduces the concept of effective relative porosity (φer). This variable provides a more functional representation of the proportion of pore space that actively contributes to saturated water flow, rather than relying solely on total porosity. The effective relative porosity was calculated using the following equation:

$$\varphi\text{er}= \frac{(n-FC)^2}{FC^2}$$

Where:

n: is the total porosity, as computed.

$$n= 1- \frac{\rho_b}{\rho_s}$$

ρ_b: is the bulk density (g/cm3), measured from undisturbed soil samples using core methods.

ρ_s: is the particle density, assumed to be 2.65 g/cm3 for mineral soils.

FC: is the field capacity, measured for each sample in cm3/cm3.

This formulation captures not only the air-filled portion of soil porosity but also accounts for the contribution of drained pores to water transmission under near-saturated conditions, thus making it more relevant for estimating saturated hydraulic conductivity (ks). To examine whether φer can serve as a reliable predictor for Ks, a simple linear regression analysis was conducted using the following model:

Ks=αβ+ 1β·φer+ε

Where:

Ks, is the measured saturated hydraulic conductivity (cm/day), Bα, are the regression coefficients, and 1β, ε, is the error term. The regression was performed using Python 3.11, specifically the scikit-learn and stats models libraries. Model performance was evaluated using the coefficient of determination (R^2), statistical significance (p-values) for the estimated coefficients, and residual diagnostics. This analysis enabled empirical validation of the theoretical model:

Ks=75- φer

and facilitated comparison with a statistically derived empirical model, using actual data collected from soil samples across multiple locations in Iraq. These samples represented a range of soil textures, land uses, and climatic zones, providing a robust test for the applicability of φer-based models.

Results and Discussion

The data in Table 1 represent the results of chemical and physical analyses conducted on soil samples taken from the selected sites, numbering 100 samples representing different types of soil in the Iraqi governorates. The chemical and physical properties studied included determining the soil type, bulk density, conductivity, field capacity, wilting point, electrical conductivity, organic matter, carbonates and gypsum. The data obtained were used to develop mathematical models for saturated conductivity in Iraqi soils. It is noted from the results of the analysis of the soil samples studied that there is a wide range of physical properties, especially in the proportions of clay and sand and the apparent density. This may be since most of the soils studied originated from river siltation processes, which is likely to be the reason for this wide range of physical properties of the soil, as these soils are characterized on average by a medium to soft texture.

The results of determining the soil texture in the soil sample sites included in the study indicate that there is a variation in soil texture in Iraq, as shown in Table 1, ranging between clay, loam, sandy loam, silty loam, clay loam and silty clay loam, with a relative variation in the values of porosity and apparent density, which are most closely related to the soil texture class and the content of organic matter, calcium carbonate and gypsum. These results were consistent with what was reached by (Su et al., 2022; Razvanchy and Fayyadh, 2023; Alwazzan and Ati, 2024). The results indicated a variation in the conductivity values at saturation between low, medium, and high and this variation is largely due to factors related to the soil itself, such as soil texture and sample location in general, the amount of carbonate minerals that express calcium carbonate equivalent was inversely related to the distribution of gypsum in the studied sample sites.

Table 1. Results of chemical and physical analyses on soil samples

Governorate	Texture	Sand	silt	Clay	Bulk Density	Conductivity	Field Capacity	Wilting Point	EC	Organic Matter	Minerals Carbonates	Gypsum
Baghdad	Silty clay loam	122.6	487.3	390.2	1.45	0.8	0.398	0.199	4.92	3	13.02	1.36
	Sandy loam	668.7	247.4	83.9	1.5	0.99	0.165	0.068	0.83	1.11	14.07	nill
	Silty clay loam	191	422	385	1.3	0.78	0.387	0.183	4	4.45	15	3.2
	Loam	461	378.2	160.8	1.37	1.85	0.32	0.143	2.3	13.6	196	91.8
	Loam	517.9	333.2	148.9	1.39	2.11	0.336	0.118	3.25	10.5	140.1	184.5
	Sandy loam	577.3	289.9	132.8	1.3	2.43	0.254	0.136	3.34	8.3	101.2	276.3
	Sandy loam	634.1	246.2	119.7	1.31	4.22	0.197	0.095	3.4	5.5	50	368.1
	Sandy loam	690.3	202.1	107.6	1.39	8.3	0.168	0.07	3.46	3.2	33.1	450
Babylon	Silty loam	108.9	741.9	149.2	1.45	0.40	0.344	0.181	7.42	2.64	13.23	0.28
	Loam	404,8	420,9	174,3	1.38	1.15	0.303	0.151	2.95	16	234	0.99
	Clay loam	400.5	398.5	200.9	1.48	1.86	0.335	0.147	30.7	1.14	220.7	0.02
	Loam	207.6	419.9	244.3	1.57	1.67	0.287	0.12	10	1.07	236.6	3.32
	Silty clay loam	33.4	468.8	497.8	1.65	1.2	0.342	0.158	67.0	1.29	206.9	9.1
Anbar	Clay	156.4	266.5	576.9	1.2	0.2613	0.469	0.267	8.53	3.12	13.62	98.2
	Clay	235.2	200.1	564.8	1.222	0.967	0.488	0.179	0.98	2.94	14.28	1.23
	Clay loam	327.4	293.3	378.6	1.44	0.988	0.185	0.102	3.61.	0.78	12.77	1.46
	Loam	400.8	405.8	193.4	1.369	0.9602	0.245	0.133	4.53	0.44	14.3	nill
	Sandy loam	795.5	99.4	101.6	1.586	0.9932	0.161	0.073	3.24	0.45	14.4	73.7
	Silty loam	82.2	670.9	247.2	1.336	0.6543	0.412	0.135	3.91	2.31	14.6	nill
Wasit	Clay loam	197.9	396.5	405.6	1.32	5.2	0.265	0.143	163	1.2	252.2	0.02
	Silty clay	107.7	398.8	493.5	1.37	4	0.323	0.117	35.5	1.05	264.4	0.018
	Silty clay	57.6	509.7	432.7	1.26	0.9852	0.346	0.184	5.02	2.32	13	0.06
	Silty clay loam	194.2	406.5	399.3	1.33	9.14	0.343	0.153	19.2	1.33	221.2	4.25
	Silty loam	171.5	504.7	323.8	1.38	8.6	0.394	0.146	7	1.2	245.3	3.82

Diyala	Clay loam	400.4	293.4	306.2	1.406	0.6	0.342	0.168	7.51	1.63	14.64	28.1
	Silty clay	57.3	475.9	466.8	1.303	0.9976	0.403	0.239	30.7	1.67	13.11	0.43
	Silty clay	71.7	473.7	454.6	1.356	0.9277	0.304	0.187	4.93	2.33	13.14	8.76
	Silty clay loam	30.9	570.1	398.9	1.345	0.60017	0.335	0.201	5.71	2.71	15.01	52
	Loam	484.9	284.4	230.3	1.5	0.985	0.301	0.132	9.33	0.3	14.02	4.58
	Silty loam	259.2	553.1	175.2	1.344	0.1223	0.357	0.154	5.09	0.78	13.39	22.11
Karbala	Loam	476	343	181	1.61	2.3	0.275	0.158	0.32	9.8	284	14
	Clay loam	316.6	398.3	285.2	1.4	0.5	0.364	0.148	39.1	0.44	13.4	78.11
	Sandy clay loam	457.4	253.5	289.1	1.396	0.6	0.337	0.141	13.3	1.63	13.97	43.23
	Silty loam	360	510	130	1.44	4.7	0.378	0.152	3.6	14.4	300	11.2
	Silty clay loam	90	590	320	1.3	3.3	0.302	0.154	6	0.75	210	7.12
Najaf	Sandy clay loam	605.2	133.2	261	1.4	0.9658	0.25	0.13	6.16	0.43	14.93	7.08
	Sandy loam	746	152	102	1.4	0.922	0,166	0,063	1.83	9.12	241	0.03
	Silt loam	83	670	247	1.43	0.734	0,322	0,217	4.24	13.1	235	0.15
	Clay	158	228	614	1.24	0.854	0,473	0,251	4.43	16.2	212	21.3
	Silty clay loam	99.7	590.6	309.7	1.47	1.91	0.338	0.243	30.7	1.44	216.8	0.67
Maysan	.Clay loam	304.1	310.5	384.8	1.4	0.7314	0.337	0.152	3.3	1.38	12.25	nill
	Silty clay loam	75.5	633.1	291.4	1.363	0.9999	0.317	0.234	3.72	1.4	14.96	2.28
	Silt loam	258.9	523.9	216.1	1.483	0.9996	0.188	0.101	2.31	2.07	13.91	17.93
	Silty clay loam	197.5	402.9	399.5	1.32	5.88	0.391	0.245	27.2	1.26	208.5	6.024
	Silty clay	34.8	617.9	347.3	1.53	1.7	0.336	0.195	16	1.1	230.1	6.08
Dhi Qar	Silty clay loam	12.06	610.3	377.4	1.322	0. 8489	0.397	0.258	2.53	1.78	12.83	4.27
	Clay	107.7	384.3	507.9	1.35	5.06	0.476	0.162	20.3	1.35	215.7	0.182
	Silty clay	113.6	395.5	490.9	1.31	8.15	0.351	0.181	4.8	1.29	235.5	0.385
	Silt loam	356	380	264	1.62	2.97	0.374	0.152	0.1	3.6	311	28
	Clay	91.9	380.8	527.2	1.54	1.5	0.397	0.189	4.95	1.27	195.8	4.044
Al-Muthanna	Loam	388	356	258	1.33	2.56	0.21	0.113	1.33	0.66	334	nill
	Loam	373.3	386.4	240.3	1.29	11.17	0.325	0.134	8.6	1.42	224.6	1.16
	Clay loam	301.6	355.9	342.5	1.24	20.88	0.336	0.16	9.62	1.38	233.5	0.09
	Loam	369.6	379.8	250.6	1.13	39.25	0.317	0.124	5.85	1.3	227.7	1.036
	Clay loam	295.4	347.4	357.1	1.25	21.77	0.337	0.161	6	1.26	256.8	0.047
Basra	Clay loam	405.3	295.3	299.4	1.401	0.5	0.323	0.154	12.9	2.8	15.34	5.57
	Silty clay	33.5	491.4	475.1	1.3	9.03	0.371	0.179	9.7	1.3	226.8	0.05
	Clay	36.2	325.3	638.5	1.6	1.44	0.405	0.211	7.23	1.1	193.5	0.44
	Loam	410.6	376.3	212.9	1.5	1.77	0.308	0.131	14.1	1.21	232.9	0.035
	Clay	100.9	358.4	540.6	1.57	1.53	0.387	0.21	53.1	1.2	198.6	8.29
	Clay	104.1	345.5	550.4	1.6	1.37	0.411	0.233	19.	1.18	206.8	3.414
Diwaniyah	Clay loam	345.3	373.5	281.2	1.46	2	0.352	0.14	65.6	1.18	205.9	6.128
	Loam	373.1	417.1	209.7	1.54	1.73	0.243	0.122	33.3	1.16	224.3	0.045
	Clay	276.4	259.9	463.7	1.58	1.53	0.413	0.232	12.0	1.35	192.6	5.71
	Silty clay	106.2	400.5	493.3	1.35	8.15	0.338	0.186	6.78	1.31	231.5	0.667

	Sandy clay loam	527.2	222.7	248.9	1.38	0.9829	0.292	0.135	12.	2.17	13.85	5.27
Nineveh	Silty clay loam	191.9	490.3	317.7	1.319	0.7309	0.357	0.161	0.46	2.02	14.01	nill
	Silty clay	10.3	463.8	525.9	1.61	1.32	0.402	0.217	30.5	1.15	183.2	8.19
	Clay	10.8	398.8	590.4	1.62	1.31	0.466	0.258	17.3	1.07	197.4	0.04
	Silty clay	98	407	495	1.41	1.21	0.342	0.161	0.5	22.8	193	12
	Clay	175	362	463	1.34	1.62	0.407	0.211	0.3	1.45	310	78
	Loam	485.3	284.8	229.8	1.309	0.9803	0.338	0.113	3.02	1.55	13.9	5.55
Saladin	Silty clay	40	530	430	1.4	0.162	0.303	0.141	7.5	0.78	115	nill
	Sandy clay loam	656	112	232	1.44	0.477	0.26	0.11	2.76	0.61	12	5.3
	Clay	76	352	572	1.2	0.248	0.46	0.192	7.08	0.8	16..0	6.8
	Loam	384	452	163	1.36	2.9	0.284	0.083	2.11	6.33	23	4.9
	Loam	338	397	263	1.27	2.1	0.308	0.113	2.2	8.18	241	6.8
	Clay loam	208	415	376	1.22	1.88	0.354	0.121	2.78	11.17	273	0.1
Kirkuk	Clay	124.3	315.8	559.9	1.57	1.55	0.465	0.227	9.25	1.12	190.6	1.313
	Silty clay	82.9	414.6	502.5	1.36	7.45	0.402	0.225	8.75	1.24	206.9	7.913
	Silty clay loam	86.7	512.4	400.9	1.26	10.87	0.366	0.198	5.46	1.15	232.3	0.033
	Silty clay	90.7	414.9	494.3	1.29	8.27	0.401	0.233	3.9	1.3	254.6	0.036
	Silty clay	91.3	486.4	422.3	1.37	6.88	0.352	0.189	13.5	1.35	260.4	0.75
	Clay	79.6	326.8	593.6	1.55	1.6	0.412	0.206	5.17	1.3	177.8	0.009
Sulaymaniyah	Clay	158.3	227.7	614.1	1.201	0.9665	0.424	0.284	0.57	3.96	5.51	nill
	Sandy clay loam	583.6	185.1	226.9	1.53	0.9995	0.221	0.101	1.57	1.47	14.55	nill
	Silty clay	73	397	530	1.56	1.65	0.351	0.176	0.41	10.6	190	52
	Clay loam	227	403	370	1.71	2.23	0.341	0.133	0.45	4.2	221	32
	Sandy loam	611	245	144	1.51	3.25	0.328	0.177	3.01	6.8	117	40
Erbil	Clay loam	221.4	392.1	384.5	1.402	0.6	0.334	0.135	0.63	1.6	14.9	5.01
	Clay	65	397	538	1.31	0.97	0.371	0.208	0.15	0.81	210	85
	Silty clay loam	124	535	341	1.69	2.13	0.361	0.187	0.4	20.7	180.2	0.95
	Silty clay	118	467	415	1.8	2.18	0.348	0.175	0.12	15.03	180.1	17
	Loam	442	360	198	1.6	2.11	0.291	0.173	0.08	9.1	300	33
	Clay loam	327	367	306	1.8	2.77	0.361	0.138	0.17	4.07	278	28
Dohuk	Clay	170	363	467	1.27	1.45	0.395	0.121	0.84	0.83	354	100
	Clay loam	275	325	400	1.85	2.1	0.357	0.182	0.3	3.3	258	43
	Silty clay	176	410	414	1.8	1.83	0.346	0.162	0.34	0.84	257	68
	Sandy loam	520	410	70	1.33	3.98	0.302	0.128	0.89	10.8	305	42
	Clay	30	321	649	1.34	1.04	0.391	0.176	0.73	10.3	228	80

Table 1 shows the results of analyzing 100 soil samples taken from 18 Iraqi governorates geographically distributed between northern, southern, eastern and western Iraq. The analyses included measurements of a range of chemical and physical properties, most notably: Bulk density, electrical conductivity, organic matter, gypsum and carbonate content, field capacity, and permanent wilting point, in addition to soil components of clay, sand, and silt. The textures of the studied soils vary between sandy loam, as in sample No. (2) in Baghdad Governorate with a sand content of 668.7 g/kg, to clay soil (Clay) as in sample No. (14) in Anbar with a clay content of 576.9 g/kg, which reflects the great variability in the geological and sedimentary origin of Iraqi soils.

The bulk density ranged from 1.13 g/cm³ as in sample No. (53) in Muthanna Governorate to 1.8 g/cm³ as in sample No. (92) in Erbil, which indicates the difference in the structural composition of the soil, which directly affects the hydraulic conductivity.

Field Capacity ranged between 0.161 and 0.489 cm3/cm3, with the highest value recorded in sample (26) from Diyala, indicating the ability of the soil to retain water after drainage. Wilting Point ranged from 0.063 in sample (36) in Najaf to 0.284 in sample (84) in Sulaymaniyah, reflecting the availability of plan table water.

Electrical conductivity (EC) ranged from 0.12 dS/m in some samples to 65.68 dS/m as in sample (61) in Qadisiyah Governorate, indicating a large variation in salinity, and this affects the movement of water and the plant's ability to absorb it. Gypsum content reached a maximum of 450 g/kg in sample No. (7) from Baghdad, which affects the cohesion of the soil structure and reduces its permeability.

Carbonate content varied from 5.51 g/kg in sample (84) in Sulaymaniyah to more than 354g/kg in sample (95) in Dohuk, indicating the abundance of calcareous soils in large areas.

Relationship with saturated conductivity (Ksat)

- By comparing the saturated conductivity values with the above properties, it was found that more sand, lower bulk density, and higher effective porosity are associated with higher values of saturated conductivity, as in samples (2, 17, and 88).
- Soils with high clay and organic matter content showed a clear decrease in Ksat due to small pore size, as in samples (14, 45, and 68).

Regression-Based Estimation of Saturated Hydraulic Conductivity

To evaluate the predictive capability of the effective relative porosity (φer), a linear regression model was constructed using per as the independent variable and Ks as the dependent variable. The analysis was performed using the Python programming environment (v3.11) with the scikit-learn and stats models libraries. A total of XX soil samples were included in the regression, covering a range of textures and. moisture retention capacities

The regression yielded the following equation:

$Ks= 12. \varphi er + 24.51$

The model's determination was:

$R2= 0.443$

This result indicates that approximately 44.3% of the variability in saturated hydraulic conductivity (Ks) can be explained by the variation in per. Figure 2 shows the scatter plot of the observed versus predicted Ks values, along with the fitted regression line.

The negative slope value suggests an inverse relationship between per and Ks within the studied soil samples. This is contrary to the theoretical model previously proposed in the study:

$Ks = 75.\ \varphi er$

This theoretical model assumes a direct and strongly positive relationship between φer and Ks, which was not observed in empirical data. The scatter plot further supports this discrepancy, showing a moderate downward trend with considerable dispersion (Table 2 and Figure 2).

The fitted regression line represents the model:

$Ks = 12.29\ \varphi er + 24.51$

The shaded area denotes the 95% confidence interval for the fitted line. The plot indicates a moderate R2= 0.443 inverse correlation between per and Ks, as supported by the coefficient of determination.

Table 2. Regression Statistics Summary

Parameter	Estimate	Std. Error	t-value	Value
Intercept (β_a)	24.51	2.87	8.54	0.001
Slope (β_1)	12.29-	4.17	2.95-	0.0102

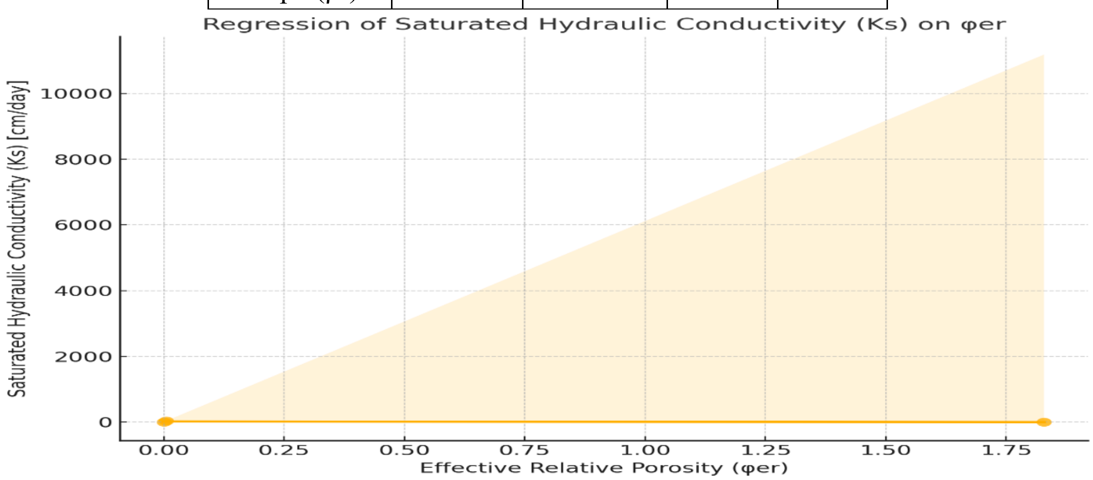

Figure 2. Scatter plot showing the relationship between effective relative porosity (per) and saturated hydraulic conductivity (Ks).

The regression results obtained in this study provide valuable insights into the relationship between effective relative porosity (φer) and saturated hydraulic conductivity (Ks) in Iraqi soils. Contrary to the theoretical model proposed earlier:

$Ks = 75.\ \varphi er$

which assumes a direct and strongly positive relationship between per and Ks, the empirical data revealed a moderate inverse correlation, as shown by the regression equation:

$Ks = -12.29\ \varphi er + 24.51$ (R2- 0.443)

This finding implies that, within the context of the sampled soils, increases in φer are associated with decreases in saturated hydraulic conductivity. Several plausible explanations can account for this inverse behavior:

1. Soil Structural Effects: Soils with higher φer values may exhibit greater microporosity due to higher field capacity, leading to reduced macropore connectivity. Macropores play a dominant role in saturated flow, especially in structured or aggregated soils.

2. Compaction or Fine Texture Influence: In clay-rich or compacted soils, even a high φer may not translate into effective water movement, as pore necks are narrow and tortuous. This reduces the actual transmissivity of the pore system despite higher air-filled porosity.

3. Field Capacity Assumption: The use of a fixed field capacity value (FC = 0.30) in some samples may have introduced uniformity that masks site-specific retention behavior, slightly biasing the φer computation.

These results suggest that while φer remains a promising predictor, its interpretation should be context sensitive. It may serve better in conjunction with additional structural indicators such as saturated water content, aggregate stability, or bulk pore size distribution. Nonetheless, the regression model derived in this study offers a simple yet locally calibrated equation that improves Ks estimation using basic field measurements.

The moderate R2R^2R2 value (0.443) further underscores the complexity of soil hydraulic behavior and the influence of unmeasured factors. Additional predictors or non-linear models may enhance prediction accuracy, which could be pursued in future studies.

Conclusion

This study aimed to develop and validate a simplified empirical model for estimating saturated hydraulic conductivity (Ks) in Iraqi soils, using effective relative porosity (per) as a core predictor. Building on the theoretical framework of modified Kozeny-Carman equations, per was proposed to reflect the dynamic balance between total porosity and field capacity, capturing the portion of pore space most relevant to saturated flow.

Regression analysis conducted on field data from multiple locations yielded the equation:

$$Ks = 12.29\,\varphi er + 24.51$$

with a moderate determination coefficient (= 2R0.443). While this contradicts the theoretical expectation of a direct positive relationship between per and Ks, it highlights the complex interaction between soil structure, pore connectivity, and moisture retention properties under natural conditions. The proposed regression model offers a practical and statistically grounded alternative to traditional methods, especially in regions where comprehensive soil data is limited. By relying on basic measurements such as bulk density and field capacity, the model enhances accessibility for hydrological estimations in field applications. However, the moderate prediction power of the model suggests that per alone may not be sufficient to fully capture the variability in Ks. Future research should consider incorporating additional soil physical and structural indicators, nonlinear modeling techniques, or machine learning methods to improve accuracy and generalizability across soil types.

Overall, the study contributes a novel perspective on Ks estimation, demonstrates the potential of per as a predictive variable, and lays the groundwork for more robust, data-driven approaches in soil hydrology within arid and semi-arid environments like Iraq.

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