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RESEARCH ARTICLE

Evaluation of hydrological properties of gypsiferous soils cultivated with wheat under varying gypsum content

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Abstract

Gypsum-rich soils are widespread and play a significant role in agricultural productivity and water management, especially in arid and semi-arid regions. Understanding the effect of gypsum content on soil water movement is essential for optimizing irrigation and soil conservation in wheat-based systems. This study, conducted on wheat-cultivated soils under field conditions, aimed to evaluate key hydrological properties across varying gypsum levels. The gypsum levels in the studied soils were 45, 92, 156, 248, 468 and 583 g kg^{-1}. Field infiltration rates were measured using the double-ring infiltrometer method and sorptivity was estimated using standard infiltration models. Saturated hydraulic conductivity (Ks) was also determined for each soil type. The pattern of cumulative infiltration generally mirrored the upward trend in Ks, underscoring the close relationship between infiltration dynamics and saturated hydraulic conductivity. Cumulative infiltration varied irregularly with gypsum content, ranging from 1.4 to 8.7 cm. Results showed a general increase in saturated hydraulic conductivity with increasing gypsum content, likely due to enhanced soil structure and macroporosity at higher gypsum levels. The Philip and Smith & Knight models provided more consistent predictions of water movement over longer infiltration times. The findings highlight the importance of gypsum content as a key factor influencing soil water behavior and provide insight into selecting appropriate models for estimating infiltration parameters. These results are particularly relevant for irrigation design and soil management in wheat cultivation on gypsiferous soils.

Keywords: gypsiferous soil; infiltration; irrigation; Philip equation; saturated hydraulic conductivity; Smith & Knight; water dynamics

Introduction

Wheat (*Triticum* spp.) is one of the most important grain crops around the world, which acts as an important food for an important part of the global population. The cultivation extends to different agricultural class areas due to its adaptability and nutritional significance. However, wheat productivity is greatly affected by soil properties, especially in challenging environments such as plaster-fray soil, which is characterized by high gypsum content. These soils show unique physical and chemical properties that affect water retention, infiltration and availability of nutrients, affecting the growth and yield of wheat. Understanding the interaction between wheat cultivation and gypsiferous soil properties is necessary for adaptation of irrigation handling and improvement of permanent crop production in plaster-rich areas (1).

The water infiltration in the soil is a dynamic process that changes over time. At the onset of rainfall or irrigation, infiltration rates are typically high but gradually decline until reaching a steady state, known as the basic infiltration rate. This reduction is affected by many interconnected factors, including the dissolution of structural gradient voltage, worsening of the soil structure due to the spread of the set under the influence of the water, clogging of the pores with fine particles, soil swelling and air in the pores, which provides internal planting. Additionally, the initial soil moisture content plays a critical role in determining the rate and pattern of infiltration (2).

A mathematical model describing the movement of water in unsaturated soil through the solution of the general water-spread equation (3). This model is a time-based exponential chain, where coefficients depend on soil hydraulic conductivity (K), water spread (D) and moisture content (ϴ). Sourpability (s) dominate the water movement in the early stages of infiltration, while the effect of gravitational forces (A) becomes more important over time and eventually reaches the saturated hydraulic conductivity (K_S) under a stable state.

Later, Smith & Knight demonstrated that the coefficient in Philip's equation does not necessarily equal Ks under practical field conditions and proposed a method to estimate sorptivity from the slope of cumulative infiltration versus the square root of time during the initial infiltration phase (4).

Ks is a fundamental property that governs water movement through the soil profile. It is influenced by multiple factors including soil structure, bulk density, porosity, moisture content, salt type and particle composition (5, 6). Ks increase with the rising of soil moisture and reaches the maximum when being saturated. When found in moderate quantity as component of soil matrix, gypsum improves the physical properties by way of good structure of soil, aeration, water movement and it increased bulk density (7). Nevertheless when gypsum content is > 2 %, soil water holding can be reduced depending on crystal size, clay content, organic matter and soil structure (8, 9). Gypsum is highly soluble (2.2–2.6 g L^{-1}), which in moderate to rapid water flow regimes, such as those commonly found in gypsum-rich soils dissolution will readily occur (10). In addition, the gypsum aggregates are easily fragile because of poor bonding between gypum particles.

Gypsum soils in Iraq are rated the fourth largest worldwide with an area of nearly 8.7 million ha (ca. 20 %) of total land in the country(11, 12). Although gypsum soils are common in Iraq, less is known about the impact of different gypsum levels on main properties dealing with water movement and their effects on wheat production. High-gypsum soil can limit the availability of water to wheat roots through modification of soil structure or reduction in plant-available moisture, which may be a limitation to sustainable wheat development. This lack of information highlight the need to study how different gypsum content affects soil-water interactions. As such, the present investigation is designed to assess the effect of gypsum content on some soil physical properties and particularly water infiltration by formulating the Philip equation and estimating sorptivity using the Smith and Knight technique.

Materials and Methods

Six sites with varying gypsum contents, all cultivated with wheat were selected from different locations in Tikrit city, Salah al-Din Governorate. The area is located at latitude 34°40'58.2° N and longitude 43°38'54.9° E and experiences a semi-arid climate, with hot dry summers (average temperatures around 35 °C- 40 °C) and mild winters and an average annual rainfall of about 150-200 mm- conditions that strongly influence soil-water behaviour. The soils were classified, according to USDA Soil Taxonomy, as fine, mixed, active, hyperthermic, calcareous Typic Torrifluvents (13). Physical and chemical analyses were conducted following standard soil analysis procedures (14) (Table 1). The texture could not be estimated because of sedimentation due to the high percentage of gypsum in the soil (15).

Measurements included in the study

Available water

Field capacity and permanent wilting point were determined using undisturbed soil cores placed in plastic rings on a porous plate and saturated with water for 8 hr. A pressure of 0.33 bar was applied using a pressure plate apparatus to determine field capacity, while a pressure of 15 bar was applied to other samples to determine permanent wilting point. Available water was then calculated as the difference between field capacity and permanent wilting point (16).

Capillary rise and contact angle calculation

Air-dried soil samples were sieved (< 2 mm) and packed into a glass column (1.5 cm inner diameter, 65 cm length) to a height of 60 cm. The column was gently tapped to ensure uniform packing and then placed vertically in contact with water at the base. Water was supplied from the bottom under a constant tension of 1 cm for 24 hr. The rise of water and the advance of the wetting front within the soil column were recorded over time. The effective pore radius during capillary rise was calculated using the Laplace-Young capillary equation (17):

$$\bar{r} = \frac{4X_o I_o n}{f t_o \gamma \cos\sigma} \qquad \text{Eqn 1}$$

where:

$\bar{r}$ = Effective pore radius

X_0 = Maximum water range in soil pipes (cm)

I_0 = Total depth of water entering the soil (cm)

n = Water viscosity (g/cm sec)

f = Soil porosity

t_0 = Time (sec)

γ = Surface tension of water, equal to (72.75 dynes cm^{-1})

cos σ = Cosine of the contact angle, assuming the value of a equals zero

Field infiltration

Field infiltration measurements were conducted using a double-ring infiltrometer, with an outer ring of 50 cm diameter (to minimize lateral water movement) and an inner ring of 25 cm diameter (for measurement). A constant head water supply system was designed using a water tank of the same diameter as the inner ring, fitted with a transparent graduated tube and mounted on supports above the soil surface. The tank was connected to the inner ring through a float device to maintain a constant water head of 9 cm. Prior to installation, the soil surface was cleared of weeds and residues and the rings were inserted to a depth of 10 cm. Water was then added simultaneously to both the inner and outer rings.

The vertical flow of water into the soil through the inner ring was monitored by recording water level changes in the supply tank. A camera was positioned laterally to document water movement and ensure precise time–flow measurements. Photographs taken at regular intervals were used to calculate cumulative infiltration and infiltration rates over time. The resulting infiltration curves were plotted and analyzed using Microsoft Excel 2010 (2).

For short infiltration periods (up to 10 min), sorptivity was calculated using the Smith & Knight equation (3).

Table 1. Some physical and chemical properties of the study soils

location						Unit	Soil traits
6	5	4	3	2	1		
7.52	7.51	7.35	7.35	7.25	7.22	-	pH
3.34	3.11	2.78	2.65	2.06	1.20	dS m^{-1} at 25 °C	EC
582.55	468.16	247.93	155.67	91.75	45.32		$CaSO_4$
17.42	19.76	19.84	20.03	21.68	28.45	g kg^{-1}	$CaCO_3$
9.63	10.32	10.59	10.87	11.76	12.16		Organic matter (OM)
1.25	1.36	1.45	1.48	1.52	1.56	Mg m^{-3}	bulk density

Saturated hydraulic conductivity:

Ks was determined using the falling head method. Undisturbed soil samples were collected in metal cylinders (6 cm diameter × 4 cm height). The falling head apparatus was connected to the samples and Ks was calculated using the standard equation (Eqn. 2) (18):

$$K_S = \frac{a}{A}\ x\ \frac{L}{\Delta t}\ x\left(ln\frac{H_1}{H_2}\right) \quad \text{Eqn. 2}$$

where:

K_S = Saturated hydraulic conductivity (L T^{-1}).

A = Cross-sectional area of the glass tube (L^2).

A = Area of the metal cylinder (L^2).

L = Sample length (L).

H_1 and H_2 change in water level in the glass tube (L)

Results and Discussion

The relationship between available water and gypsum content of soil

Fig. 1 shows the relationship between available water and soil gypsum content. Available water ($cm^3\ cm^{-3}$) increased with rising soil gypsum content, reaching 0.13, 0.14 and 0.15 $cm^3\ cm^{-3}$ at gypsum contents of 45, 92 and 156 g kg^{-1} respectively. Beyond this point, available water decreased to 0.12, 0.11 and 0.10 $cm^3\ cm^{-3}$ at gypsum contents of 248, 468 and 583 g kg^{-1}. These results suggest that increasing gypsum content up to about 15 % based on our experimental findings and earlier research, enhances soil porosity and consequently available water. These findings align with previous studies which reported similar effects in gypsum soils of Iraq. Such relationships highlight the importance of managing gypsum levels to optimize soil-water availability and guide irrigation scheduling in arid regions. But the availability of water in the soil decreases with high percentages due to the low percentage of organic matter and clay colloids or the presence of sand-sized gypsum crystals. This supports previous studies which stated that gypsum soils in Iraq have a weak water-retaining capacity.

The relationship between capillary rise and gypsum content of soil

Fig. 2 shows the relationship between capillary rise and soil gypsum content. The capillary rise of water increased to 25.6, 27.3, 31.6, 32.5 and 35.7 cm day^{-1} as gypsum content increased. Structural effect: The presence of gypsum crystals enlarges soil pore sizes, which reduces water-retention capacity and promotes upward water movement. Chemical effect: Dissolution of gypsum releases SO_4^{2-} and Ca^{2+} ions, reducing hydrogen bonding in water and leading to enhanced soil wettability (21).

The relationship between average effective pore radius and gypsum content of soil

Fig. 3 shows the relationship between soil gypsum content and the effective pore radius (cm). The pore radius decreased as gypsum content increased, with values of 0.0064, 0.0058, 0.0054, 0.0046, 0.0041 and 0.0011 cm respectively. Together, these results indicate that gypsum dissolution and subsequent redistribution or blockage of soil particles reduce pore diameters as gypsum content rises. The reduction in pore size with increasing gypsum content may also explain the observed decline in available water and the changes in capillary rise (Fig. 1 & 2). Similar trends have been reported in gypsum-rich soils of arid and semi-arid regions, where gypsum accumulation narrows pore spaces and alters soil-water dynamics (1).

The relationship between cumulative infiltration and soil gypsum content

Fig. 4 illustrates the relationship between cumulative infiltration and soil gypsum content. Cumulative infiltration initially declined at moderate gypsum levels but increased substantially at higher gypsum contents. The final cumulative infiltration values–measured as the total depth of water infiltrated (cm) after 6 hr–were 3.3, 1.5, 1.4, 2.4, 6.4 and 8.7 cm at gypsum contents of 45, 92, 156, 248, 468 and 583 g kg^{-1} respectively.

This pattern may be attributed to gypsum dissolution, which affects the soil's capacity to absorb and transmit water. Increased gypsum levels enhance vertical water movement and overall porosity, thereby reducing resistance to water entry and promoting

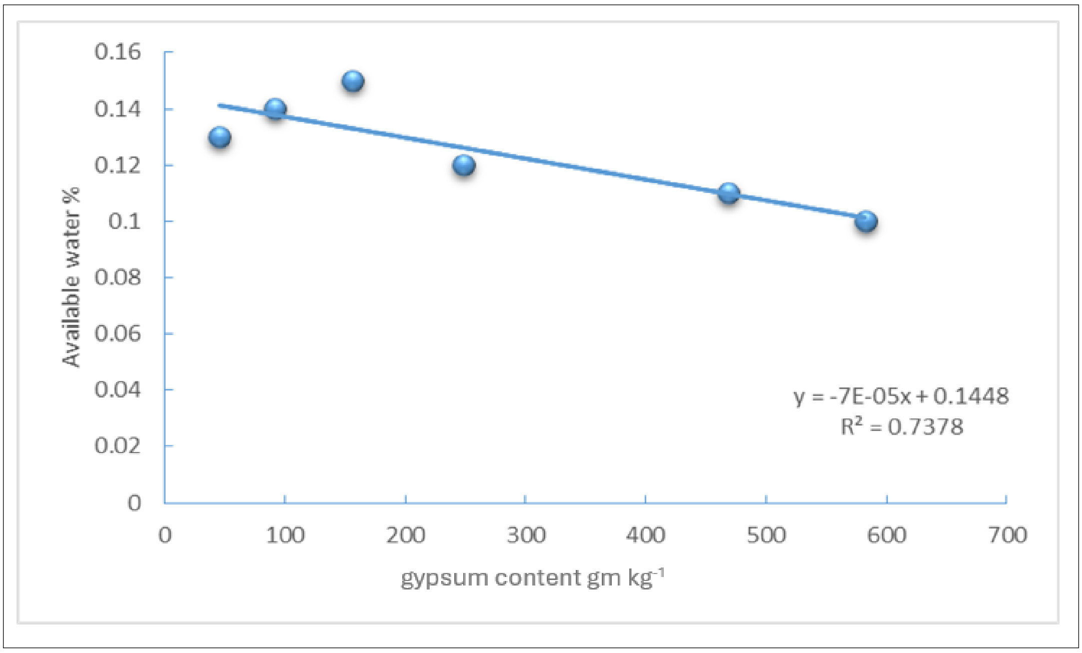

Fig. 1. The relationship between available water and gypsum content of soil.

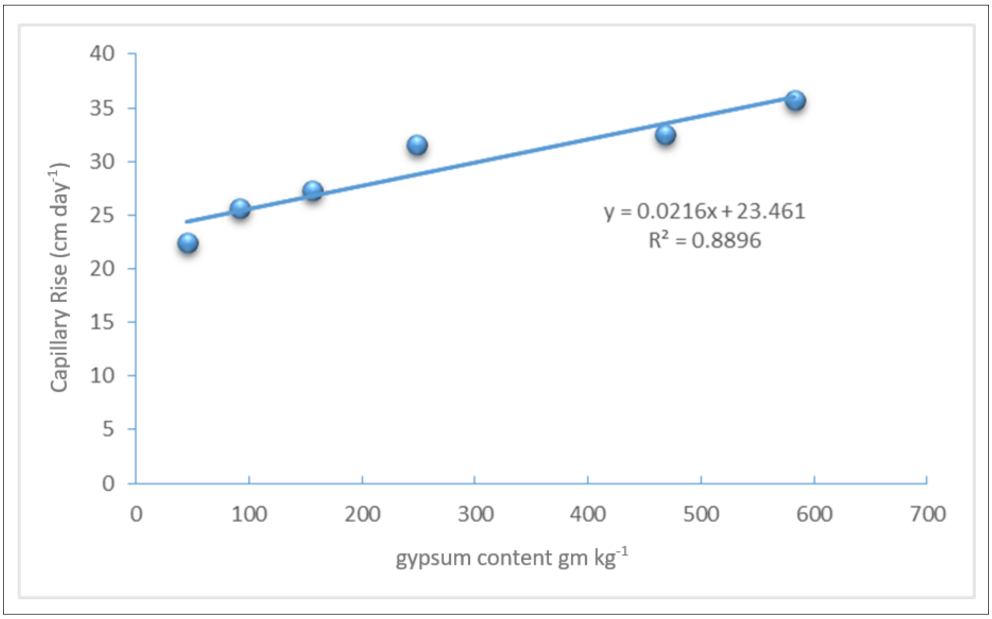

Fig. 2. The relationship between capillary rise and gypsum content of soil.

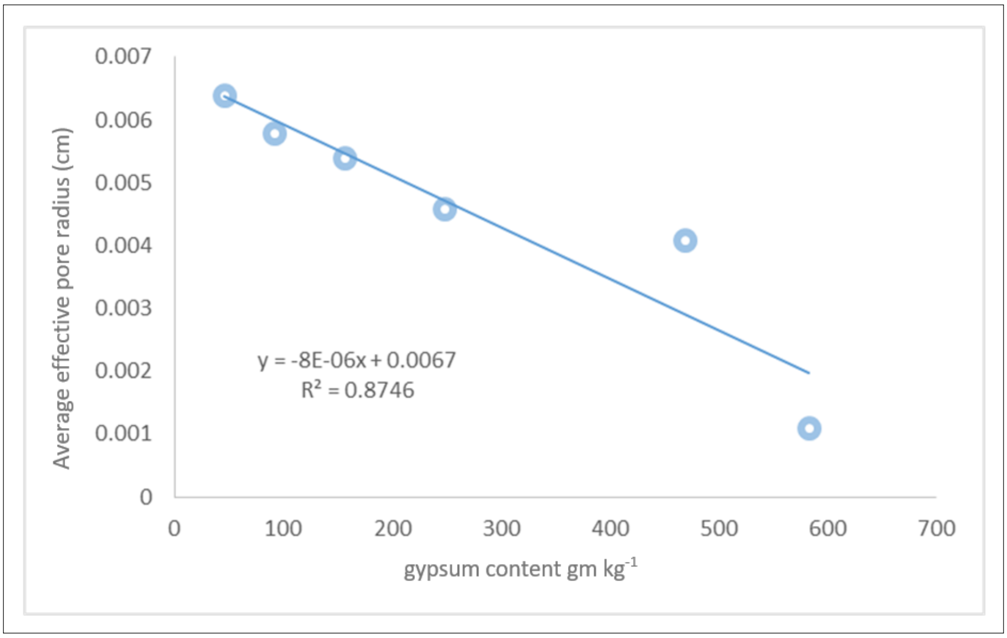

Fig. 3. The relationship between average effective pore radius and gypsum content of soil.

higher infiltration rates (22-24). Soils with higher gypsum content may behave similarly to sandy soils, where coarse particles and large pores promote rapid water movement. In these soils, infiltration rates are higher in gypsum-rich soils due to the coarse texture imparted by gypsum crystals, which strongly influences soil-water dynamics. However, while infiltration increases, the soil's water-retention capacity may decline, potentially reducing plant-available water (25, 26).

Fig. 5 shows the relationship between the sorptivity measured by the Philip equation and the gypsum content of the soil. The figure shows that the sorptivity values reached their highest value of 0.0754 cm $s^{0.5}$ for a gypsum content of 45.32 g kg^{-1}, then decreased with the gypsum level of 91.75 g kg^{-1} to 0.0173 cm $s^{0.5}$, then the lowest sorptivity value reached 0.0159 cm $s^{0.5}$ for a gypsum content of 155.67 g kg^{-1}, then the sorptivity values returned to rise again with higher gypsum ratios than that. This variation in the results was reflected in the value of the correlation coefficient R^2, which gave a low value of 0.0464. The weak correlation suggests that sorptivity measured by the Philip equation may not adequately capture the non-linear response of gypsum soils. This division was made because the Philip equation is more suitable for estimating sorptivity over long periods, while the Smith & Knight modification provides more reliable sorptivity estimates during short initial infiltration times. This behavior can be attributed to the varying characteristics of gypsum, which are related to the size and behavior of gypsum particles, as well as the amount of gypsum present in the soil (22).

Sorpitivity calculated using the equation (3) for soils with different gypsum content

Fig. 6 shows the relationship between the sorpitivity measured by the Smith & Knight equation and the gypsum content of the soil. The figure shows that the sorpitivity values reached 0.0924 cm $s^{0.5}$ for the lowest gypsum content of 45.32 gm kg^{-1}, then decreased to the lowest value of 0.0173 cm $s^{0.5}$ with the gypsum level of 155.67 gm kg^{-1}, then the sorpitivity values increased gradually again with the higher gypsum ratios to reach their highest value of 0.2317 cm $s^{0.5}$ for the highest gypsum content of 582.55 gm kg^{-1}, as the gypsum ratio of 155.67 gm kg^{-1} represented the inflection point for gypsum soils at

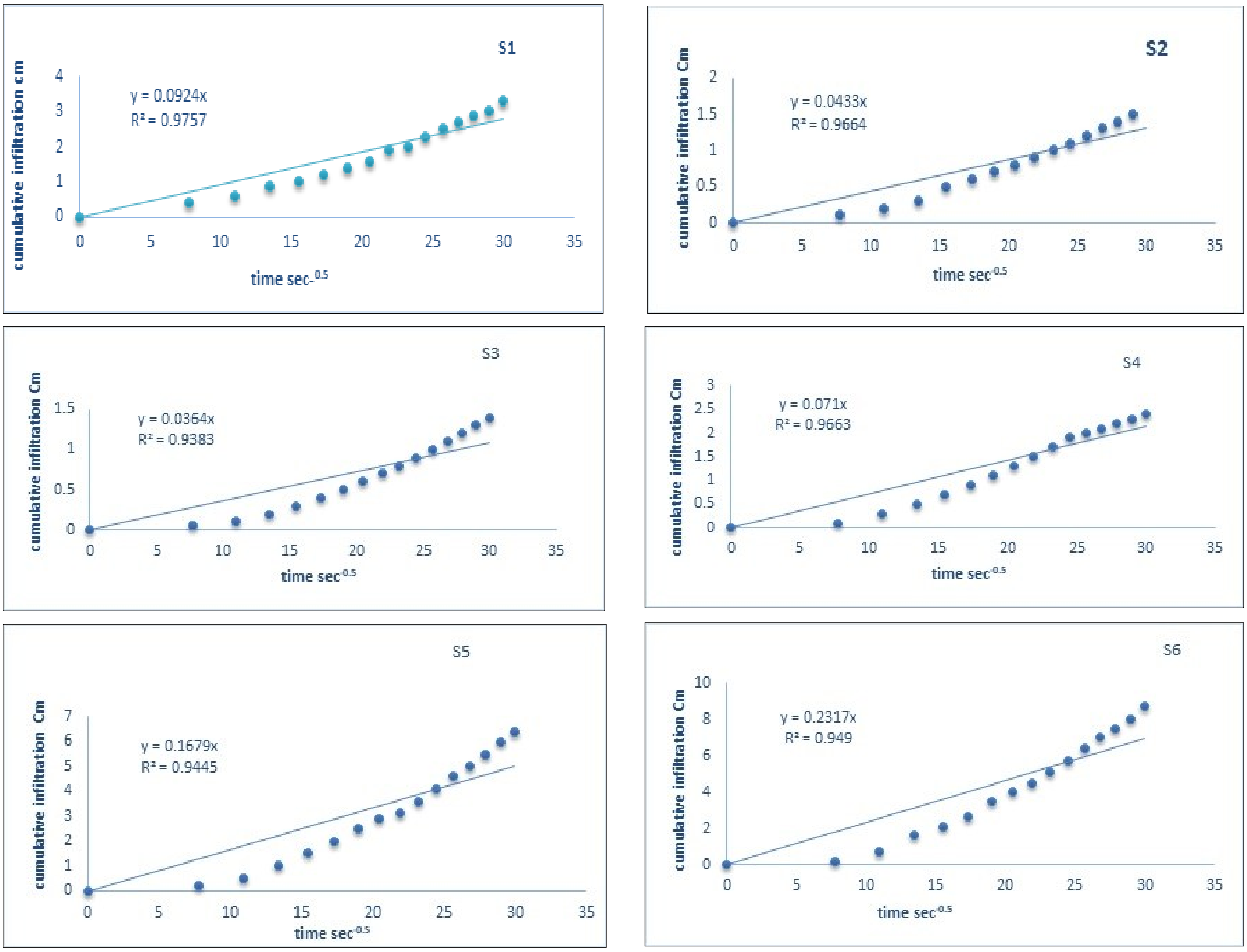

Fig. 4. The relationship between cumulative infiltration and soil gypsum content.

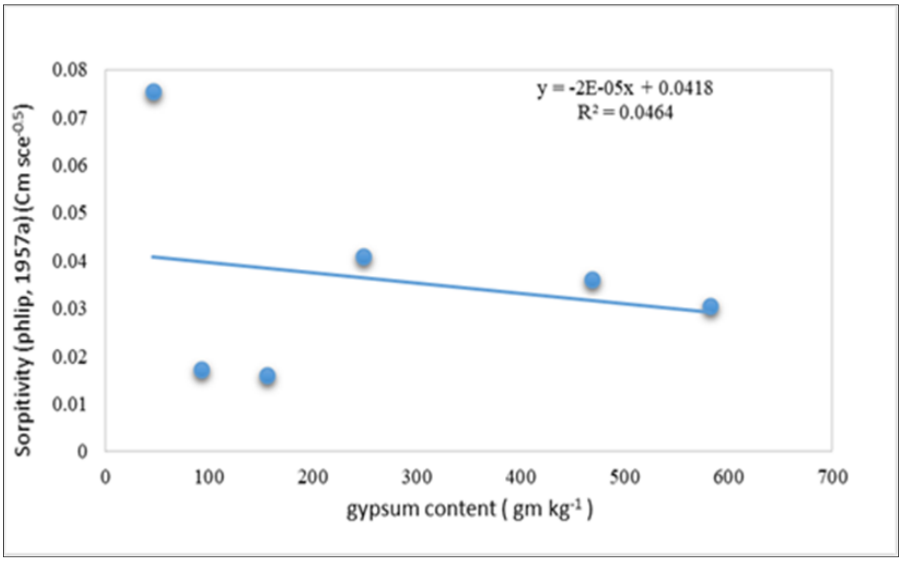

Fig. 5. The relationship between sorpitivity measured by sorpitivity (Philip, 1957a) and gypsum content.

which the soil behaviour changed with the absorbance (25, 27). The figure also indicates the correlation value between the sorpitivity measured by the Smith & Knight equation and the content of gypsum was higher than the correlation coefficient value of the Philip equation, which may be attributed to the heterogeneous behaviour of gypsum soils, in addition to the fact that the Smith & Knight equation measures the sorpitivity from the slope of the relationship between the cumulative seepage and the square root of time for the early seepage stages, which shows more stability than long periods (28, 29). Smith & Knight model may be more suitable for gypsum-rich soils due to their heterogeneity and unstable infiltration behaviour.

Saturated hydraulic conductivity of soils with different gypsum content

Fig. 7 shows the Ks values according to the gypsum content for each soil in the study. Ks increased from 0.51 cm hr^{1} at 45.32 g kg^{1} gypsum to 3.94 cm hr^{1} at 582.55 g kg^{-1}, with the steepest rise between 247.93

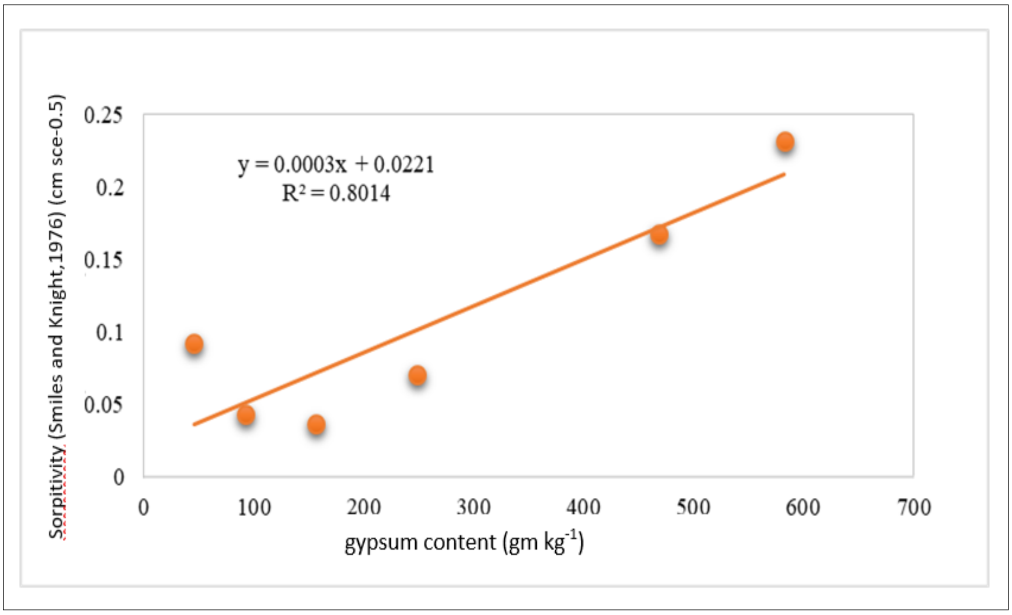

Fig. 6. The relationship between sorpitivity measured by Smith & Knight, 1976 and gypsum content.

and 468.16 g kg-1. The largest increase occurred when moving from a gypsum content of 247.93 g kg-1 to 468.16 g kg-1. The increase in the Ks values with increasing gypsum content may be due to the increase in the size of large pores as a result of the decrease in the apparent density values with increasing gypsum content in the soil (30). Also, the occurrence of depressions and preferential flow resulting from the dissolution of gypsum and the activity of organisms and the movement of roots, which causes the formation of water passages in the soil, thus facilitating the movement of water within the soil core and thus increasing the values of Ks (31). The increase in the gypsum content in the soil to the limits of 250 and 500 g kg-1 led to an increase in the values of Ks compared to the gypsum content of 125 g kg-1 (32). Increasing the gypsum content of the soil increases the amount of solute from it and the type of its particles in the soil greatly affects the solubility, substantially affecting the values of hydraulic conductivity (31).

Conclusion

The Philip and Smith & Knight equations are among the most important models describing soil infiltration and related water properties. Both equations performed well under the conditions of gypsiferous soils, which occupy a relatively large area in Iraq. Cumulative infiltration and saturated conductivity increased with rising gypsum content. However, compared to the Philip model, the Smith & Knight equation provided more stable and accurate estimates of sorptivity during short measurement periods, particularly in gypsum-rich soils, indicating its relative superiority for these conditions.

Authors' contributions

All authors contributed equally to the writing and preparation of the manuscript. Each author was involved in the preparation of the original draft, as well as the revision and final approval of the submitted version.

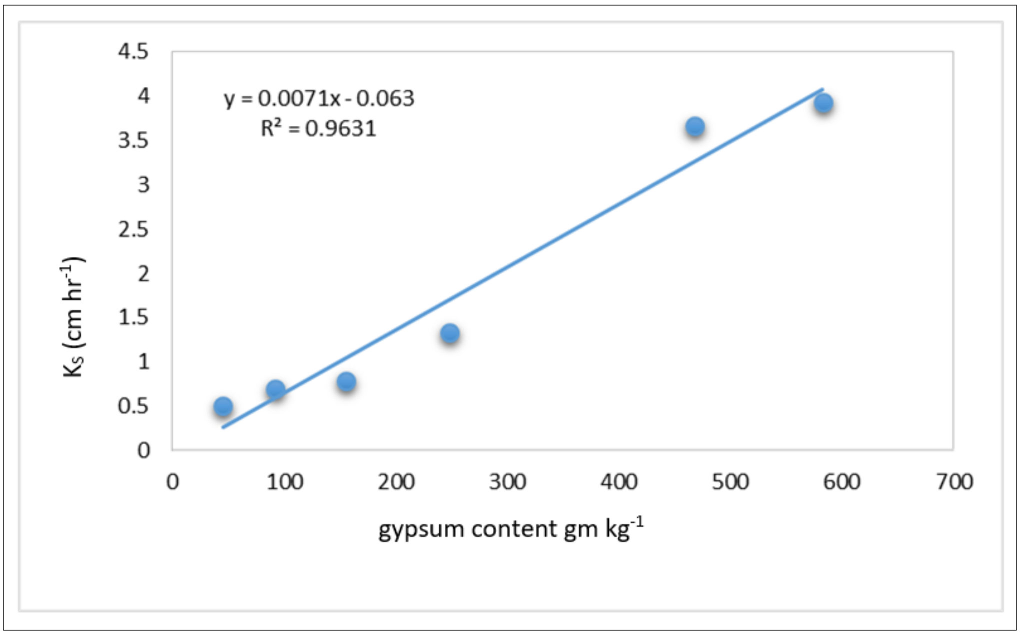

Fig. 7. The relationship between K_s (cm hr^{-1}) and gypsum content.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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