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Effect of Zeolite on the Hydraulic Parameters of Soil and Simulation of Water Flow Using HYDRUS-2D

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ABSTRACT

Zeolites are recommended to utilize in agricultural sector due to their water holding and cation exchange capacity. Effect of zeolite on the hydraulic parameters of sandy loam soil was investigated and HYDRUS-2D was used to simulate the movement of water in the soil. Data needed were collected by conducting laboratory experiments. The studied treatments included four levels (Z_{zero}, Z_5, Z_{10}, and Z_{15} g kg^{-1} of soil) to determine the effect of zeolite on hydraulic parameters including saturation moisture (θ_s), residual moisture (θ_r), shape parameter (n), point check air permeability (α), and saturated hydraulic conductivity (K_s) of the soil. Four rounds of irrigation were done based on readily soil moisture and the soil moisture values before and after irrigation were measured using the Wet Sensor in the depth and radial directions and recorded for 45 days. The initial value of hydraulic parameters including θ_s, θ_r, α, n, and K_s were determined using Rosetta. Results showed that with the increase in the amount of zeolite, the parameters θ_s, θ_r, and n increased and the value of α decreased, which indicated a decrease in the rate of water discharge from the soil. However, the values of K_s tended to decrease. In fact, mixing zeolite causes soil to hold more water because of micro-pore structure of zeolites. The Efficiency Coefficient (EF) of HYDRUS-2D model, which shows the quality and how to fit the observed and estimated data, varied between 0.82 and 0.97, showing the high efficiency of the model in simulating humidity.

Keywords: Advance curve, Soil texture, Water holding capacity.

INTRODUCTION

Hydraulic properties of soil play an important role in the water cycle. They are used as fundamental information in the design of irrigation and drainage systems, hydrological issues, and soil quality assessment. These properties can be measured or estimated using different direct and inverse methods. However, direct measurement of these properties is difficult, costly, and time-consuming. Moreover, due to their high spatial and temporal variability, a large number of samples are required for accurate characterization (Asgarzadeh *et al*., 2014). The HYDRUS-2D model (Šimůnek *et al*., 1999), is a Windows-based model for analyzing water flow, solute transport, and heat transfer under two-dimensional conditions. It is capable of estimating the hydraulic properties of soil and/or solute transport parameters using an inverse solution approach. The model uses the linear finite element (Galerkin method) for the numerical solution of governing equations and the Levenberg-Marquardt method for parameter optimization (Marquardt, 1963).

The HYDRUS model has been used in numerous laboratory and field studies to simulate soil moisture and hydraulic properties (Siyal and Skaggs, 2009). Several studies have investigated the effect of zeolite on soil hydraulic parameters (Colombani *et*

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al., 2014; Soudejani *et al*., 2020), among which some researchers have used the HYDRUS model to simulate the effect of zeolite on soil moisture (Li *et al*., 2021; Ibrahim and Alghamdi, 2021; Colombani *et al*., 2015).

In a study conducted by Colombani *et al* (2014), they examined changes in flow parameters and salt transport resulting from adding zeolite to silty-loamy soil. They reported that zeolites enriched with $NH4^+$ increased water retention capacity in silty-loamy soils, thus limiting water and salt losses. Additionally, another study conducted by Ibrahim and Alghamdi (2021) investigated the effect of particle size of natural Clinoptilolite Zeolite (CZ) on Water Content (WC) and hydraulic properties of sandy loam soil and simulated it using the HYDRUS-1D model. They reported that available water content and soil water storage were increased by 3.6-14.7% and 6.8-10.5%, respectively. The changes in infiltration rate and hydraulic conductivity were statistically significant, with a reduction of 25.6% and 19.3% compared to the control, only for the smallest CZ particle size. Their results demonstrated that the HYDRUS-1D model accurately simulated soil moisture content and water retention capacity. Their results also showed that the use of CZ in the form of nano-sized particles increased water retention capacity and reduced hydraulic conductivity in soils with a light texture, thus improving water use efficiency and aiding water conservation in dry areas.

In sandy soils, the addition of organic matter can alter the physical and chemical properties by reducing large pores, water, and nutrient leaching rates (Blanco-Canqui and Lal, 2009), thereby increasing water holding capacity. Therefore, improving soil structure and texture increases water availability, nutrient availability, and crop yield (Samreen *et al*., 2017).

One of the commonly used mineral materials for improving the physical properties of soil, particularly increasing soil moisture retention capacity, is zeolite. Zeolites are natural or synthetic mineral compounds with a three-dimensional crystal structure with an open and highly porous network, which results in a large internal surface area (several hundred square meters per gram) and cation exchange capacity (McGilloway *et al*., 2003). The most widely used zeolite in Iran for agricultural purposes, especially for amending sandy soils due to nutrient leaching, is clinoptilolite. Among all aluminosilicate groups, clinoptilolite has the highest silica content, which gives it the highest absorption capacity among different types of natural zeolites (Reid *et al*., 2021; Samolej and Chalupnik, 2021). Due to the high ion exchange capacity of clinoptilolite and its strong affinity for absorption, it has received much attention in agriculture (Jha and Hayashi, 2009). These materials are highly hydrophilic and provide water and dissolved nutrient availability to plant roots easily when needed (Tohidi-Moghadam *et al*., 2009). Considering their properties, the use of zeolites with diverse applications is rapidly increasing in various fields (Sangeetha and Baskar, 2016). Several industrial applications, such as chemical, optical, and microelectronics industries, have been documented (Jarosz *et al*., 2022), and their use for environmental protection purposes has been reported (Belviso, 2020).

In recent years, zeolites have been widely used in agriculture, which is currently the main consumer of zeolite production worldwide (Szatanik-Kloc *et al*., 2021). They have been used as soil conditioners due to their impact on the chemical and physical properties of soil (Belviso *et al*., 2022). Generally, zeolites can alter the total porosity, pore size distribution, pore channel connectivity, and soil compaction with varying effects depending on the soil composition, nature of the zeolite, water properties, and even experimental conditions (Sepaskhah and Yousefi, 2007). Several articles have discussed the effects of zeolites on soil permeability (Szerement *et al*., 2014), saturated hydraulic conductivity (Jakkula *et al*., 2018), soil water content, and water holding capacity (Ravali *et al*., 2020).

They increase soil permeability, saturated hydraulic conductivity, water retention capacity, aeration, and many other factors (Jakkuld and Wani, 2018). In light-textured soils, such as sandy soils and loamy soils, the addition of zeolite usually has the effect of increasing the soil moisture characteristic curve and water retention capacity while reducing saturated hydraulic conductivity (Ks) and permeability (Colombani *et al*., 2015). In heavy-textured soils (such as clayey and silty-clayey soils), zeolites may have very different effects (Jarosz *et al*., 2022).

In another stud by Gholizadeh and Sepaskhah (2013), the effects of applying calcium-potassium zeolite on saturated hydraulic conductivity and water infiltration equation in soils with different irrigation salinities were investigated under laboratory conditions. The results showed that, in all treatments with the same amount of zeolite and salinity, the final saturated hydraulic conductivity decreased as the soil texture became heavier. Additionally, in a specific soil texture and salinity, the application of zeolite up to a certain limit increased the saturated hydraulic conductivity. However, the optimal zeolite application rate varies for different soil textures (Szatanik *et al*., 2021). In another research, Torkashvand and Shadparvar (2013) reported that the use of 10 grams of zeolite per kilogram of soil could retain a maximum of 8.4% of available moisture capacity and delay the wilting point in loamy sandy soils in Iran.

Razmi and Sepaskhah (2012) examined the effect of zeolite on saturated hydraulic conductivity and crack behavior in expanding silty clayey soils. Their results showed a significant increase in saturated hydraulic conductivity with the application of 8 grams of zeolite per kilogram of soil. According to studies conducted by Abedi Kupai and Sohrabi (2004), using 8 grams of zeolite per kilogram of soil increased the volumetric moisture percentage by 3.5 to 8.4 times in sandy soil, 2.2 times in loamy soil, and 1.1 to 9.1 times in clayey soil compared to the control. In each soil texture and at each application level, adding moisture absorbers distanced the soil moisture characteristic curve from the control, indicating a significant difference in volumetric moisture percentage at each suction point of the curve compared to the control. In clayey and loamy soils, this difference increased the water retention in these textures. These results have shown that the addition of different zeolite rates to soils has variable effects on their porosity, structure, and hydraulic properties (Pal *et al*., 2006).

Simulating soil moisture using the HYDRUS model in potted crops is a very suitable and novel research field. Crops are commonly grown in pots, but so far, no research has been conducted on estimating soil hydraulic parameters using the HYDRUS-2D software in different zeolite treatments in potted experiments. Therefore, the purpose of this research was to investigate the effects of using different amounts of zeolite on soil hydraulic parameters in a light soil texture and to simulate the water flow of the soil treated with zeolite using HYDRUS-2D.

MATERIALS AND METHODS

Site Description

Experimental studies were conducted using 10 kg plastic pots (length of pot 25cm, top and down diameters 22 and 18 cm, respectively). It is mentioned that the whole pot had not been filled with soil. The height of soil in the pot was 22 cm and the top radius of the filled soil was approximately 11cm, and by creating a hole in the bottom of the pot, a structure similar to a lysimeter was created. Then, by placing a container with a lid under the pots and using a graduated container, the amount of outgoing water after each irrigation was measured (Figure 1). The pot floor was filled with a layer of 2 cm coarse sand as drainage. Then, the pots were placed on a platform 20 cm above the ground. Clinoptilolite zeolite was added and mixed at four levels (without zeolite, 5, 10 and 15 grams of zeolite per kilogram of soil, respectively). The bulk density of the soil was determined using the cylinder method (Balke and Hartg, 1986), and the soil texture was determined using the hydrometer method (Klute, 1986) and Electrical Conductivity (EC) and acidity (pH) using an EC meter and pH meter and the moisture content at field capacity and wilting point were measured by pressure plates (Richards, 1965). The physical and chemical characteristics of the soil are shown in Table 1.

The zeolite used in this study was clinoptilolite type zeolite obtained from the hot water zeolite mine in Semnan Province. The zeolite was crushed using a rod mill and sieved to a particle size of 0.075-0.180 mm using a sieve. The properties of the zeolite used are shown in Table 2. Irrigation time was also determined based on soil moisture in the control pot and using Eq. 1:

$$D = \frac{(\theta_{fc} - \theta_{pwp})}{100} D_{rz} \times \text{MAD} \quad (1)$$

Where, θ_{fc} is field capacity (cm^3 cm^{-3}), θ_{pwp} moisture at wilting point (cm^3 cm^{-3}), D readily available soil moisture (L), D_{rz} Depth of the pot (L) and MAD is the Management Allowed Depletion. The investigations showed that the readily available soil moisture was about 50% of the available water content. After 14-day, the soil moisture was receiving this water content and this subject was the reason for selecting 14-day irrigation frequency. The same amount of irrigation water was used for all treatments. Since no crop was cultivated, with the same amount of irrigation water the mentioned effect can be compared better in the different treatments.

In this study, the HYDRUS 2D model was used to simulate soil moisture based on the numerical solution of the Richards equation (Šimunek *et al.,* 2006). Due to the high symmetry of the right and left halves of the soil moisture profile under realistic conditions, the simulation of the moisture profile was only performed for the right half and then compared with the actual conditions. In this research, to define the two-dimensional simulation environment in the HYDRUS model, a pot with a top width of 11 cm, a bottom width of 9 cm, and a height of 22 cm was defined.

The irrigation cycle was 14 days as the average irrigation interval based on the readily available soil moisture that was about 50% of the available water content. In total, 4 stages of irrigation, and in each irrigation cycle, a variable water height was established on the top of the pots for irrigation.

Modeling Soil Moisture Distribution Using the HYDRUS-2D Model

The HYDRUS-2D model is a simulation model that simulates water and solute flow in one, two, or three dimensions under saturated and unsaturated conditions. This model simulates the two and three-dimensional movement of water in soil using the numerical solution of Richard's equation. In this study, the two-dimensional form of the model was used, which assumes homogeneity and uniformity, and the two-dimensional movement is presented as Eq. 2 (Celia *et al*., 1990).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial h}{\partial x}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z} + K(h)\right] \quad (2)$$

Where, θ is the volumetric soil moisture content (cm^3 cm^{-3}), h is the water pressure in the soil (L), x and z are the horizontal and vertical coordinates (L), t is the Time (T), K(h) is the unsaturated hydraulic conductivity of the soil (L T^{-1}). Considering the water movement assumption in the initial part of the software, the geometry includes a pot length of 22 centimeters, a vertical soil column, and one soil layer. The selected model for the hydraulic properties of the soil is the Van Genuchten-Mualem model. The hydraulic characteristics of the soil were obtained using the Van Genuchten relationship (Van Genuchten, 1991), which is described as follows:

Figure 1. Schematic view of the pot in the laboratory.

Table 1. Physical properties of the experimental soils.

Depth (cm)	Texture	Sand	Silt	Clay	Bulk density	pH	EC
			%		(g cm^{-3})	-	(dS m^{-1})
0-30	Sandy loam	66	19	15	1.43	7.67	0.850

Table 2. Chemical analysis of the zeolite used.

LOI*	CaO	Na_2O	Al_2O_3	SiO_2	P_2O_5	TiO_2	MnO	Fe_2O_3	Cl	CEC
			(%)						ppm	(meq g^{-1})
10-12	0.6	3.8	11	68.5	0.01	0.03	0.04	0.2-0.9	1600	2.6

$$\theta(h)=\begin{cases}\theta_r + \frac{\theta_s+\theta_r}{(1+\alpha h^n)^m} & h<0 \\ \theta_s & h\geq 0\end{cases} \quad (3)$$

$$K(h)= K_s S_e^{l}\left[1-(1-S_e^{1/m})^m\right]^2 \quad (4)$$

Where:

$$S_e = \frac{\theta(h)-\theta_r}{\theta_s-\theta_r}, \quad m=1-\frac{1}{n}, \; n>1$$

In these relationships, there are independent hydraulic there are independent hydraulic parameters including θ_r residual moisture (cm^3 cm^{-3}), θ_s saturation moisture (cm^3 cm^{-3}), K_s saturated hydraulic conductivity of soil (L T^{-1}), α inverse of air entry suction (L^{-1}) and n pore size distribution index (-) respectively. The relative saturation S_e and l in the hydraulic conductivity function represent the parameters for the pore connectivity and tortuosity, respectively, which were estimated as 0.5 for most soils (Mualem, 1976). It is necessary to accurately determine these parameters for solving the Richards equation numerically in HYDRUS 2D. The initial value parameters were estimated for hydraulic conductivity, K_s, residual moisture, θ_r, and saturation moisture, θ_s, in Van Genuchten form, using the information of soil mechanical analysis (soil texture) and bulk density measurement in Rosetta model. (Schaap *et al.,* 2001).

The simulation in the HYDRUS model is conducted by numerically solving the governing equations for water flow based on the appropriate selection of values for the parameters in these equations, as well as the determination of the appropriate initial and boundary conditions (Crevoisier *et al.,* 2008). Generally, the calibration process of the model was applied to the calibration of soil hydraulic parameters (Van Genuchten-Mualem parameters). For calibration of soil hydraulic parameters, including saturated hydraulic conductivity (K_s), shape parameters (n and α), residual moisture (θ_r), and saturation moisture (θ_s) were used.

In order to measure the amount of pots evaporation in laboratory conditions, the simplest form of the water balance equation was used. In this research, the amount of irrigation water and drained water from the pots were measured and used in the equation 5, (Hillel, 2004).

$$E_s = I - \sum(\Delta\theta)\, d - D \quad (5)$$

Where, E_s is the Evaporation from the soil surface (mm), I is the amount of Irrigation water (mm), $\Delta\theta$ is the moisture changes in the soil profile (mm), d is the depth of the moisture layer (mm) and D is the Depth of the drained water (mm).

Since no crop was cultivated, transpiration was considered to be zero.

In this experiment, the soil moisture in the treatments was measured daily at the center of the pods at a depth of 5 cm using the Wet Sensor (Delta-T, made in England). This sensor was portable and can be moved from one pot to another Figure 2. Based on Figure 2, the soil profile was considered as a checkered grid and these readings were recorded at a horizontal interval of 11cm and a vertical interval of 5cm after each irrigation for 45 days. The initial conditions for water distribution in the soil were determined by the moisture content present in the soil before irrigation at multiple points, using a Wet Sensor device, measured in the laboratory before the experiment for the soil layer (0 to 22 cm), and their averages were used in the model.

The upper boundary condition during irrigation was considered as a variable water head. The end of the model was considered as a free drainage boundary condition because this type of boundary condition is used for most soil columns in laboratory conditions and for cases where they are in contact with air from below and due to considering pressure the pressure in the bottom of the pot is zero Figure 2.

Performance Evaluation Indices of the Models

In this research, 80% of the measured data were used for model coefficient calibration and 20% of the data were used for validation. For evaluating the efficiency of the model validation and credibility of the model, evaluation indices such as Efficiency coefficient of the model (EF), the Normalized Root Mean Square Error (NRMSE), Coefficient of Residual Mass (CRM) and the coefficient of determination (R^2) were used for the simulated and observed soil moisture values (Adeboye and Alatise, 2007; Loague and Green, 1991).

$$EF = 1 - \frac{\sum_i^n (P_i - O_i)^2}{\sum_i^n (O_i - \bar{O})^2} \quad (6)$$

$$NRMSE = \frac{RMSE}{\bar{O}} 100 \quad (7)$$

$$CRM = 1 - \left[\frac{\sum_{i=1}^n P_i}{\sum_{i=1}^n O_i}\right] \quad (8)$$

$$R^2 = 1 - \frac{\sum_i^n (P_i - O_i)^2}{\sum_i^n (O_i - O_i)^2} \quad (9)$$

In these relationships, RMSE stands for Root Mean Square Error, P_i represents observed values, O_i represents Observed values of moisture, $\bar{O}$ represents the average Observed values, $\bar{P_i}$ represents the average measured values of moisture, and n

Figure 2. A representation of a physical model.

represents the number of samples being examined. The negative value of EF indicates that the average of the measured values has a better estimate than the predicted values. The simulation is considered excellent with NRMSE less than 10%, “good” if NRMSE is greater than 10 and less than 20%, “fair” if NRMSE is greater than 20 and less than 30%, and “poor” if NRMSE is greater than 30% (Bannayan and Hoogenboom 2009). The values of the CRM index show the ability of the model to estimate the values compared to the measured values. The negative CRM values indicate the tendency of the model to overestimate the measurements, the closer the CRM value is to zero, the better the simulation effect will be (Jamieson *et al*., 1991). R^2 index expresses the simulation process and the closer it is to one, the more accurate the simulation process is. If all measured and simulated data are identical, CRM and NRMSE are zero and EF is equal unit (Loague and Green, 1991).

RESULTS AND DISCUSSION

The application of zeolite in light soil increases the number of fine pores in the soil, leading to a decrease in K_s compared to the treatment without zeolite. Clearly, in light soils, the use of zeolite to reduce the amount of K_s is desirable because it reduces water transfer capacity in the soil, resulting in less vertical infiltration and water loss. The results of this study were consistent with the studies conducted by Jakkula *et al*. (2018). Similar results were also observed by Gholizadeh and Sepaskhah (2013) and Szatanik-Kloc *et al*. (2021).

Regarding the values of soil hydraulic parameters, the percentage of θ_s increased with increasing zeolite content, with the highest value recorded at 0.601% cm^3 cm^{-3} in the treatment with 15 grams of zeolite per kilogram of soil (Table 3). Due to the fine and porous nature of zeolite, the weight of moisture content also increased. Since light soils have a limited capacity to store and retain moisture, adding a superabsorbent (zeolite) to the soil not only increases the water retention capacity in the soil but also reduces the evaporation rate of water from the soil. Additionally, θ_r increased with the application of zeolite in loamy soil due to increased water retention caused by the presence of zeolite in the soil. These results are consistent with the studies conducted by Comegna *et al*. (2023). Due to its porous structure, zeolite can increase the capillary porosity of the soil, and by absorbing water, it can increase the amount of water holding capacity in sandy soils; because of this, θ_s increased. The increase of zeolite has led to the increase of delicate pores in the soil, which reduces the amount of K_s as the pores become smaller. Similar results were also observed by Jabro (1992) and Sepaskhah and Yousefi (2007).

Effect of Zeolite on Moisture Retention Characteristics

Factors affecting the shape of the curve, the model coefficients, or the function of the moisture retention curve also have an

Table 3. Hydraulic parameters of soil and some of the HYDRUS model validations in the calibration phase.

Zeolite application (g kg^{-1})	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (m^{-1})	n -	K_s (cm d^{-1})
0	0.0543	0.5	0.16	1.7	120.43
5	0.063	0.523	0.13	1.84	112.56
10	0.067	0.543	0.09	2.08	90.87
15	0.07	0.601	0.083	2.58	75.80

impact. Among them, the coefficients α (air-entry value) and n (slope of the moisture retention curve) are included in the van Genuchten curve (Van Genuchten *et al*., 1991). The shape coefficients indicate the rate of moisture discharge from the curves under the influence of gravity or evaporation energy. Based on the results of investigating the effect of zeolite on the van Genuchten model coefficients, parameter α decreased with the increase of zeolite in sandy loam soil (Table 3). This is due to the changes resulting from increased water holding capacity and delay in losing gravitational and non-gravitational water, in which zeolite's positive effect on creating finer porosity and increased water retention becomes evident. A decrease in this parameter indicates an increase in fine pores and an increase in fine defects can alleviate the problem of water retention in light soils. It also indicates the superiority of matric potential over gravitational potential, which is why the water infiltration rate in the soil is low at the beginning of entry into the soil, consistent with some studies (Shaddox, 2004).

The results obtained from Table 3 show that θ_s and θ_r differ depending on the treatment, where the highest saturation and residual moisture percentages belong to the treatment with 15 grams of zeolite per kilogram of soil. With the addition of moisture absorbents, the moisture characteristic curve of each treatment deviates from the previous treatment, indicating a significant difference in volumetric moisture content among different zeolite treatments. With the increase in zeolite application, this deviation distance between the moisture characteristic curves increases, resulting in increased water retention in these treatments. This study's results align with research by Abedi Koupai and Sohrab (2004). Due to its porous structure, zeolite can increase the porosity of the soil structure and also increase moisture retention in sandy soils by absorbing water. Water retention in higher suction is due to zeolite absorption, leading to an increase in the amount of usable water in light-textured soils. In general, it was observed that as the percentage of zeolite in the soil increased, the characteristic moisture curves shifted upwards. This effect is evident in all different zeolite and soil treatments, which is consistent with the results of a study by Comegna *et al*. (2023).

The values of calibration coefficients for soil hydraulic parameters in the four mentioned treatments are presented in Table 4. As it is clear in this table, the amount of NRMSE error in the simulation of water flow in the soil in the two stages of validation and calibration, respectively, in the treatments of not using zeolite in the range (16.5-20.11%) and for 5 gram of zeolite is in the range of 13.68-13.90%.

Table 4. Statistical evaluation of the simulation of water content in the soil columns by the HYDRUS-2D model.

Zeolite application (g kg^{-1})	NRMSE (%)	R^2	CRM	EF
Validation				
0	16.5	0.83	0.01	0.97
5	13.68	0.89	-0.06	0.82
10	6.97	0.95	-0.01	0.94
15	8.31	0.95	0.01	0.89
Calibration				
0	20.11	0.85	0.03	0.95
5	13.90	0.88	-0.05	0.83
10	6.59	0.95	-0.02	0.94
15	6.69	0.95	0.10	0.92

Based on this statistic, the volume of water content modeling by HYDRUS is average. For the treatments of 10 grams of zeolite (6.97-6.59 percent) and 15 grams of zeolite (8.31-6.69%). Based on this statistic, the volume of water content modeling by software is less than 10 percent.

The high R^2 value of the results shows the power of HYDRUS -2D software in estimating soil moisture in different soil treatments. The value of CRM statistic was obtained for the two stages of validation and calibration for the treatment of 5 and 10 grams of negative zeolite, which showed that the software tended to overestimate. For the two control treatments and 15 grams of zeolite, the positive value showed that the software tends to underestimate and predicts the water content more than the measured values. The efficiency value of the EF model, which indicates the quality and how to fit the observed and the estimated data, varied between 0.82 and 0.97. In other researches, the RMSE error value in the simulation of soil moisture changes are reported in the range of 0.015-0.017, 0.011-045, and 0.028-0.033 $cm^3\ cm^{-3}$ (Simunek *et al.,* 2012; Ibrahim and Alghamdi, 2021). The low values of ME error in the table show the appropriate performance of the model. Soudejani *et al*. (2020) stated that HYDRUS-1D numerical model with average RMSE and NRMSE from 0.013 to 0.032 $cm^3\ cm^{-3}$ and 0.076 to 0.195, respectively. They were changing. The coefficient of determination values varied from 0.57 to 0.92. (Nazari *et al*., 2021; Sun *et al*., 2023) have also stated the high accuracy of HYDRUS simulation in modeling soil moisture changes.

The graphs presented in Figure 3 show the output of the model in comparison with the volumetric water content values measured in different zeolite treatments at a depth of 0 to 5 cm (moisture measured with Wet sensor) during a period of 45 days. In the treatment of 15 grams of zeolite, it can be seen that at a depth of 0-5 cm in four rounds of irrigation, the amount of saturated moisture was 23% more than the control. After 14 days of irrigation, the amount of moisture was 30% higher than the control, which

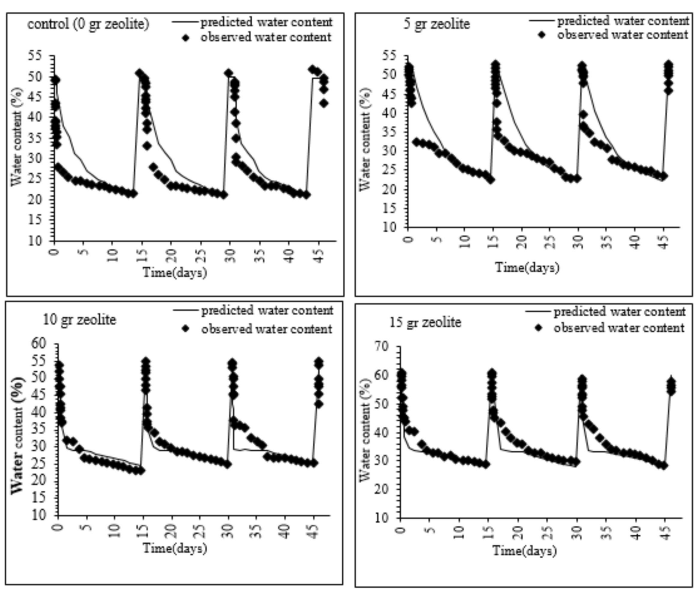

Figure 3. Comparison of the measured and simulated changes in soil moisture using HYDRUS-2D in the depth (0 to 5 cm from the soil surface) in different zeolite treatments, where the circles indicate measured data and the solid line indicates the estimated by the HYDRUS-2D model.

indicates the high absorbability of zeolite due to its high specific surface area.

The comparison of the calibration and validation results obtained from the Hydrus model with the water content values measured in the laboratory is shown in Figures 4 and 5. The high R^2 of the results shows the power of HYDRUS -2D software in estimating soil moisture in different soil treatments. Also, the slope of the 1:1 line is close to one, indicating that the model does not overestimate or underestimate. Other factors affecting the difference between the measured and modeled values can be caused by the errors in the water content measurement by the Wet sensor and the accuracy of the device itself. As Figures 4 and 5 show, in the treatment of 15 and 10 grams of zeolite per kilogram of soil, it has high accuracy and the simulated and measured values show a very high agreement.

The reason for the increase in water content after irrigation in zeolite treatments indicates that, unlike clay minerals, in zeolites, the structural framework is large enough and this feature creates the unique properties of zeolites: they can easily move within the network without changing the structure of the zeolite network.

In figures 6, 7, and 8, the front of the water content in the treatments of not using zeolite, 5, 10, and 15 grams of zeolite in the period of 0.016, 1.1 and 14 days are presented. The changes of the front of moisture advance in three time periods were presented to show the effect of zeolite on the three critical periods of moisture changes, i.e. after irrigation, one day after irrigation, and 14 days after irrigation, on the soil water holding capacity.

According to Figure 6, at the time of 0.016 days, the moisture front day in the treatment of 15 grams of zeolite is less than the other treatments. The reason can be attributed to the fine particles and pores of zeolite, which caused changes in gravitational and non-gravitational water loss. It also shows the superiority of the buoyant potential over the gravitational potential, which is why the speed of the advancing front is slower at the beginning of entering the soil, and was consistent with the studies (Ibrahim and Alghamdi, 2021; Shaddox, 2004).

According to Figure 6, at the time of 0.016 days, the moisture front in the treatment of 15 grams of zeolite is less than other treatments. The reason can be attributed to the fine particles and pores of zeolite (Shaddox, 2004). The progress of the moisture front in the treatment of not using zeolite is more than the other treatments, because zeolite, due to its micro pore structure and porosity, reduces infiltration at the beginning of entering the soil (Ibrahim and Alghamdi, 2021) and was consistent. Figure 8 shows the progress of moisture after 14 days in different treatments. The distribution of the moisture profile after 14 days of irrigation in the treatment of 15 grams of zeolite was different from other treatments. After 14 days, this shows that with the increase in the irrigation time, the moisture front increased in the zeolite treatment, which is the opposite of the treatment without zeolite. One of the reasons is that zeolite is very hydrophilic, which, while having the speed and capacity to absorb water, easily absorbs water when needed and dehydrates when needed, and the three-dimensional network structure of zeolite can absorb water for a long time. Due to its porous structure, zeolite can increase water retention by absorbing water, especially in sandy soils. Also, the open skeleton of zeolites has channels and holes containing cations and water molecules. The pores of zeolite are connected and form long wide channels with different sizes depending on the type of the mineral. These channels allow ions and water molecules to easily move in and out of the structure. The results of this research were consistent with Ibrahim and Alghamdi (2021) and Shaddox (2004).

In Figure 9, the water holding capacity by different zeolite treatments at depths of 2,7, 10, and 15 cm from the soil surface in 0.01, 1.1, and 14 days are presented.

According to Figure 9, in the period of 1.1 days, the water holding capacity at a depth of 10-15 cm in Z_{15} is more than the other treatments. The highest and lowest moisture

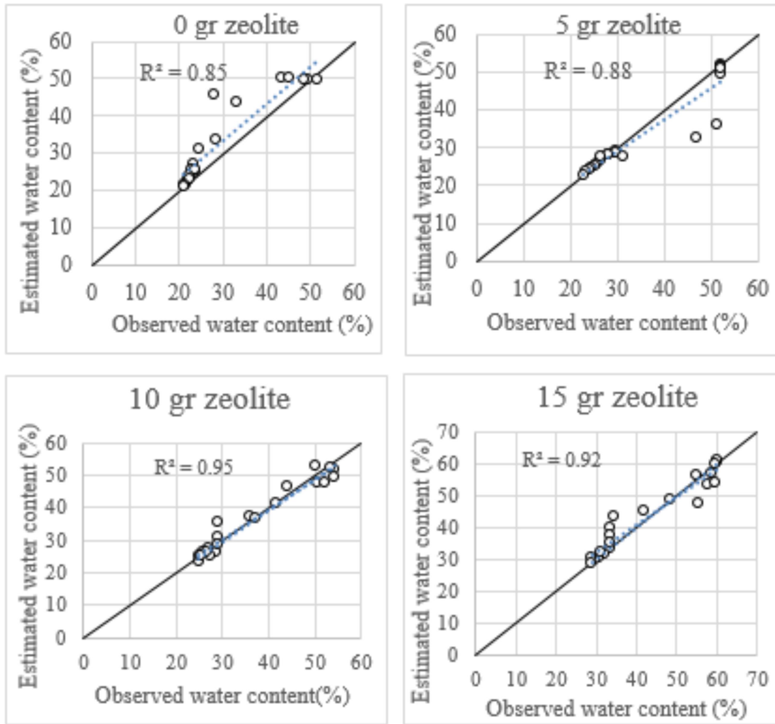

Figure 4. Observed and measured values for calibration of water content in different treatments at a depth of 0-5 cm.

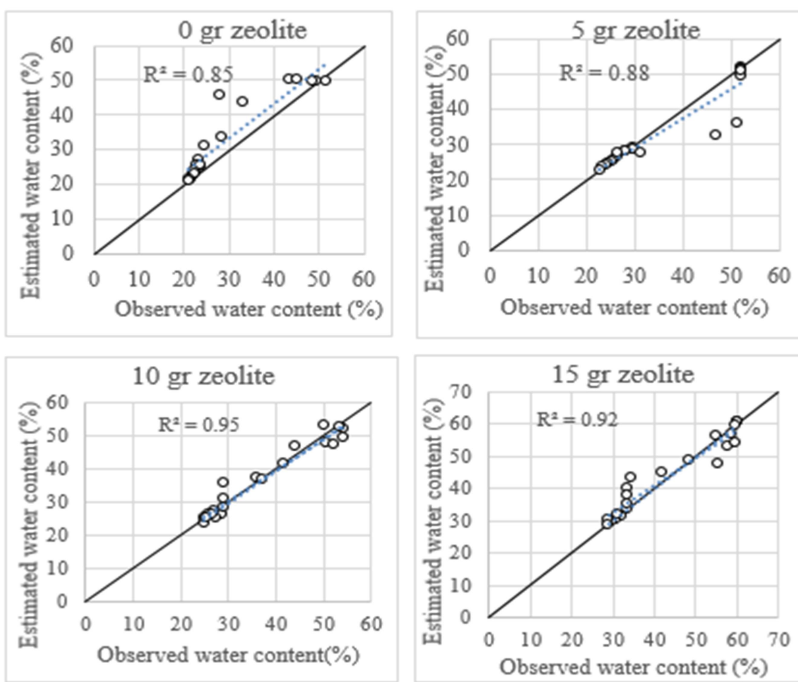

Figure 5. Observed and measured values for validation of water content in different treatments at a depth of 0-5 cm.

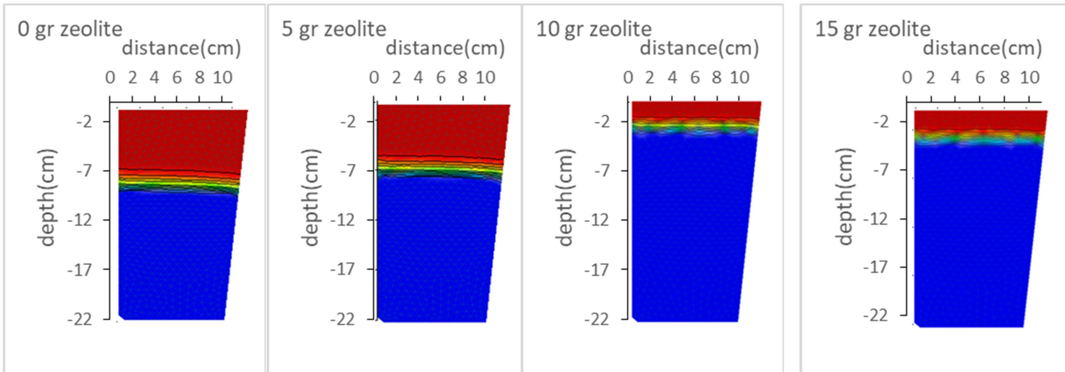

Figure 6. Spatial soil moisture distribution at time 0.16 day.

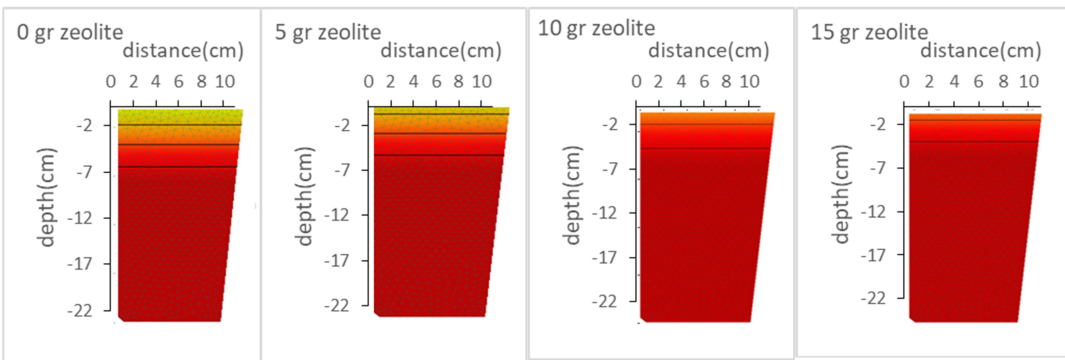

Figure 7. Spatial soil moisture distribution at time 1.1 day.

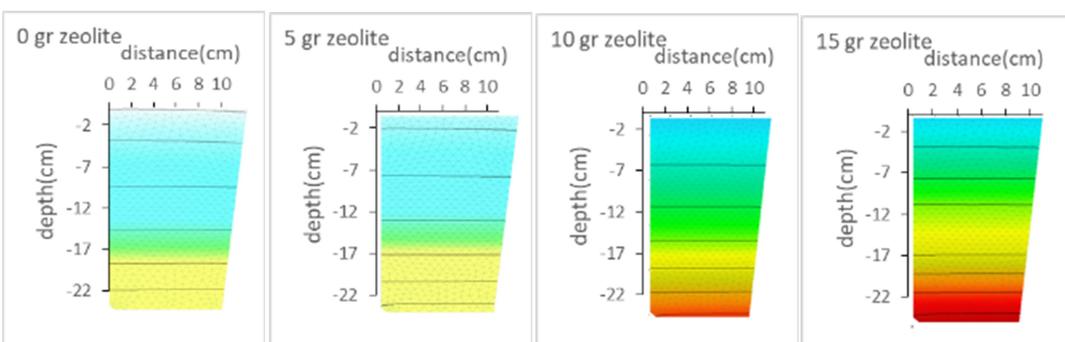

Figure 8. Spatial soil moisture distribution at time 14 day.

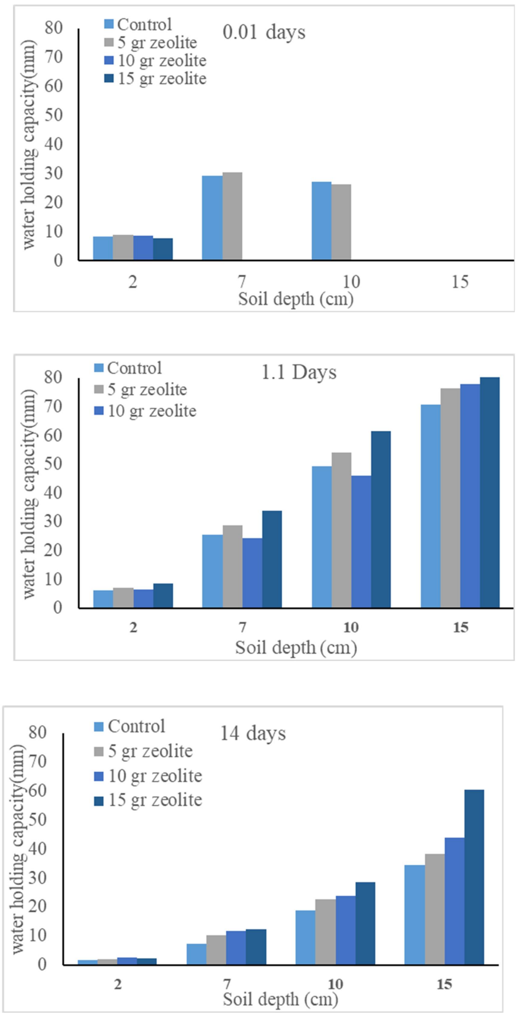

Figure 9. Represents the water holding capacity for the durations of 0.01, 1.1, and 14 days in different zeolite treatments.

content was related to Z_{15} and Z_0, whose values are 87.2 and 70.9 mm, respectively. While increasing the water holding capacity in light soils, zeolite can increase the irrigation intervals by quickly absorbing water and keeping it. For 14 days at a depth of 10-15 cm, the moisture kept in the treatment of Z_{15} is more than Z_0. The present results were consistent with studies of de Campos Bernardi *et al*. (2013). Zeolites, by rapidly absorbing water and preserving it, also increase the irrigation intervals, and the amount of this increase depends on the amount of zeolite used and the physical conditions of the soil (Zangui Nasab *et al*., 2012). The results of the present study were consistent with some other studies (Xiubin and Zhanbin, 2001; Szerement *et al*., 2014; Colombani *et al*., 2014). Xiubin and Zhanbin (2001) stated that the soil mixed with zeolite increased the moisture retention rate by 30-50% and increased the soil moisture by 1.8-0.4% in drought conditions and 15-5% in normal conditions.

CONCLUSION

We investigated the effect of clinoptilolite zeolite on soil hydraulic parameters and soil moisture retention in a sandy loam soil. Experiments showed that, after adding zeolite, sandy loam soil showed a change in its hydraulic parameters proportional to the level of applied zeolite. With the use of 15 grams of zeolite, the hydraulic parameters θs, θr and n were higher than the control. In fact, by adding zeolite into light soil, it increases the fine pores in the soil, which increases the moisture content of the soil. Small pores gradually caused changes in the pores from macro- to micro-pores and the value of Ks decreased compared with the control treatment. Therefore, the addition of zeolite to light soil led to the water holding capacity in the soil after 14 days of irrigation that the porous structure of zeolite causes water to be kept tightly inside the cavities of the aluminosilicate layer.

HYDRUS-2D model was able to simulate soil moisture under specified initial and boundary conditions. Based on the obtained results, EF it was found that HYDRUS-2D model had a high ability to estimate the moisture content of soil mixed with zeolite and was able to accurately estimate high moisture conditions in soil mixed with zeolite. The study of laboratory conditions showed significant results in the properties of soil hydraulic parameters due to the addition of zeolite, showing that the addition of zeolite to the soil guarantees several benefits in terms of improving the physical and hydraulic properties. In addition to reducing K_s, it increases the efficiency of water consumption and helps to reduce the amount of water used for irrigation. Due to the cheap price of zeolite in the country, this material can be used, especially in light soils, to increase the amount of water holding capacity and increase the irrigation intervals of plants in pots.

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58.

تاثیر زئولیت بر پارامترهای هیدرولیکی خاک و شبیه‌سازی جریان آب در خاک با استفاده از مدل HYDRUS -2D

معصومه شادان، جواد بهمنش، سینا بشارت، و نسرین آزاد

چکیده

زئولیت‌ها به دلیل ظرفیت بالای نگهداری آب و تبادل کاتیونی برای استفاده در بخش کشاورزی توصیه شده‌اند. در این مطالعه اثر زئولیت بر پارامترهای هیدرولیکی خاک لوم شنی بررسی شد. بدین منظور از مدل HYDRUS-2D جهت شبیه‌سازی حرکت آب در خاک استفاده شد و داده‌های مورد نیاز جهت واسنجی و صحت‌سنجی مدل با انجام آزمایشات آزمایشگاهی (گلدانی) جمع‌آوری گردید. تیمارهای مورد مطالعه شامل چهار سطح (صفر، ۵ و ۱۰ و ۱۵ گرم زئولیت در هر کیلوگرم خاک) بود تا تاثیر زئولیت بر پارامترهای هیدرولیکی شامل رطوبت اشباع (θ_s)، رطوبت باقیمانده (θ_r) پارامتر شکل (n)، نقطه ورد هوا (α) و هدایت هیدرولیکی اشباع (K_s) خاک بررسی شود. ٤ دور آبیاری براساس رطوبت سهل‌الوصل صورت گرفت و مقادیر رطوبت خاک قبل و بعد آبیاری، با استفاده از (Wet sensor) سنسور در جهت عمقی و شعاعی اندازه-گیری و به مدت ٤٥ روز ثبت گردید. مقدار اولیه پارامترهای هیدرولیکی θ_r،θ_s ، α ، n و K_s با استفاده از Rosetta مشخص شد. نتایج نشان داد که با افزایش مقدار زئولیت مقادیر پارامترهای θ_r، θ_s و n افزایش و مقدار α کاهش یافته که نشان‌دهنده کاهش سرعت تخلیه آب از خاک بود. در حالیکه مقادیر K_s تمایل به کاهش یافت. به‌طور کلی زئولیت به دلیل ساختار ریز منافذ به مخلوط خاک و زئولیت اجازه می‌دهد تا آب بیشتری را در خود نگه دارد. مدل HYDRUS-2D با ضریب کارایی EF که نشان دهنده کیفیت و چگونگی

برازش داده‌هاي مشاهده‌اي و برآورد شده ميباشد بين ۰/۸۲ تا ۰/۹۷ متغيير بود كه اين نشان دهنده كارايي بالاي مدل در شبيه سازي رطوبت است.