Experimental Testing of the Philip Equation in Soils with Varying Gypsum Content

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Abstract

A field experiment was conducted at the Soil Science Department Research Station, College of Agriculture, University of Tikrit, in soils with varying gypsum content (42.2, 237.2, 432.8, 570.7) g kg-1 to test the performance of the Philip,1957 equation for estimating water infiltration. The infiltration was measured using a double ring infiltrometer, which consists of two rings with diameters of 25 cm and 50 cm for the inner and outer rings, respectively. The system is connected to a constant head tank, equal in diameter to the inner ring, and equipped with a transparent, graduated tube for measurement. Infiltration values were recorded over time. The calculated cumulative infiltration values showed a high degree of agreement with the field-measured cumulative infiltration values at all sites. Regarding the infiltration rate, the results indicated good agreement between the measured and calculated rates in soils with low to moderate gypsum content. However, in soils with high gypsum content, the equation's performance deteriorated significantly.

Keywords: infiltration, Philip equation, irrigation, soil, gypsiferous soil.

Introduction

Efficient and precise irrigation in arid and semi-arid regions, characterized by annual rainfall ranging between 150 and 300 mm, is one of the key methods for achieving agricultural development and managing irrigation processes effectively. Given the vast areas of these regions worldwide, the potential for significant water wastage can be substantial.[1]. One of the main factors contributing to reduced irrigation efficiency is the deep percolation of irrigation water beyond the root zone, caused by the application of uncalculated amounts of water. The movement of water

within the soil profile plays a crucial role in estimating and calculating irrigation requirements.[2]. Representing this movement through mathematical equations is important for saving time, effort, and money. Therefore, many scientists have proposed empirical equations to describe water movement in soil. These equations are based on physical, experimental, and semi-empirical models related to soil properties, as well as mathematical and statistical principles. Mathematical models have been used since the early 20th century, with each model having its advantages, limitations, and specific application conditions [3]. Gypsiferous soils are soils that contain gypsum in quantities sufficient to hinder plant growth. These soils are characterized by poor structure and limited ability to retain water and nutrients. In Iraq, gypsiferous soils cover approximately 12% of

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the total land area. [4] This study was aimed to test the performance of the Philip equation in gypsiferous soils, in addition to evaluating its potential for predicting water

infiltration

Material and Methods

Five sites were selected at the Soil Science Department Research Station, College of Agriculture, University of Tikrit, located at a latitude of 34°40′58.2″N and a longitude of 43°38′54.9″E, within arid and semi-arid regions with varying gypsum contents (42.2, 141.5, 237.2, 432.8,570.7) g kg-1. Pits measuring 1 x 1m were excavated at different depths, with three pits at a depth of 0.6m and three at a depth of 0.3m. The purpose of these excavations was to obtain moderate and high gypsum content, while the low gypsum content was found in the surface layer.

*The purpose of the excavations was to obtain high gypsum content ratios.

Soil samples were collected from each study site, then dried, ground, and sieved through a 2 mm mesh. Some chemical and physical properties were measured and calculated as follows: (Table 1(

Field Work

Water infiltration measurements were conducted in the soils of the study sites using a double ring infiltrometer, following the method described in ASTM D3385.[5]. The inner ring had a diameter of 25 cm, while the outer ring had a diameter of 50 cm, with both rings being 60 cm in height, as shown in Figure (1). The two rings were driven into the soil to a depth of 5-10 cm. A float was placed inside the inner ring and connected to a plastic tube leading to a cylindrical metal tank that was 80 cm tall and had a diameter equal to that of the inner ring, allowing for water supply. A graduated glass tube was installed vertically on the side of the tank for measuring the infiltrated water over time. Data were recorded using a camera positioned beside the setup to capture images of the water movement and analyze its dynamics over different time intervals. The soil inside the inner ring was covered with transparent polyethylene sheets to prevent water from seeping into the soil and to avoid any disturbance to the soil surface. The two rings were filled with water to the level of the float, after which the polyethylene sheets were removed. The cumulative infiltration values were recorded over time for different durations at each site until the water entry rate into the soil equalized. The inner ring was then covered with a piece of polyethylene to prevent evaporation during the measurement period, with two replicates for each site. Water was added to the outer ring periodically to maintain a consistent water level within both rings.

Philip Equation

[6]provided a solution to the nonlinear partial differential equation formulated by [7], which describes water flow in porous media in both horizontal and vertical directions. This solution enabled the application of the flow equation to deep, homogeneous soils with a uniform initial moisture content, under ponding conditions. He indicated that the infiltration rate can be expressed

$f(t)=1/2\ st^{(-0.5)}+A$……………(1(

Were

f(t)= infiltration rate

S= Soil water sorptivity ($LT^{-0.5}$(

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A= is a constant known as the soil-water transmissivity (LT-1(
t= time

The cumulative infiltration can be calculated as follows:
F(t)=St^0.5+At………………..(2(

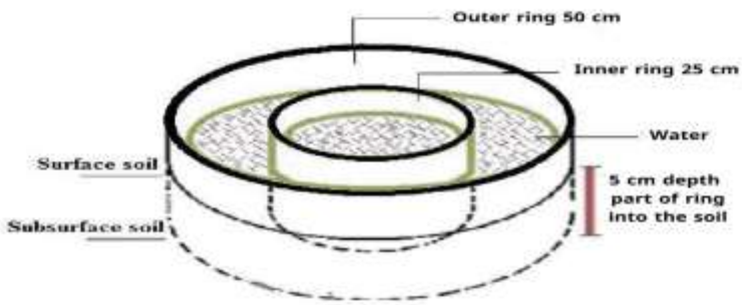

Figure 1. Schematic of the Double Ring Infiltrometer for Measuring Water Infiltration
SPSS Program:

extracted, and the coefficient of determination (R^2) was calculated using the SPSS software. This was done to achieve the best fit by minimizing the sum of the squares of the differences between the measured values and the estimated values of the model. [8, 9], employing nonlinear regression, which is one of the most commonly used methods.[10[

Table 1: Some Physical and Chemical Properties of the Study Soils

		Location				
Property	**Unit**	**1**	**2**	**3**	**4**	**5**
pH		7.21	7.34	7.53	7.24	7.51
EC	dS m^{-1}	1.2	2.16	2.63	3.01	3.28
CaSO4		42.2	141.5	237.2	432.8	570.7
CaCO3	g kg^{-1}	210	202	187	128	107
O.M	%	0.723	0.539	0.433	-----	-----
Pb	Mg m^{-1}	1.36	1.55	1.46	1.19	1.22

Results and Discussion
Measured Cumulative Infiltration
Figure 2 illustrates the infiltration values obtained from the field, where it can be observed that infiltration values increase with increasing gypsum content. Consequently, the amount of water entering the soil is substantial, reaching 20.4 cm when the gypsum content was 42.2 g kg-1 of soil. With

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an increase in gypsum to 141.5 g kg-1, the cumulative

infiltration increased to 21.1 cm. Further, with the gypsum content rising to 237.2 g kg-1, the cumulative infiltration reached 29.1 cm. At higher gypsum levels, cumulative infiltration values increased significantly, reaching 85 cm when the gypsum content increased to 432.8 g kg-1, and 169.2 cm when the gypsum content reached 570.2 g kg-1. The increase in infiltration values at higher gypsum concentrations could be due to the lower bulk density values of 1.19 and 1.22 Mg m-3 (Table 1) for soils with gypsum contents of 432.8 and 570.7 g kg-1, respectively, which leads to increased porosity and permeability of the soil, thus enhancing infiltration. Additionally, the behavior of gypsiferous soils may be similar to that of sandy soils, resulting in higher infiltration rates. Gypsum crystals impart a rough texture to the soil, affecting the soil's water-related properties [11, 12]. It may also be due to the dissolution of gypsum, which increases the soil's ability to absorb water. As a result, the water movement speed across the surface and through the soil profile increases, leading to higher infiltration values.[13]. This increase in cumulative infiltration positively affects the infiltration rate, which also rises with increasing gypsum content.

Measured Infiltration Rate

Figure 2 illustrates the infiltration rate data in the study soils with varying gypsum content. It shows that the infiltration rate values in the soil with 42.2 g kg-1 of gypsum initially decreased smoothly during the first hour. However, after an hour and a half from the start of the measurement, the values slightly increased, continuing to rise until two and a half hours before slightly decreasing again and then remaining stable thereafter. When the gypsum content increased to 141.5 g kg-1, the infiltration rate values fluctuated more, especially during the first hour and a half. Initially, they were stable, then began to decrease during the first half-hour, increased after an hour, and then decreased again. After two hours, the data became relatively stable, but some fluctuations occurred between 3-4 hours, after which they stabilized completely. With higher gypsum content, at 237.2, 432.8, and 570.7 g kg-1, it was observed that the infiltration rate increased initially with increasing gypsum content, unlike the behavior at lower gypsum levels. In the soil with 237.2 g kg-1 of gypsum, the rate increased during the first 10 minutes, then decreased and slightly increased in the first half-hour. After an hour, it rose again, remained steady for a short period, then decreased and continued for six hours before stabilizing. As the gypsum content increased to 432.8 g kg-1, the rate rose during the first 15 minutes, decreased until the half-hour mark, then rose again. After an hour, it stabilized, then decreased during the next two and a half hours before becoming stable after five hours. With a gypsum content of 570.7 g kg-1, the values increased in the first 15 minutes, then decreased. The infiltration rate data showed continuous fluctuations, but after five hours, they stabilized completely. These fluctuations in infiltration rate data may be due to preferential flow resulting from cracks in the soil caused by roots and animals, as well as the high gypsum content, which leads to faster water infiltration and an increase in infiltration rate. Additionally, variations in soil

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density and heterogeneous initial wetting conditions at the start of the measurements may have contributed to this behavior.

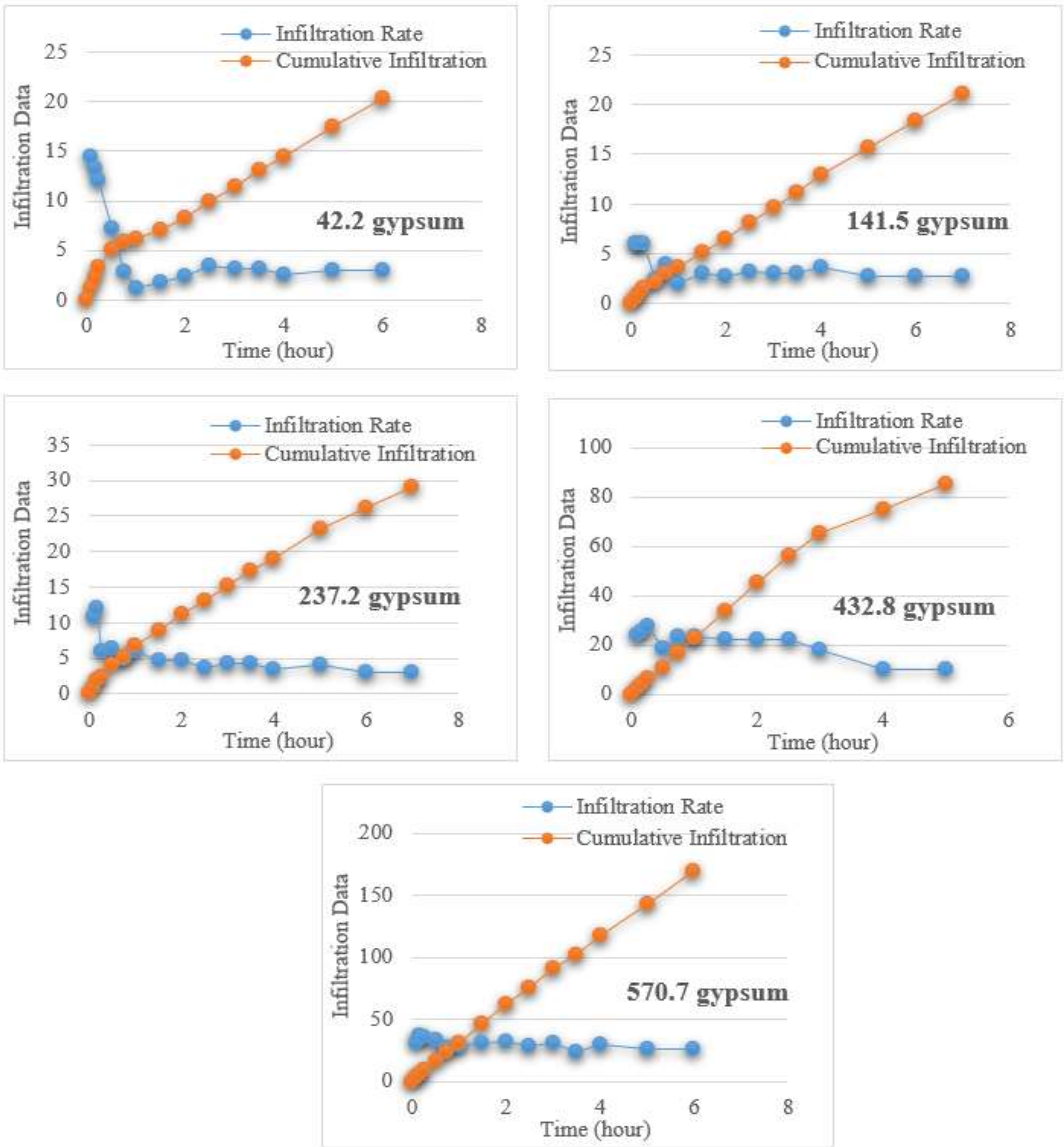

Figure 2 Cumulative Infiltration and Measured Infiltration Rate at Different Gypsum Content

Parameters Values of the Philip Equation for cumulative infiltration

Table 2 shows the parameter values for the Philip equation. The parameter "s" for soil with a gypsum content of 42.2 g kg^{-1} was 4.378, while the value of "A" was 1.476. At a gypsum content of 141.5 g kg^{-1}, "s" was 1.055 and "A" was 2.630. For a gypsum content of 237.2 g kg^{-1}, "s" was 3.982 and "A" was 2.733. When the gypsum content increased to 432.8 g kg^{-1}, "s" reached 11.116 and "A" was 13.238. Finally, at a gypsum

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content of 570.7 g kg^{-1}, "s" was 5.839 and "A" was 26.095.

Table 2: Parameter Values of the Philip Equation Based on Gypsum Content

Equation Model	Parameter		Gypsum g kg^{-1}
Philip	**S**	**A**	
	4.378	1.476	**42.2**
	1.055	2.630	**141.5**
	3.982	2.733	**237.2**
	11.116	13.238	**432.8**
	5.839	26.095	**570.7**

Comparison of Calculated Cumulative Infiltration with Field-Measured Infiltration

Figure 3 and Table 3 present the infiltration data calculated from the Philip equation alongside the cumulative infiltration values measured in the field. In soils with a gypsum content of 42.2 g kg^{-1}, the coefficient of determination R2 was 0.987, and the Nash-Sutcliffe Efficiency (NSE) was 0.988, with a Root Mean Square Error (RMSE) of 0.632. For soils with a gypsum content of 141.5 g kg^{-1}, the R2 value reached 0.999, and the NSE was also 0.999, with an RMSE of 0.161. In soils with a gypsum content of 237.2 g kg^{-1}, the R2 value was 0.999, showing a similar NSE and an RMSE of 0.275. Meanwhile, for soils with a gypsum content of 432.8 g kg^{-1}, both R2 and NSE were 0.986, with an RMSE of 3.400. When the gypsum content increased to 570.7 g kg^{-1}, R2 was 1.00 and NSE was 0.999, with an RMSE of 0.203.

These results demonstrate a high correlation between the measured and calculated cumulative infiltration data. This aligns with the findings of. [14, 15, 16, 17, 18], who noted that the Philip equation provides a better fit when estimating infiltration compared to field measurements.

Table 3: Evaluation of the Performance of the Philip Model for Cumulative Infiltration Using Key Statistical Criteria

		Gypsum g kg^{-1}				
Equation Model	**Statistical parameters**	**42.2**	**141.5**	**237.2**	**432.8**	**570.7**
Philip	**R^2**	0.987	0.999	0.999	0.986	1.000
	R	0.993	0.999	0.999	0.992	1.000
	NSE	0.988	0.999	0.999	0.986	0.999
	RMSE	0.632	0.161	0.275	3.400	0.203

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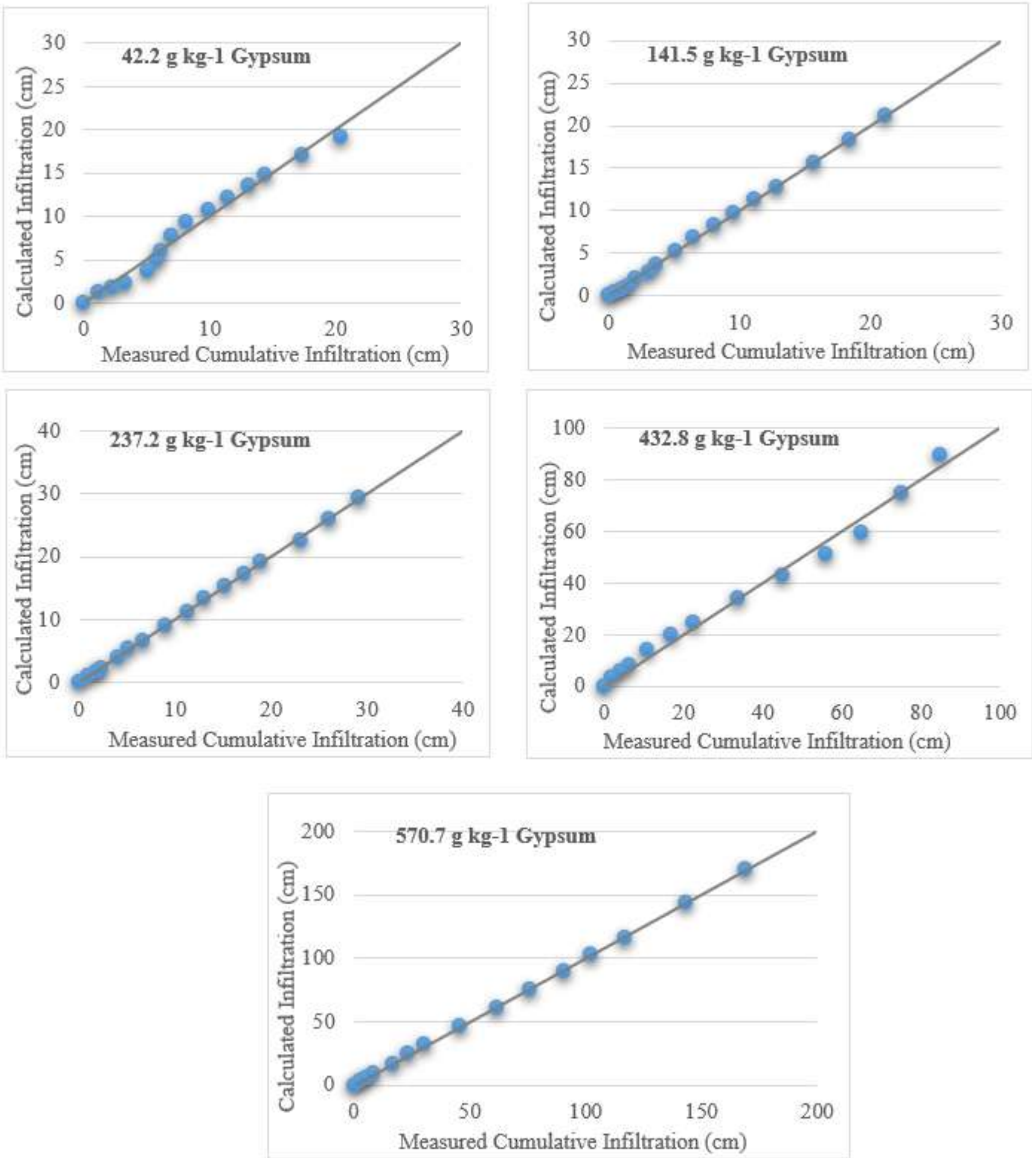

Figure 3: Comparison of field-measured infiltration with infiltration calculated using the Philip model in soils with different gypsum content.

Parameters Values of the Philip Equation for infiltration rate

Table 4 shows the parameter values for the Philip equation. The parameter "S" for soil with a gypsum content of 42.2 g kg^{-1} was 9.264, while the value of "A" was 0.085. At a gypsum content of 141.5 g kg^{-1}, "S" was 2.507 and "A" was 2.169. For a gypsum content of 237.2 g kg^{-1}, "S" was 5.475 and "A" was 2.372. When the gypsum content increased to 432.8 g kg^{-1}, "S" reached 6.855 and "A" was 16.220. Finally, at a gypsum content of 570.7 g kg^{-1}, "S" was 5.393 and "A" was 26.698.

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Table 4: Parameter Values of the Philip Equation Based on Gypsum Content

Equation Model	Parameter		Gypsum g kg^{-1}
	S	A	
Philip			
	9.264	0. 085	**42.2**
	2.507	2.169	**141.5**
	5.475	2.372	**237.2**
	6.855	16.220	**432.8**
	6.855	16.220	**570.7**

Assessment of the Philip model performance concerning the infiltration rate

Table 5 shows the performance of the Kostiakov models using various statistical criteria: R^2, R, NSE, and RMSE for different gypsum concentrations of 42.2, 141.5, 237.2, 432.8, and 570.7 g kg^{-1}. At a gypsum content of 42.2 g kg^{-1}, the values were R^2 and NSE of 0.85, RMSE of 1.701, and R of 0.92. When the gypsum content increased to 141.5 g kg^{-1}, the model performance slightly decreased, with R^2 and NSE values dropping to 0.687, R value to 0.828, and RMSE to 0.730. This decrease could be attributed to the higher values of soil bulk density (Table 1), which caused soil compaction and packing, thus reducing the pore volume that contains gypsum crystals, leading to the closure of many soil pores and hindering water movement. This in turn affected the infiltration rate values and, consequently, the model's performance. As the gypsum content increased to 237.2 g kg^{-1}, model performance improved, reaching R^2 and NSE values of 0.84, RMSE of 1.02, and R of 0.91. However, with an increase in gypsum to 432.8 g kg^{-1}, the performance deteriorated significantly, showing R^2 and NSE values of 0.328, RMSE of 4.375, and R of 0.57. The performance further declined when the gypsum content reached 570.2 g kg^{-1}. The results indicate that soils with low to medium gypsum content exhibited good to very good performance of the infiltration equations, with performance deteriorating as gypsum content increased to higher concentrations. This decline may be attributed to the variability in the measured infiltration rates in the field. The measured infiltration data show that the decrease in values is non-linear, with values fluctuating over time, especially with increased gypsum content, which in turn affects the equations used. The presence of gypsum influences the water and physical properties of the soil, as its dissolution disrupts water movement due to the mixing caused by the migration of gypsum crystals from the surface horizons to the subsurface horizons of the soil [19, 20]. When matching the measured and calculated infiltration rate data, especially at high gypsum concentrations, a significant deterioration occurs in the equations due to this fluctuation in the measured data.

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Table 5: Evaluation of the Performance of the Philip Model for infiltration rate Using Key Statistical Criteria

Gypsum g kg-1

		Gypsum g kg^{-1}				
Equation Model	**Statistical parameters**	**42.2**	**141.5**	**237.2**	**432.8**	**570.7**
Philip	R^2	0.850	0.687	0.843	0.328	0.382
	R	0.920	0.828	0.918	0.572	0.618
	NSE	0.850	0.687	0.843	0.328	0.382
	RMSE	1.701	0.730	1.024	4.375	2.982

Figure 4 shows the measured and calculated infiltration rate data based on gypsum content".

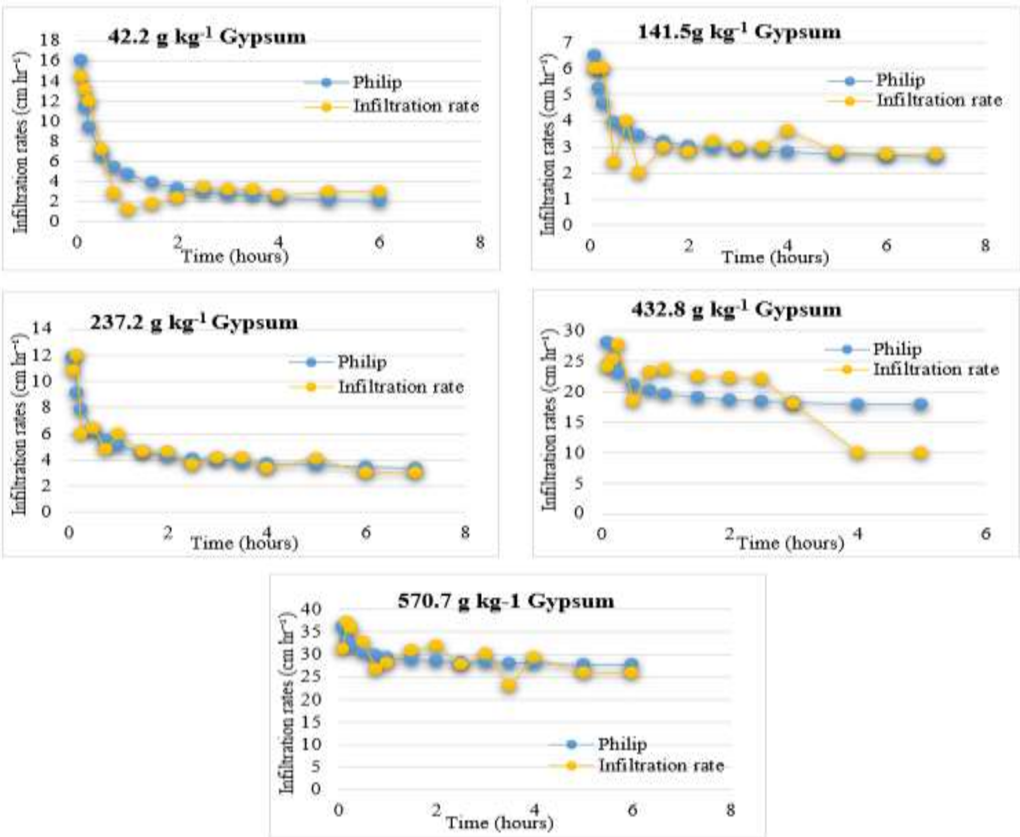

Figure 4: Measured and Calculated Infiltration Rate Data Based on Gypsum Content

Conclusion

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The Philip equation demonstrated good predictive capability for cumulative infiltration values in soils with low to moderate gypsum content, while its performance deteriorated in soils with high gypsum levels. The study showed that increasing gypsum content enhances infiltration rates due to its effect on bulk density and permeability, making the soil more absorbent. However, fluctuations in these rates were observed due to mechanical changes in soil properties. It is recommended to use the Philip equation for soils with low to moderate gypsum content and avoid its application in highly gypsiferous soils without additional calibration. Additionally, studying the effects of other factors, such as bulk density and porosity, is advised to improve prediction accuracy.

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