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Original Article

Calibration of the SPAW model for estimating plant available water in the Kurdistan region of Iraq

Rebaz Aziz Ahmad [1], Mohammed Abdulrazzaq Fattah [*, 1], Zhalla Yadgar Taha [1], Shadan Hama Khurshid[1], Rekar Rasul Ismael [1], Saman Farhad Abdul [1]

[1] *Department of Natural Resources, College of Agricultural Engineering Sciences, University of Sulaimani, Sulaymaniyah, Kurdistan Region, Iraq.*

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ABSTRACT

The SPAW computer model can predict soil moisture under various tensions based on particle size distribution, gravel content, compaction, salinity, and organic matter. This ability may be decreased in soils with high levels of calcium carbonate due to its effect on soil properties related to moisture content. Therefore, this research evaluated and calibrated this computer model for predicting field capacity (FC) and wilting point (WP) in calcareous soil. A dataset of ninety-two soil samples used to cover a wide span of calcium carbonate and clay content. Seventy-six soil samples were used as input data (training set) to determine FC and WP through SPAW computer model application. The calibrated SPAW models ($SPAW_{cal}$) were formulated via relationship between predicted data from the SPAW computer model and training set. Sixteen soil samples were used as a testing dataset for validating predicted FC and WP values by (SPAW & $SPAW_{cal}$). The results showed that the accuracy of the $SPAW_{cal}$ model outperformed the SPAW original model, as predicted data by $SPAW_{cal}$ model were closer to actual data. The RMSE decreased from 3.316 to 2.642 for WP and from 3.104 to 2.247 for FC. The Bland-Altman analysis presented a shift in the mean difference from overestimation to underestimation (from -1.648 to 0.455 for FC and from -1.320 to 0.251 for WP). These results confirm that in view of calcium carbonate content in the estimation of both FC and WP significantly improves prediction accuracy. Thus, the calibrated $SPAW_{cal}$ model bids a more accurate and reliable tool for soil moisture prediction in calcareous soils.

Keywords: SPAW, calcareous soil, calibrating model, wilting point, field capacity.

1 Introduction

The management of water resources in agriculture is a paramount concern for ensuring food security and sustainable crop production. Soil moisture plays a crucial role in plant growth, ecosystem dynamics, and various hydrologic processes, and is therefore a critical metric in soil science research [1, 2]. Numerous soil properties, such as texture and structure, significantly impact on soil moisture. Soil pore size and arrangement are influenced by soil structure and factors affecting it such as texture, organic matter, organisms activity and compaction state, Which are play a crucial role in estimating the plant available water (PAW) [3].

The most accurate method for mesuring soil water content at different tensions is the pressure plate method, but it can be time and cost-consuming when used daily for large-scale application.

* Corresponding author
E-mail address rebaz.ahmad@univsul.edu.iq (Instructor).
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Estimating soil moisture at FC and WP is useful for irrigation scheduling when irrigation criterion is established for a specific crop and environment. Integrating the knowledge of soil water holding capacity with proper irrigation criterion can help reduce water losses during irrigation [4]. Plant Available Water (PAW) is defined by [5, 6] as maximum amount of water plants can absorb from the soil; PAW is equal to water content at FC minus water content at permanent WP.

Measuring soil moisture at different tensions proves useful for irrigation scheduling when specific criteria are established for a particular crop and environment [7]. While the pressure plate method remains the most precise approach for measuring soil water content at different tensions, such as FC and PWP, its daily application for large-scale purposes can be both time and cost-consuming [8]. To address these challenges, certain researchers have proposed mathematical models for estimating soil water retention, known as pedotransfer functions (PTFs) [9-11]. Rudiyanto et al. [12] proposed an alternative method using pedotransfer functions (PTFs) in soil databases to predict water content (WC) values based on readily accessible soil properties such as particle size distribution (PSD), bulk density (BD), and organic matter (OM). It is critical to develop reliable estimates of PAW before utilizing simulation models to analyze the influence of conservation strategies on water management and agricultural output at broad regional scale. However, there is no agreement on the best approach for estimating PAW, and large variances have been seen depending on geography and input factors [13-15]. Plant-available water models usually formulated from linear or non-linear parametric regression, clustering algorithms or non-parametric machine learning [16–18].

An inclusive mathematical and computational tool used in soil and agriculture science to study soil-water dynamics and evaluate plant water availability is SPAW (Soil Plant Atmosphere Water) computer model [10]. It is widely used in a hydrological and agricultural research to evaluate available water to plant via simulating the water balance in the soil, plant, and atmospheric system. The SPAW is a simple water balance model as presented by [19]. Because of low input data requirement, it is particularly appealing to researchers from various agroclimatic zones. Many authors, including those from India, have recognized its reliability in assessing soil moisture [20-22]. Furthermore, this computer model was adapted for irrigation purposes, known as SPAW-IRRIG, by [23] in 1983. It was noted to produce sufficient performance on both a daily and seasonal basis. However, its accuracy may vary depending on the location and conditions [24]. As a result, it's important to test and calibrate the SPAW model to predict plant-available water (PAW) when working with particular soil like calcareous soil, as their distinct chemical and physical features can significantly affect how they retain water. In this context, calibration ensures that the model can more accurately reflect the real conditions encountered in different regions. Kurdistan region is classified as calcareous soil since its calcium carbonate concentration exceeds 20% [25]. Calcium carbonate form bonds with clay and/or silt particles, which affects particle size analysis [26]. It is possible for highly aggregated, stable clay soils to behave similarly to coarse sands, which could cause them to be mistaken for sands or coarse loams in the field. The soil's high calcium carbonate content can have a dual impact: firstly, it can reduce both the size and quantity of soil pores, as documented by [27], resulting in a subsequent decline in soil moisture levels. Secondly, the presence of exceedingly fine carbonate particles, as noted by [28], can potentialy adhere to clay and silt particles. These interactions alter the soil structure and water retention behavior, making it necessary to recalibrate standard models to maintain prediction accuracy. The objective of this work was to assess the performance of the existing SPAW model in calcareous soils and optimize its performance for this soil type by calibrating the SPAW model according to the local conditions prevailing in the study area.

2 Methods and Materials

2. 1 Site description

The study spots in the region are located within specific geographic coordinates: latitude between 34° 18' 34"-36° 20' 56" N, longitude between 43° 25' 41"-46° 28' 01" E, and varying altitudes, ranging from 200 m at the southern boundary to more than 1800 m along the Iranian borders. The climate in this area is considered semi-arid Mediterranean, characterized by mild and short winters followed by hot, dry, and long summers. Rainfall exhibits a unimodal pattern from October to May. Annual rainfall ranges from as low as 200mm to as high as 800mm in the mountainous area near the Iraqi-Iranian border. However, there is no rainfall during the summer months. The mean annual temperature is 25 ºC, with maximum temperatures reaching 48ºC in July and minimum temperatures dropping to -10 ºC in January [29]. Regarding the soil characteristics, the soil reaction in the area is slightly alkaline, and the soil is non-saline, with an electrical conductivity (EC) of the saturation extract below 2.5 dS m^{-1}. All soils at this site are calcareous, typically containing more than 20% lime content [30]. The dominant soil types fall under Vertisols, Mollisols, Inceptisols, and Entisols. Additionally, scattered spots of red mudstone, blue marl, and chalky formations from Gercus, Kolosh, and Shiranish can also be found [31]. Overall, the studied area exhibits a wide range of clay content and relatively low organic matter content.

2. 2 Measuring and predicting FC and WP

This part of research work consisted of three main steps to predict the FC and WP of soil using the SPAW model.

The first step involved the collection of soil samples from ninety-two locations in agricultural farms during April and May, at a depth of 0-50 cm. To obtain a representative sample that reflects the average soil condition at each location, two samples of equal mass were mixed to minimize local heterogeneity between closely spaced samples. The soil samples air-dried, and sieved at a 2 mm sieve to remove gravel, ensuring it didn't affect the subsequent FC and WP analysis with the SPAW model. The FC and WP were measured (named: observed values) using the 0803 Pressure membrane apparatus at pF value 4.2 for WP and the 0802 Sand/Kaolin box at pF 2.0 for coarse texture and pF 2.7 for fine texture to determine FC (both methods from Eijkelkamp, The Netherlands).

In the second step, the collected soil samples underwent physical and chemical analyses required to run the SPAW model and formulate new models. Particle size distribution was determined using the pipette method as described by [32]. Total organic matter was measured using the Walkley and Black method with wet dichromate oxidation following [33]. According to Richards, calcium carbonate content was determined using the acid neutralization method as described in [34]. Although the electrical conductivity of saturation soil extract was measured with an EC-meter, it had no significant effect on the FC and WP values in the SPAW model.

In the third step of the research, the SPAW program, version 6.02.74, was utilized to enter information of seventy-six soil samples as the training data set, including sand, clay, organic matter, and electrical conductivity. The objective was to determine FC and WP (named: predicted by SPAW model values).

The water content at field capacity could be found according to this equation [10]:

$\Theta_{33} = \Theta_{33t} + 1.283*\Theta_{33t}^2 - 0.374*\Theta_{33t} - 0.015$

$\Theta_{33t} = -0.251S + 0.195C + 0.011OM + 0.006(S*OM) - 0.027(C*OM) + 0.452(S*C) + 0.299$

As well as for the water content at welting point:

$\Theta_{1500} = \Theta_{1500t} + 0.14*\Theta_{1500t} - 0.02$

$\Theta_{1500t} = -0.024S + 0.487C + 0.006OM + 0.005(S*OM) - 0.013(C*OM) + 0.068(S*C)+0.031$

Θ_{1500t} is 1500 kPa moisture, first solution, %v

Θ_{1500} is 1500 kPa moisture, normal density, %v

Θ_{33t} is 33 kPa moisture, first solution, %v

Θ_{33} is 33 kPa moisture, normal density, %v

To convert volumetric water content (Θ_{1500} and Θ_{33}) to gravimetric water content (FC_{SPAW} and WP_{SPAW}), 95% of the soil's bulk density was used.
In the same step, calibrated SPAW model ($SPAW_{cal}$) was formulated by establishing the relationship between the predicted FC and WP values obtained from the SPAW program (considered as independent variables) and the observed FC and WP values (considered as dependent variables).
This step plays a crucial role in fine-tuning the SPAW model's performance, as it aligns the model's predictions with the actual FC and WP values observed from the collected soil samples. The $SPAW_{cal}$ Model is anticipated to provide more dependable and area-specific data, allowing for better-informed decisions on agricultural practices and water management methods in the research area. The close alignment between predicted and observed FC and WP values obtained through this calibration process serves as a validation of the SPAW model's suitability and effectiveness for predicting soil water characteristics under varying compaction conditions.

2. 3 Validation of SPAW and SPAWcal models

In order to assess the accuracy predicted values of FC and WP obtained from the SPAW and the SPAWcal models, sixteen soil samples were utilized as testing data. The observed FC and WP values for the relevant soil samples were compared with the predicted FC and WP values from each model for the evaluation. Several statistical efficiency criteria were used to accomplish this goal. Among these tests were Root Mean Square Error (RMSE). The proportion of the data variance that the models represented was calculated by the coefficient of determination (R^2). A higher R^2 denotes a more favorable match between the predicted and observed values. Additionally, the Bland-Altman analysis and the Shapiro-Wilk (W) test were used. The Shapiro-Wilk W test offers understanding of the models' suitability in managing the data and helps assess the normality of the data distribution. The Bland-Altman analysis is a graphical method used to assess the agreement between two measurement methods[35]. The Bland-Altman plot was generated to visualize the differences between the observed and predicted FC and WP values; a positive result denotes underestimation and a negative result denotes overestimation. Any outer points in the plot represent the samples where the deviation from the expected frequency is larger.

3 Results and Discussions

3. 1 Descriptive statistics of training and testing data set

Table 1 displays descriptive statistics for soil characteristics in the study areas. In the calibration dataset, the minimum and maximum FC values were 8.08% and 36.75%, respectively, while for WP, they were 4.26% and 24.42%. Remarkably, the minimum and maximum values in the testing dataset closely resembled these values, suggesting a similar distribution between these two datasets.

Tabel 1: Descriptive statistics for soil characteristics in the entire dataset (N=92).

Soil characteristics	Training data set (n = 76)				Testing data set (n = 16)			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Sand %	1.060	64.60	18.15	15.79	4.16	71.48	18.82	17.20
Clay %	6.590	60.02	34.93	15.22	8.51	53.26	37.93	13.06
Organic matter %	0.170	3.72	1.32	0.73	0.48	2.200	1.498	0.46
Calcium carbonate %	2.120	62.35	20.87	12.06	4.25	36.50	22.22	9.02
Wilting point %	4.26	24.42	15.85	5.16	4.95	24.81	16.89	5.43
Field capacity %	8.08	36.75	26.55	6.81	9.48	36.81	27.81	5.60

The table 1 also shows that soil textures various quite a bit across the study area, especially when you look at the standard deviation for sand (17.20) and clay (13.06). This kind of variation is not unusual for calcareous soil, especially in semi-arid and mountain area. These dereference are really affect how soil holds water and how to behaves overall [8, 12].

On the other hand, the organic matter (OM) did not vary much across the sites, with a standard deviation of just (0.46). This suggests that the amount of organic material added to the soil, or the rate at which breaks down, is pretty consistent throughout the area. The low variability in OM means that differences in land use or vegetation type probably do not have on much impact on organic input in the short term. While having similar OM level makes it easier to model soil behavior. It might also mean that there has not been too much improvement in soil fertility in these regions. A small amount of organic matter can make a big difference in improving soil structure and helping the soil hold onto water, especially in soils that don't have much carbon [36]. This really shows how important organic matter is for soil water movement and for making our models more accurate, even if there is not a lot of variation in OM across the sites.

The differences in sand and clay content really highlight why it's important to calibrate models for each specific site, especially in calcareous soils. Abdelbaki [37] Emphasized that selecting the right pedotransfer functions (PTFs) based on soil texture and matric potential is crucial for reducing prediction errors. [38] showed that using standard PTFs can underestimate water retention by as much as 20% in soils with high carbonate content, which ties what it was found in this study. This supports the effectiveness of the calibrated SPAW approach for achieving more accurate regional predictions. Using these general models without calibration can lead to big errors. Therefore, even though SPAW is usually a strong model, it still needs to be adjusted to local soil conditions to give reliable results in semi-arid or calcareous areas.

3. 2 Relationship between measured and predicted (FC and WP) values

The SPAW model, designed to assess soil moisture under various tensions such as FC and WP, is a valuable tool for irrigation scheduling. However, it may have limitations in certain soils due to its lack of consideration for specific soil properties related to moisture, such as high levels of calcium carbonate. Therefore, calibration is necessary to adapt it to the specific conditions of the study area. Figures 1a and 1b illustrate the relationship between measured FC and WP values and their corresponding predicted values by the SPAW model for the purpose of developing a calibrated SPAW model, referred to as $SPAW_{cal}$, with the equation $SPAW_{cal} = 5.8799 + 0.7289SPAW_{FC}$ for FC (Figure 1a) and $SPAW_{cal} = 6.2234 + 0.572SPAW_{WP}$ for WP (Figure 1b). In both figures, the dashed line represents a 99% confidence interval. Remarkably, no data points deviate from the confidence interval lines for FC, while only one data point falls outside the interval for WP. This highlights a strong correlation and agreement between the two datasets, with R^2 values of 0.8283 and 0.7937 for FC and WP, respectively.

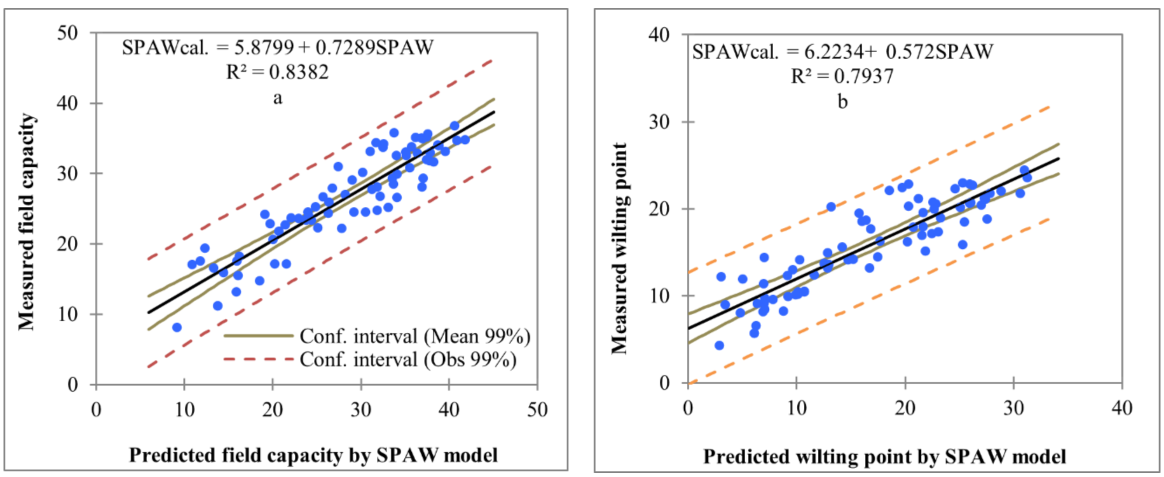

Figure 1: Relationship between predicted FC and WP by the SPAW model and measured values.

3. 3 Validation of SPAW and SPAWcal models for predicting (FC and WP)

After calibrating the SPAW model for predicting FC and WP in calcareous soils, with the goal of reducing their RMSE and enhancing overall reliability, a validation process was undertaken to compare the performance of the SPAW model and the $SPAW_{cal}$ model. This comparison was conducted using a testing dataset consisting of 16 data points. The results are presented in Figures 2 and 3, as well as Table 2. It is evident from these figures and the table that the SPAW model demonstrated an increasing tendency to overestimate as soil moisture levels rose (in FC the overestimation was more than in WP). Conversely, the $SPAW_{cal}$ model exhibited an increasing tendency to underestimate with rising soil moisture levels. This observation underscores the superior performance of the $SPAW_{cal}$ model over the SPAW model. The necessity of analyzing particle size distribution without removing $CaCO_3$ in calcareous soils to accurately represent the soil's natural characteristics led to an underestimation of FC and WP values.

Both models at FC, as validated by the Shapiro-Wilk test, showed quite similar results (0.955 for the SPAW model and 0.941 for the $SPAW_{cal}$ model). However, other criteria such as RMSE were reduced from 3.104 to 2.247. Based on the Bland-Altman plot, the outer lines indicating the 95% limits of agreement improved from 3.190 and -6.487 to 4.610 and -3.699, respectively. Additionally, the mean difference shifted from an overestimate of -1.649 in the SPAW model to an underestimate of 0.455 in the $SPAW_{cal}$ model (Figure 2). This shift is significant, as it reflects not only an improvement in accuracy but also a correction in the direction of bias-an essential factor in predictive model performance, particularly for irrigation management decisions.

At WP, the Shapiro-Wilk value improved slightly from 0.889 to 0.922 when the SPAW model was calibrated, indicating a better fit of the residuals to a normal distribution. The RMSE decreased from 3.316 to 2.642, confirming enhanced predictive performance. In the Bland-Altman plot, the limits of agreement improved from 4.361 and -7.001 (SPAW) to 5.227 and -4.725 ($SPAW_{cal}$), and the mean difference between measured and predicted WP also followed a similar trend to that observed in FC, shifting from an overestimate of -1.320 in the SPAW model to an underestimate of 0.183 in the $SPAW_{cal}$ model (Figure 3). These improvements demonstrate the benefit of calibration and support the suitability of $SPAW_{cal}$ for calcareous soils, where standard models often fail to capture the effects of soil chemical characteristics on moisture retention. The results together confirm that the shift from overestimation to underestimation in both the prediction of FC and WP after calibrating the SPAW model indicates a superior performance. The enhanced accuracy, reduced error margins, and correction of bias direction in $SPAW_{cal}$ make it a more reliable tool for water retention estimation in calcareous soils.

Tabel 2: Validation of SPAW and SPAWcal models for predicting FC and WP using a testing data set (n=16).

SM	Models	RMSE	Shapiro-Wilk (W)	Bland- Altman		
				ULA Diff.+(1.96*SD)	LLA Diff.-(1.96*SD)	Mean Difference
FC	SPAW	3.104	0.955	3.190	-6.487	-1.649 overestimate
	$SPAW_{Cal}$	2.247	0.941	4.610	-3.699	0.455 underestimate
WP	SPAW	3.316	0.889	4.361	-7.001	-1.320 overestimate
	$SPAW_{Cal}$	2.642	0.922	5.227	-4.725	0.251 underestimate

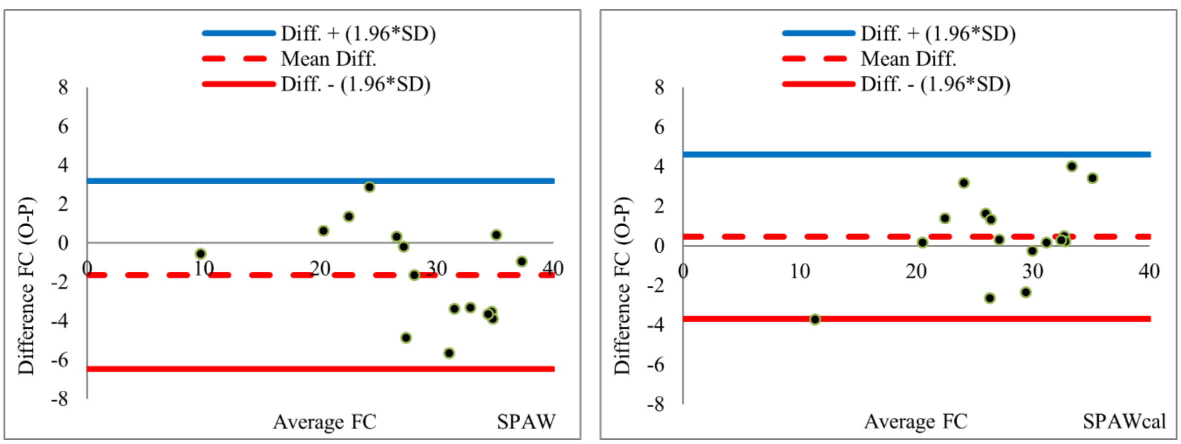

Figure 2: Bland-Altman plot comparing FC values measured in the laboratory to FC values predicted by SPAW and SPAWcal models. The outer lines indicate the 95% limits of agreement, and the center line shows the mean difference.

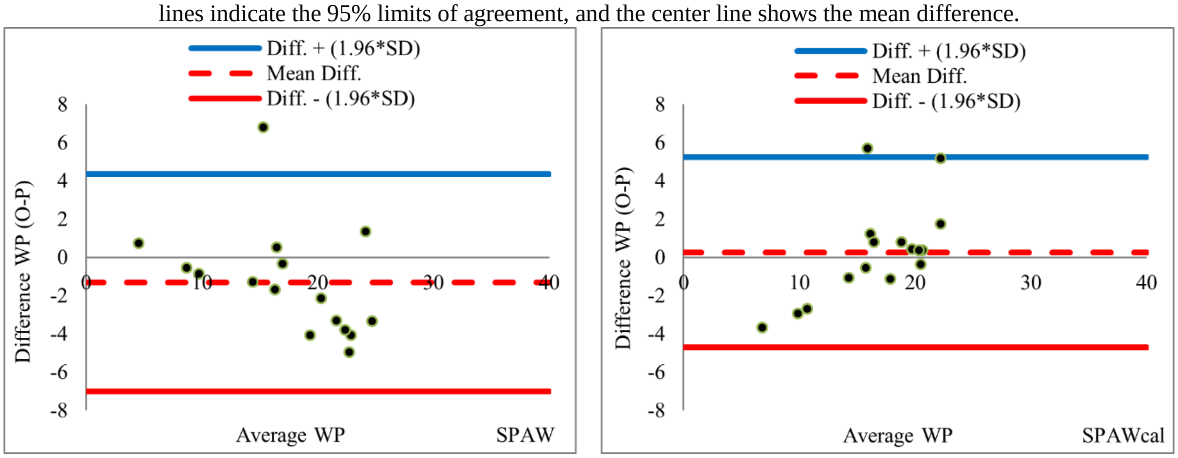

Figure 3: Bland-Altman plot comparing WP values measured in the laboratory to WP values predicted by SPAW and SPAWcal models. The outer lines indicate the 95% limits of agreement, and the center line shows the mean difference.

4 Conclusion

This study aimed to assess the performance of SPAW model and its calibrated SPAW ($SPAW_{cal}$), in predicting FC and WP in calcareous soils. The SPAWcal model was created by building a regression between the measured field capacity (FC) and wilting point (WP) values and the ones predicted by the original SPAW model. There was a strong correlation between the two sets of data, with R^2 values of 0.83 for FC and 0.79 for WP, showing that the calibration worked really well. Subsequent validation of the $SPAW_{cal}$ model against the SPAW model, utilizing various criteria such as RMSE, Bland-Altman analysis, and Shapiro-Wilk tests, revealed its superior performance. The observed improvements in RMSE and the shift from overestimation to underestimation in both FC and WP predictions following calibration emphasized the enhanced performance of the $SPAW_{cal}$ model. This demonstrates the importance of analyzing particle size distribution in calcareous soils without the removal of calcium carbonate, as this contributed to more accurate FC and WP estimates. Which offering valuable insight for effective irrigation management and agriculture practices in such environments.

Authors contribution

Rebaz Aziz Ahmad was responsible for drafting the manuscript. Mohammed Abdulrazzaq Fattah analyzed the data, formulated models using specialized software, and edited the paper. The remaining authors collected samples and performed laboratory work.

Conflict of intrestrst

Authors have no conflict of interests

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