

DETERMINING THE WATER QUALITY INDEX OF TREATED WASTE WATER FOR REPELLENT AND WETTABLE SANDY LOAM BASED ON INFILTRATION CHARACTERISTICS

ZHAO, X.^{1A} – CHAI, H. Y.^{1,2A} – CAI, Y. H.¹ – CHEN, J. Y.^{1*} – WU, P. T.¹ – LI, Y.¹ – CHEN, H. Y.³

¹*College of Water Resources and Architectural Engineering, Key Laboratory of Agricultural Soil and Water Engineering in the Ministry of Education, Northwest A&F University, Yangling, Shaanxi 712100, China*

²*Northwest Research Institute of Engineering Investigations and Design, Xi'an, Shaanxi 710000, China*

³*Department of Foreign Languages, Northwest A&F University, Yangling, Shaanxi 712100, China*

^A*These authors contributed equally to this work.*

**Corresponding author
e-mail: cjyrose@126.com*

(Received 10th Dec 2019; accepted 24th Mar 2020)

Abstract. Treated waste water (TWW) has been replacing fresh water (FW) partly in irrigation. However, irrigation with TWW can cause soil water repellency that affects infiltration characteristics. In order to determine the water quality index with full consideration taken into infiltration characteristics, one dimensional infiltration experiments were conducted in wettable and repellent sandy loams with TWW irrigation. Five kinds of TWW and one tap water (TW) were chosen. The effect of water quality on the wetting front and cumulative infiltration volume was analyzed. The comprehensive water quality index (ZF) was obtained by principal component analysis. The results show that the water quality has a great effect on the cumulative infiltration and wetting front of wettable soil. The more significant the comprehensive water quality index is, the greater the cumulative infiltration volume and wetting front are. The water quality has a great effect on the cumulative infiltration and no effect on wetting front of repellency soil. Power correlation exists between sorptivity (S) and chemical oxygen demand (COD). Meanwhile, a quadratic polynomial relationship exists between the ratio of S for the wetting front coefficient and ZF, and there is a minimum value in the curve.

Keywords: *soil water repellency, soil moisture, wetting front, cumulative infiltration, COD*

Introduction

Treated waste water (TWW) irrigation has become a common practice in arid and semiarid areas to deal with water scarcity and reduce the consumption of fresh water (FW) (Wallach et al., 2005). However, such irrigation may have an impact on the chemical and hydraulic properties of soils. Long-term TWW irrigation will increase soil organic matter (OM) and form a layer of hydrophobic organic compounds on the surface of soil particles (Chen et al., 2009; Nadav et al., 2012a, 2012b), which will cause soil water repellency. The water drop penetration time (WDPT) of repellent soils could reach 802 s for sandy soils (Mataix-Solera et al., 2011) and 3600 s in clay loam with long-term TWW irrigation (Wallach et al., 2005). The occurrence of water repellency leads to a decrease of soil infiltration rate and water conductivity, which affects irrigation efficiency (Wallach et al., 2005; Leuther et al., 2018).

The reduction of irrigation efficiency is shown in the decrease of the infiltration rate and the migration rate of wetting front which becomes irregular and unstable during irrigation process. Rye and Smettem (2017) found water repellency reduced the rate of water migration and the evaporation of soil surface water. It is easy to form a preferential flow in repellency soil due to the big difference in the movement of water in horizontal and gravitational directions (DeBano, 2000; Wallach et al., 2008, 2010). The water tends to accumulate on the surface of repellent soil (DeBano, 2000) and cannot infiltrate when the depth of water accumulation is less than the matrix suction of the soil during irrigation (Jordán et al., 2009). However, the above researches mainly aim to obtain the discipline of water movement by FW irrigation in repellent soil. Irrigation water source seldom changes after the soil repellency appears for a long time of TWW irrigation. Therefore, it is very important to study the infiltration law of TWW in repellent soil.

TWW has many components such as grease, OM, suspended solids, salt and so forth (Halliwell et al., 2001). Each component will affect the characteristics of the soil, and then change its infiltration characteristics during the infiltration. Suspended particulate matter and dissolved organic matter (DOM) can clog the soil pores (Vries, 1972; Vinten et al., 1983; Levy et al., 1999). High concentration of sodium ions causes swelling and dispersion of soil clay (Durgin et al., 1984; Frenkel et al., 1992; Levy et al., 1999; Halliwell et al., 2001). Inorganic salt increases the alkalinity and salinity of the soil (Balks et al., 1998; Halliwell et al., 2001; Lado et al., 2009; Bedbabis et al., 2014). These components reduce the pores of the soil, the hydraulic conductivity of the soil and the cumulative infiltration volume. However, some components of TWW can increase soil infiltration in repellent soils. Surfactants alleviates the repellency degree of the soil which increases the cumulative infiltration after a long period of TWW irrigation (Chaney et al., 1986; Fortun et al., 1989; Piccolo et al., 1997; Dekker et al., 2018; Liu et al., 2019). Both characters of irrigated soil and irrigation water quality have great effect on soil water infiltration, and they are always interacting, continuous development and evolution (Sheng et al., 2016). Therefore, selection of right water quality index for different soils is of great significance in irrigation with TWW.

The water quality indexes standards, including biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, anionic surfactants, pH, total salt, chloride, sulfide, heavy metal content, fecal coliforms, aphid eggs, and so on, have been established for agricultural irrigation all over the world. However, these water quality indexes standards have taken the ecological environmental protection into account, but the impact of irrigation water quality on infiltration characteristics is not considered. There is no uniform comprehensive index, so it is applicative to find a comprehensive water quality index to guild TWW irrigation. The objective of this study was to determining the water quality index of TWW for repellent sandy loam (R) and wettable sandy loam (W) based on irrigation infiltration characteristics.

Materials and Methods

Soil sampling and pretreatment

The soil depth of 0~5 cm shows a certain degree water repellency after long-term TWW irrigation (Wallach et al., 2005; Mataix-Solera et al., 2011). Soil water repellency is not obvious below the depth of 5 cm. The soil samples were collected in 0~5 cm surface sandy loam in the first terrace of Wei River, Yangling (34°18'N, 108°24'E), Shaanxi Province, China. The bulk density, grain-size distribution of the soil was measured by the drying

method and Mastersizer 2000 laser particle size analyzer in the laboratory, respectively. The soil, whose bulk density is 1.65 g/cm^3 , is composed of 14.4% of clay, 24.7% of silt and 60.9% of sand. Therefore, the soil texture is identified as wettable sandy loam. The soil, after air-drying and impurity removal, was subjected to standard sieving of 10-mesh (2 mm). The soil moisture after air drying and saturated soil moisture were $0.029 \text{ cm}^3/\text{cm}^3$ and $0.363 \text{ cm}^3/\text{cm}^3$, respectively.

The field water-repellent soil is prone to disturbance in the sampling, which may destroy its original water-repellent characteristics. Therefore, surface active material, octadecylamine ($\text{C}_{18}\text{H}_{39}\text{N}$), is added to wettable soil to obtain a relatively stable water-repellent soil (J&K Scientific Ltd.). Octadecylamine, a white waxy solid crystal with alkalinity, is practically insoluble in water. Its melting point is 52.3°C . The repellency soil was obtained by mixing $\text{C}_{18}\text{H}_{39}\text{N}$ with the air-dried soil sample at a ratio of 0.1 g/kg. Then the mixed soil was placed in an oven at 80°C for 24 hours, and the soil sample was stirred for 5 minutes every 2 hours to make the liquid $\text{C}_{18}\text{H}_{39}\text{N}$ fully mixed with the soil particles (Li et al., 2017). This approach eliminated the confounding time effects associated with unstable water repellency systems and allowed for the identification of basic mechanisms (Carrillo et al., 2000). The relatively stable water-repellent sandy loam was obtained after the whole process. The repellency was determined by water drop penetration time test (WDPT) (Letey, 1969; Dekker et al., 1990). According to the water repellency classification standard proposed the mixed soil is slightly water repellent (Bisdorf et al., 1993).

Water sampling and water quality index

The TWW sample was taken from pools under different treatments, namely the catchment, the anaerobic pool, the oxidation pool, the sedimentation pool and the outlet pool, in a domestic sewage treatment plant in China. The reference water is tap water in Yangling, China. The water quality index is given in Table 1.

Table 1. Water quality index of TW and pools under different treatment

The location of the water	Tap water	Catchment	Anaerobic pool	Oxidation pool	Sedimentation pool	Outlet pool
pH	7.92	7.29	7.31	7.31	7.36	7.07
Electric conductivity($\mu\text{S}\cdot\text{cm}^{-1}$)	143	811	825	811	849	799
Dissolved oxygen($\text{mg}\cdot\text{L}^{-1}$)	7.52	0.24	0.43	3.00	4.61	4.03
Total hardness($\text{mmol}\cdot\text{L}^{-1}$)	0.89	0.49	0.64	0.61	0.68	0.79
Total alkalinity($\text{CaO mg}\cdot\text{L}^{-1}$)	27.96	169.81	176.32	164.37	167.67	153.21
Sodium adsorption ratio a	1.23	6.12	6.16	6.98	6.77	7.01
Turbidity	0	125	187	510	4.77	3.95
Total dissolved substances($\text{mg}\cdot\text{L}^{-1}$)	95	226	360	260	412	420
Total suspended solids($\text{mg}\cdot\text{L}^{-1}$)	0	170	198	780	325	242
Total nitrogen($\text{mg}\cdot\text{L}^{-1}$)	18.23	69.27	100.3	63.83	36.22	30.12
Chemical oxygen demand($\text{mg}\cdot\text{L}^{-1}$)	0	331.5	423	588	37.15	22.15
Biochemical oxygen demand ($\text{mg}\cdot\text{L}^{-1}$)	0	171	100	143	11	11

a. The sodium adsorption ratio (SAR) refers to the ratio of the sodium ion concentration to the square root of the mean value of the calcium ion concentration and the magnesium ion concentration in the cation exchange reaction of calcium, magnesium, sodium, etc. The formula of the sodium adsorption ratio is $\text{SAR} = \frac{C_{(\text{Na}^+)}}{\sqrt{C_{(\text{Ca}^{2+})} + C_{(\text{Mg}^{2+})}}}$ (Bughici and Wallach, 2016), where, the values are expressed in $\text{mmol}\cdot\text{L}^{-1}$.

There are 12 water quality parameters, including pH, Electric conductivity, dissolved oxygen, total hardness, total alkalinity, sodium adsorption ratio (SAR), turbidity, total dissolved substances (TDS), total suspended solids (TSS), total nitrogen (TN), Chemical oxygen demand (COD) and Biochemical oxygen demand (BOD). Principal component analysis was conducted on each water quality index using SPSS software (v. 21.0, SPSS Inc, 2013) in order to quantitatively evaluate the water quality. First, three principal components are extracted, and then the water quality comprehensive evaluation index is established according to the contribution rate of the characteristic value of each principal component in initial eigenvalues *Eq.1*.

The formula for the comprehensive index of water quality is as follows.

$$Z_F = \frac{\lambda_1}{\lambda_1 + \lambda_2 + \lambda_3} \cdot F_1 + \frac{\lambda_2}{\lambda_1 + \lambda_2 + \lambda_3} \cdot F_2 + \frac{\lambda_3}{\lambda_1 + \lambda_2 + \lambda_3} \cdot F_3 \quad (\text{Eq.1})$$

where λ_1 , λ_2 and λ_3 are eigenvalues of the first, second and third principal components, respectively. F_1 , F_2 and F_3 are the calculated values of the three components, respectively.

Infiltration experiments

The infiltration experiments were carried out in Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, China.

Two kinds of soils (wettable soil and repellency soil) were irrigated by six kinds of water with different quality in one-dimensional water infiltration experiments. The experiments consisted of 12 treatments, and each treatment was repeated 3 times. For convenience, in the rest part of the paper, R and W are repellent sandy loam and wettable sandy loam, respectively; R-TW and R-TWW1~5 refer to the six water quality experiment waters that are ranked according to the comprehensive water quality index from small to large. Among them, TW is tap water, R-TWW1 is the water from outlet pool, R-TWW 2~5 are waters from sedimentation pool, catchment, anaerobic pool and oxidation pool, the same below.

The experiment device is shown in *Fig. 1*. The water supply device is a Mariotte bottle to provide a stable water head. The column is 80 cm in height 12 cm in diameter. The bottom of the column is equipped with a 10 cm of quartz sand filter layer to prevent air resistance. The soil sample is loaded into the soil column according to the actual bulk density of 1.65 g/cm³. The soil is layered into the soil column and each layer is 5 cm. The layers were slightly roughened to prevent delamination. The soil column is 65 cm in height. The soil columns were placed for 24 hours after loading to make the soil moisture distribute evenly. A filter paper is placed on the surface of the soil column to resist the impact of water on the soil. Three paper scales are placed on the column to record wetting front. The water head is 3 cm in the experiments. The infiltration time was recorded using the stopwatch. During the first half hour of the experiments, the Mariotte scale and the wetting front were recorded at 5-min intervals. Subsequently they were recorded at intervals of 10-min from 0.5 h to 1.5 h, and 30-min after 1.5 h.

The Philip model (Philip, 1957) was used to fit the soil cumulative infiltration with time to further analyze the effect of water quality on soil infiltration. The mathematical expression of the model is as follows.

$$I = St^{0.5} + At \quad (\text{Eq.2})$$

where, I is the cumulative infiltration, cm; S is the soil sorptivity, $\text{cm} \cdot \text{min}^{-0.5}$; A is the stable infiltration rate, cm/min; t is the infiltration time, min.

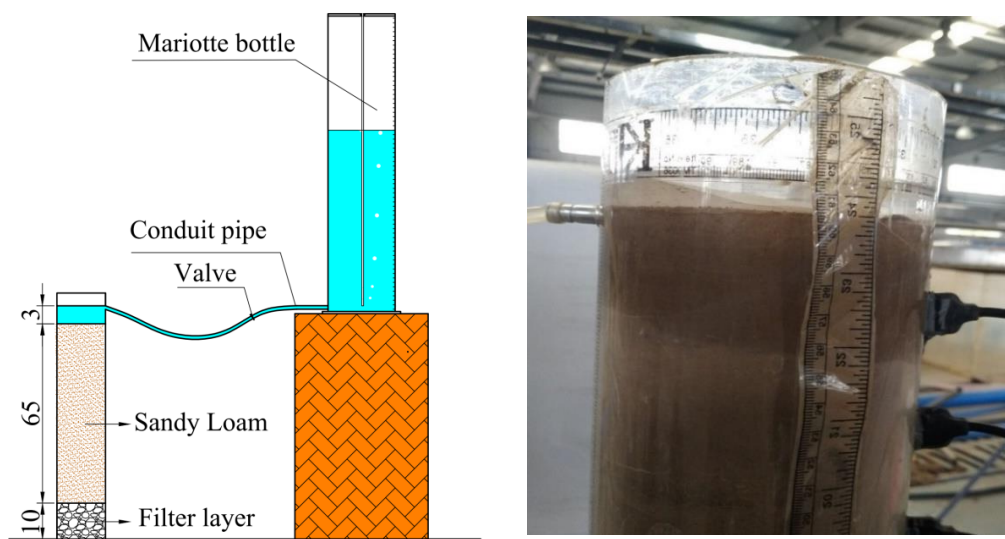


Figure 1. Laboratory setup of one-dimensional TWW infiltration

When the infiltration time of the experiment is as short as a couple of hours, the soil sorptivity (S) becomes the main influencing factor of water infiltration. That is, the effect of the stable infiltration rate A can be neglected. Then the *Eq.2* can be expressed as follows.

$$I = St^{0.5} \quad (\text{Eq.3})$$

Then this paper uses the *Eq.3* to fit the cumulative infiltration and time.

In this study, SPSS 22.0 was used to conduct analysis of variance between means, and significant differences between the treatments were compared by the least significant differences test at a 5% probability, orthogonal design, Standard analysis of variance (ANOVAR) were used to evaluate the effect of the water quality on the infiltration.

Results and Discussion

Comprehensive evaluation result of water quality

Three principal components were extracted using principal component analysis of SPSS. The first principal component eigenvalue has the highest contribution rate of 38.35%. Total dissolved substances, sodium adsorption ratio and conductivity are the main factors of water quality index of the first principal component. The contribution rate of the second principal component eigenvalue is 35.89%. BOD, COD, the total dissolved oxygen, total nitrogen and total hardness are the main factors of the second main component. The total suspended matter and turbidity take up a larger proportion of the third principal component. The cumulative contribution rate of the three principal

components eigenvalue reaches 95.21%, which can basically represent the information of all 12 water quality indexes. A comprehensive evaluation index is established according to the contribution rate of the eigenvalues as is shown in Eq.4.

$$Z_F = 40.29\% \cdot F_1 + 37.70\% \cdot F_2 + 22.02\% \cdot F_3 \quad (\text{Eq.4})$$

The comprehensive evaluation result of water quality is given in Table 2.

Table 2. Principal component analysis results, the water quality comprehensive index and the naming of water samples

Water sampling location	First principal component F_1	Second principal component F_2	Third principal component F_3	The water quality comprehensive index Z_F	Levels of TWW
Tap water	-1.812	-0.834	-0.415	-1.136	TW
Catchment	-0.133	1.372	-0.557	0.341	TWW 3
Anaerobic pool	0.197	1.007	-0.388	0.374	TWW 4
Oxidation pool	-0.063	0.117	2.032	0.466	TWW 5
Sedimentation pool	0.809	-0.748	-0.265	-0.014	TWW 2
Outlet pool	1.002	-0.914	-0.407	-0.030	TWW1

According to the water quality comprehensive index, the irrigation waters taken from different locations in the domestic sewage treatment plant are ranked from small to large of Z_F . The comprehensive water quality index of the outlet pool is the smallest, and the oxidation pond outlet is the largest. That might be because TWW needs to add biological bacteria such as nitrates for denitrification and absorption of easily degraded BOD before treated in the oxidation pond. After entering the sedimentation pond, mud and water are separated under the effect of coagulant drugs, and the water quality is greatly improved. For the convenience of the following description, TW represents tap water, TWW1, TWW2, TWW3, TWW4 and TWW5 represent the water of the outlet pool, sedimentation pool, catchment, anaerobic pool and oxidation pool respectively.

Effect of water quality on cumulative infiltration

The variation of cumulative infiltration of wettable and repellent sandy loams under different water infiltration conditions are shown in Fig. 2. The cumulative infiltration of different water quality in wettable sandy loam is significant (P value < 0.05) (Fig. 2a). The cumulative infiltration amount increases with the increase of water quality comprehensive index. That is, the greater the comprehensive water quality index is, the faster the infiltration in wettable soil is. Taking 90 min as an example, the cumulative infiltration amounts of W-TW and W-TWW1~5 are 7.19, 13.13, 13.70, 15.48, 17.18 and 16.02 cm, respectively. When the wetting front reaches the end of 40 cm infiltration, the cumulative infiltration amount is 12.65, 17.3, 17.18, 18.19, 19.96 and 18.21 cm, respectively.

There is a significant difference between TWW and TW during the infiltration of water-repellent sandy loam (Fig. 2b). However, the difference among the five groups of TWW is significantly reduced relative to the wettable sandy loam. Taking 90 min as an example, the cumulative infiltration of R-TW and R-TWW1~5 is 6.17, 11.58, 11.74, 12.06, 15.53 and 13.15 cm, respectively. The cumulative infiltration of R-TW and R-TWW1~5 was 10.50, 16.85, 17.36, 17.68, 19.84 and 17.88 cm, respectively at the end of infiltration. Comparing

Fig. 2a and Fig. 2b, it is found that the cumulative infiltration in the water-repellent soil is smaller than that in the wettable soil with the same water quality. Taking W-TWW3 and R-TWW3 as examples, the cumulative infiltration of W-TWW3 is 13.70 cm and the R-TWW3 is 11.73 cm at 90 min. Therefore, it can be inferred that regardless of tap water or sewage water, the water-repellent soil will hinder its water migration and affect its infiltration rate.

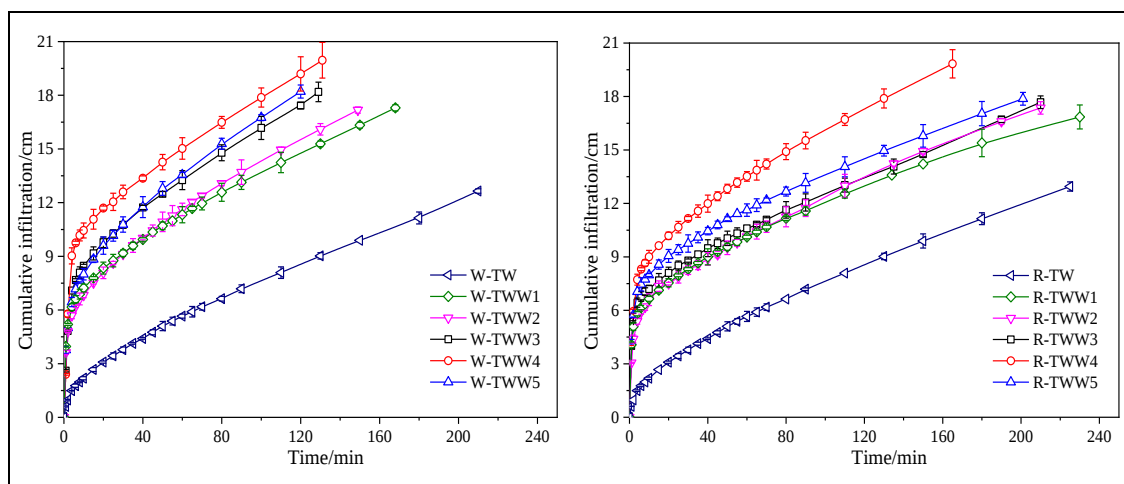


Figure 2. The cumulative infiltration versus time for different water quality in repellent and wettable sandy loams, (a) Wettable sandy loam, (b) Repellent sandy loam

Table 3 shows the relationship between the cumulative infiltration and time. The fitting accuracy of the Philip model of TWW infiltration is worse than that of tap water, but the coefficient of determination is greater than 0.7 and the root mean square error is small. Therefore, the curves fit well with the data with high Determination coefficient ($R^2 > 0.988$). There is a positive correlation between the infiltration rate and water quality (water from TW, TWW1 to TWW5) of wettable and repellent sandy loams. The infiltration rate of the wettable soil is higher than that of the water-repellent soil with the same kind of water. The regularity of the infiltration rate is the same as the law of cumulative infiltration.

Table 3. The fitting parameters of the infiltration model

Soil type	Treatment	Philip formula			Wetting front model		
		Sorptivity S ($\text{cm} \cdot \text{min}^{-0.5}$)	Determination coefficient R^2	Root mean square error RMSE	Fitting parameter a ($\text{cm} \cdot \text{min}^{-0.5}$)	Determination coefficient R^2	Root mean square error RMSE
Wettable sandy loam	W-TW	0.776	0.982	0.450	2.652	0.990	0.342
	W-TWW1	1.463	0.809	1.700	2.982	0.994	0.912
	W-TWW2	1.522	0.880	1.385	3.192	0.993	0.895
	W-TWW3	1.769	0.825	1.985	3.394	0.997	0.980
	W-TWW4	2.002	0.701	2.825	3.347	0.995	0.907
	W-TWW5	1.837	0.862	1.707	3.618	0.995	1.218
Repellent sandy loam	R-TW	0.648	0.971	0.426	2.593	0.988	1.234
	R-TWW1	1.268	0.759	1.775	2.692	0.995	1.161
	R-TWW 2	1.299	0.860	1.476	2.590	0.993	0.691
	R-TWW 3	1.338	0.737	1.933	2.530	0.990	1.032
	R-TWW 4	1.695	0.721	2.202	2.950	0.990	0.888
	R-TWW 5	1.449	0.710	2.231	2.710	0.998	1.406

Effect of water quality on wetting front movement

The wetting front depth versus time for different water quality in wettable and repellent sandy loams is shown in Fig. 3. The variation of the wetting front depth is similar to that of cumulative infiltration in wettable sandy loam (Fig. 3a). When different water infiltrates the wettable sandy loam, the greater the comprehensive water quality index is, the greater the depth of the wetting front is at the same infiltration time. The infiltration times of W-TW and W-TWW1~5 are 210, 168, 149, 129, 131 and 120 min, respectively, when the wetting front depth reaches 40 cm in wettable sandy loam. The water quality has little effect on the wetting front depth of repellent sandy loam (Fig. 3b). The infiltration times of R-TW and R-TWW1~5 are 210, 168, 149, 129, 131 and 120 min, respectively, when the wetting front depth reaches 40 cm in repellent sandy loam. There is no significance difference between infiltration time and wetting front depth among the different irrigation water quality from TW, TWW1 to TWW5 in repellent sandy loam ($P>0.05$). The wetting front depth of the water-repellent sandy loam is smaller than that of the wettable sandy loam with the same water quality (Fig. 3a and Fig. 3b). The infiltration time of the water-repellent sandy loam is greater than that of the wettable sandy loam when the wetting front depth reaches 40 cm.

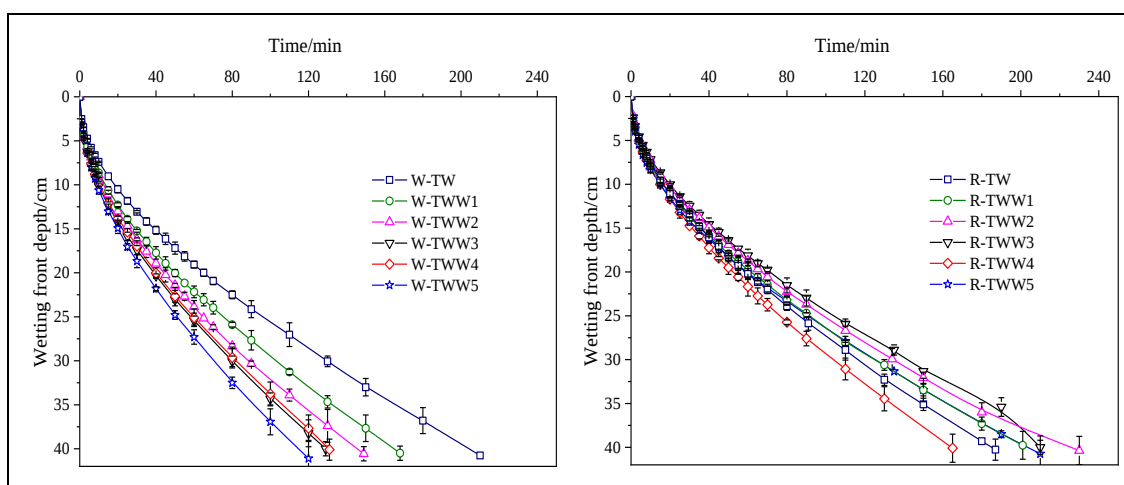


Figure 3. Wetting front depth versus time for different water quality in wettable and repellent sandy loams, (a). Wettable sandy loam, (b) Repellent sandy loa

The power function is used to fit the relationship between wetting front depth and infiltration time to analyze the effect of water quality on the soil wetting front. The mathematical expression of the model is as follows:

$$H = at^{0.5} \quad (\text{Eq.5})$$

where H is wetting front depth, cm; a is the wetting front coefficient, $\text{cm} \cdot \text{min}^{-0.5}$.

The wetting front model fitting result is given in Table 3. The fitting accuracy of the wetting front model ($R^2 > 0.98$, $\text{RMSE} < 1.3$) is high. Water quality has little effect on a in repellent sandy loam. The parameter a increases with the increase of the comprehensive water quality index in wettable sandy loam.

The effect of irrigation water quality on the infiltration is significant (*Fig. 2* and *Fig. 3*). The cumulative infiltration and infiltration rates generally increase with the increase of water quality comprehensive index.

The sorptivity of repellent sandy loam is smaller than that of wettable sandy loam with the same water (*Table 3*). According to the comprehensive water quality index from small to large (TW and TWW1~5), sorptivity decreases by 16.5%, 13.3%, 14.7%, 24.4%, 15.3% and 21.1%, respectively.

The effect of irrigation water quality on infiltration is mainly reflected in the influence of soil solute potential which is closely related to the conductivity in the water quality index. The higher the conductivity is, the greater the soil solute potential is, and the more obvious effect the water has on soil water movement. The electric conductivity value of TW is smaller than TWW (*Table 1*). Therefore, the cumulative infiltration of TWW is larger than that of TW irrigation. The cumulative infiltration shows little difference among the TWW due to the small difference in conductivity among them. It also shows the larger the conductivity is, the greater the cumulative infiltration is. The wetting front depth decreases with the increase of water quality comprehensive index in wettable sandy loam due to the large difference of solute potential. The solute potential is different because TWW contains many solute ions. The wetting front changes greatly with the same cumulative infiltration due to the different solute potential under the same condition of the matrix potential and the gravitational potential.

The water quality comprehensive index has no significant effect on the wetting front in repellent sandy loam because water repellency seriously hinders the water infiltration. So the solute potential caused by the substances contained is smaller than that of the water repellency of both TW and TWW in repellent soil. Therefore, the wetting front has no significance among TW and TWW1~5.

TWW contains many components. It's insufficient to use a single water quality index to analyze the effect of infiltration. For example, the total suspended matter in the water quality index describes the amount of insoluble matter in the water. The suspended matter will deposit on the surface layer or block the soil pores which make the soil surface crust and soil porosity reduction during the infiltration process. Then the soil infiltration rate and the hydraulic conductivity are significantly reduced. It is one of the causes of soil water repellency. However, the effect of suspended matter in TWW on soil pores during the short-term infiltration is not obvious due to the short experiments period in this study. The clogging is weak because of the large particles and soil pores in sandy loam. Soil infiltration rate and hydraulic conductivity decline significantly because the clogging, caused by sewage or TWW irrigation in soils with higher clay content, is obvious (Lado and Ben-Hur, 2009). Therefore, the suspended matter is an important index for long-term irrigation with TWW.

The water movement rate is high in the irrigation of wettable soil with the TWW. The irrigation time must be shortened when the irrigation volume is fixed, or it will cause deep leakage. The TWW contains more polluting ions which may cause groundwater pollution and soil nutrients loss (Lado and Ben-Hur, 2009). However, wetting front is of no difference under the same irrigation time interval in the irrigation of the repellent soil with the TWW. Then the greater the water quality index is, the greater the irrigation volume is. This will cause the water to stay in the upper layer of the soil for a long time, and it is difficult to reach the planned wetting layer of the irrigation design. At the same time, the evaporation of the surface layer increases, resulting in a decrease in water use efficiency. Therefore, the irrigation time should be

reduced and high frequency and small flow discharge should be used in order to increase the effective irrigation depth for the soil for high water quality index in repellent soil.

Effect of COD on infiltration parameters

There are many causes of the water repellency in the soil (Bond, 1964; McGhie et al., 1980; King et al., 1981; DeBano, 1981; Jex et al., 1985; Stenstrom et al., 1989; Shakesby et al., 1993, 2006; Dekker et al., 2000; Chau et al., 2012; Jiménez-Pinilla et al., 2016). For sewage water irrigation, water repellency is caused by the increase of the organic matter in the soil (Morales et al., 2010; Chen et al., 2013). In the irrigation with TWW, the oil and grease content in the water has a great influence on the soil water repellency, and the soil water repellency increases with the increase of oil and grease (Travis et al., 2008). As the organic matter in the soil increases, the water repellency of sandy and clay increases. The organic matter in water is measured by COD value. During the infiltration, the organic matter and grease affect the surface tension of the liquid, which in turn affects the interaction between the soil particles and the water molecules. It will affect the capillary force during the movement of soil water. And these can be described by the COD value. The relationship between COD and sorptivity is shown in Fig. 4. The relationship between sorptivity S and COD is a power function.

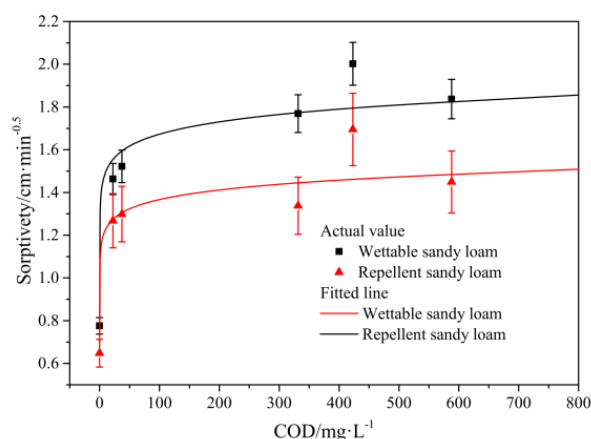


Figure 4. The relationship between the soil sorptivity (S) and chemical oxygen demand (COD)

The function is as follows.

Wettable sandy loam:

$$S_w = 1.322 \cdot (\text{COD})^{0.053}, R^2 = 0.931 \quad (\text{Eq.6})$$

Repellent sandy loam:

$$S_r = 1.104 \cdot (\text{COD})^{0.046}, R^2 = 0.955 \quad (\text{Eq.7})$$

The effect of COD on infiltration is obvious when COD is less than a certain value for wettable and repellent soils. When the COD exceeds the set value, the change of the infiltration rate is small although the COD has a large change.

With the infiltration change rate of 0.05 cm/min^{0.5} as the critical point, when the COD value of the irrigation water is greater than 170 mg/L for wettable sandy soil and 140 mg/L for repellent sandy soil, the COD has little effect on irrigation.

Therefore, the influence of COD on soil water infiltration must be considered. The Farmland Irrigation Water Quality Standard GB5084-2005 in China stipulates that the COD of irrigation water should be less than 200 mg/L for dry crop irrigation. According to this study, considering the effect of COD values on infiltration, we recommend that the COD value should be less than 170 mg/L for wettable sandy soil and 140 mg/L for repellent sandy soil in sewage irrigation.

Effect of comprehensive water quality indicators on infiltration parameters

The effect of water quality on infiltration can be seen from the above research. EC, TSS and COD all have an effect on infiltration. Previous studies focused on the impact of a water quality index on infiltration, but research shows that many water quality indexes affect soil infiltration (Singh et al., 2017; Misaghi et al., 2017; Leuther et al., 2018). Therefore, it is necessary to use comprehensive water quality indicators to analyze the impact of water quality on infiltration. The relationship between Z_F and sorptivity S was shown in Fig. 5a. The S of sandy loam increases with the increase of Z_F , and there is a positive linear correlation between them (R^2 is 0.980 and 0.950 for wettable and repellent sandy loams).

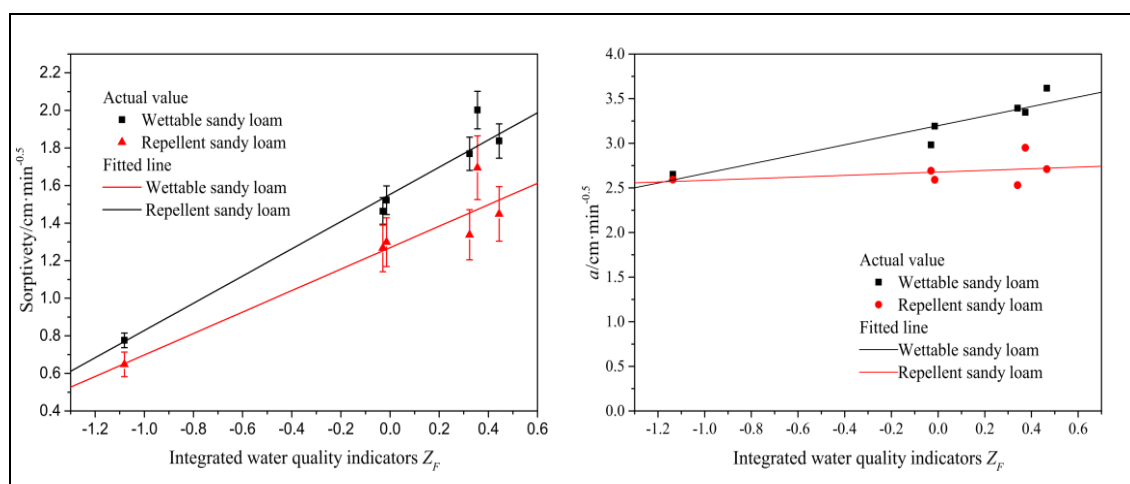


Figure 5. Relationships between soil sorptivity (S), the wetting front coefficient a and comprehensive water quality index Z_F (a). soil sorptivity, (b) the wetting front coefficient a

The function is as follows.

Wettable sandy loam:

$$S_w = 1.553 \cdot Z_F + 0.724, \quad R^2 = 0.980 \quad (\text{Eq.8})$$

Repellent sandy loam:

$$S_r = 1.269 \cdot Z_F + 0.571, \quad R^2 = 0.950 \quad (\text{Eq.9})$$

It can be seen that the larger the comprehensive water quality index is, the faster sorptivity of the soil is (Eq.8, Eq.9, Fig. 5a). The quality of TWW significantly facilitates soil infiltration. However, soil water repellency will lead to a decrease in soil infiltration rate when water infiltrates, and also slow down the tendency of infiltration rate to increase with the increase of the comprehensive water quality index. Soil water repellency will decrease soil infiltration and also slow down the tendency of sorptivity to increase with the increase of Z_F . For wettable soils, the water quality of TWW is more significant in increasing soil infiltration. The sorptivity of the wettable sandy loam is larger than that of the repellent sandy loam with the same water quality (Fig. 2 and Table 3). The effect of Z_F on sorptivity of the wettable sandy loam is larger than that of the repellent sandy loam. Therefore, it is not advisable to increase the infiltration rate of the soil in order to reduce the irrigation time and simply increase the comprehensive water quality index. The selection of the comprehensive water quality index should be within a reasonable range.

It can be seen that the larger the comprehensive water quality index is, the faster sorptivity of the soil is (Eq.8, Eq.9, Fig. 5a). The quality of TWW significantly facilitates soil infiltration. However, soil water repellency will lead to a decrease in soil infiltration rate when water infiltrates, and also slow down the tendency of infiltration rate to increase with the increase of the comprehensive water quality index. Soil water repellency will decrease soil infiltration and also slow down the tendency of sorptivity to increase with the increase of Z_F . For wettable soils, the water quality of TWW is more significant in increasing soil infiltration. The sorptivity of the wettable sandy loam is larger than that of the repellent sandy loam with the same water quality (Fig. 2 and Table 3). The effect of Z_F on sorptivity of the wettable sandy loam is larger than that of the repellent sandy loam. Therefore, it is not advisable to increase the infiltration rate of the soil in order to reduce the irrigation time and simply increase the comprehensive water quality index. The selection of the comprehensive water quality index should be within a reasonable range.

The relationship between the wetting front coefficient a and Z_F of the sandy loam is shown in Fig. 5b. The wetting front coefficient a increases with the increase of Z_F , and there is a positive linear correlation between them for wettable sandy loam. However, Z_F has little effect on the wetting front coefficient a due to the effect of water repellency in repellent sandy loam.

The relationship between the ratio of sorptivity S to the wetting front coefficient a and Z_F is shown in Fig. 6. There is a nonlinear relationship between S/a and Z_F . As Z_F increases, S/a shows a minimum point. The minimum point appears near 0.59 and 0.10 for wettable and repellent sandy loams respectively. S/a reflects the volume of water in the wetting body, i.e., the average increase in moisture content in the wetting front range. When Z_F exceeds 0.10 for the water-repellent sandy loam, the increase of S/a indicates that the wetting front coefficient is reduced with the same irrigation volume. That is to say, the increase of irrigation volume does not make the effective wetting depth increase significantly. Therefore, the value of Z_F should be less than 0.10 of TWW when irrigating repellent sandy soil. However, when the minimum Z_F value is around 0.59 for the wettable sandy loam, the water quality indicators have seriously exceeded the agricultural irrigation water quality standards in China, and it is not suitable for irrigation. Therefore, in the irrigation of wettable sandy loam with sewage, it is necessary to consider the impact of crop growth, environment, and long-term

irrigation on soil water repellency rather than simply consider its influence on infiltration characteristics.

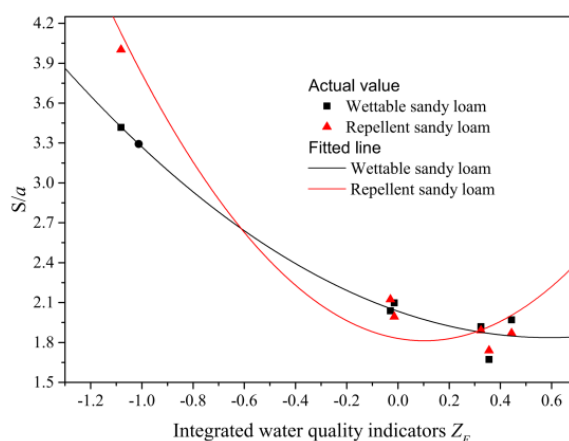


Figure 6. Relationship between S/a (the ratio of sorptivity to the wetting front coefficient) and comprehensive water quality index Z_F

Conclusions

Infiltration experiments were conducted on a wettable and a water repellent sandy loam with TWW to determine the water quality index and analyze the effect of water quality on wetting front and cumulative infiltration volume.

(1) The water quality has a great effect on the cumulative infiltration and wetting front of wettable sandy loam. The greater the comprehensive water quality index is, the greater the cumulative infiltration volume and wetting front are. But the water quality has a great effect on the cumulative infiltration but no effect on wetting front of repellency soil. Soil water repellency will decrease soil sorptivity (S). There is a power function relation and positive linear correlation between S and COD, S and Z_F , respectively. Meanwhile a quadratic polynomial relationship exists between the ratio of soil sorptivity S to the wetting front coefficient a and the comprehensive water quality index, and there is a minimum value in the curve.

(2) When both cumulative infiltration and wetting front requirements in TWW irrigation are taken into consideration, COD and Z_F should be less than 170 mg/L and 0.59, respectively, in wettable sandy loam while the two values should be less than 140 mg/L and 0.10, respectively, in repellency sandy loam. However, the study of this paper is relatively macroscopic, the changes in the microstructure between the reclaimed water and the soil pores need to be studied. When the soil water content is same, as the contact angle increases, the matrix suction will continue to decrease, making the soil infiltration rate slow down. Analyzing the relationship between the contact angle and the microstructure of soil pores during soil infiltration is a future research direction.

Acknowledgements. This work was supported by the National Natural Science Foundation of China (51409221, 51979234) and Basic Research Business Fee of Northwest A&F University (2452017116) and Humanities and Social Science Program of Northwest A&F University (Z109021405) and National Key R&D Program of China (2017YFC0403503).

REFERENCES

- [1] Balks, M. R., Bond, W. J., Smith, C. J. (1998): Effects of sodium accumulation on soil physical properties under an effluent-irrigated plantation. – *Australian Journal of Soil Research* 36: 821-830.
- [2] Bedbabis, S., Rouina, B. B., Boukhris, M., Ferrara, G. (2014): Effect of irrigation with treated wastewater on soil chemical properties and infiltration rate. – *Journal of Environmental Management* 133: 45-50.
- [3] Bisdom, E. B. A., Dekker, L. W., Schoute, J. F. T. (1993): Water repellency of sieve fractions from sandy soils and relationships with organic material and soil structure. – *Geoderma* 24-28: 105-118.
- [4] Bond, R. D. (1964): The influence of the microflora on the physical properties of soils. II. field studies on water repellent sands. – *Australian Journal of Soil Research* 2(1): 123-131.
- [5] Bughici, T., Wallach, R. (2016): Formation of soil-water repellency in olive orchards and its influence on infiltration pattern. – *Geoderma* 262: 1-11.
- [6] Carrillo, M. L. K., Letey, J., Yates, S. R. (2000): Unstable Water Flow in a Layered Soil: II. Effects of an Unstable Water-Repellent Layer. – *Soil Science Society of America Journal* 64: 456-459.
- [7] Chaney, K., Swift, R. S. (1986): Studies on aggregate stability. II. The effect of humic substances on the stability of re-formed soil aggregates. – *Journal of Soil Science* 37(2): 337-343.
- [8] Chau, H. W., Goh, Y. K., Vujanovic, V., Si, B. C. (2012): Wetting properties of fungi mycelium alter soil infiltration and soil water repellency in a γ -sterilized wettable and repellent soil. – *Fungal Biology* 116(12): 1212-1218.
- [9] Chen, X. H., Song, J. X., Cheng, C., Wang, D. M., Lackey, S. O. (2009): A new method for mapping variability in vertical seepage flux in streambeds. – *Hydrogeology Journal* 17(3): 519-525.
- [10] Chen, J., Zhang, Z., Gillerman, L., Wang, Z. (2013): Analysis of principal components of wastewater affecting soil water repellency. – *Journal of Drainage and Irrigation Machinery Engineering* 31(5): 434-439.
- [11] DeBano, L. F. (1981): Water repellent soils: a state-of-the-art. – United States Department of Agriculture Forest Service General Technical Report PSW-46.
- [12] DeBano, L. F. (2000): Water repellency in soils: A historical overview. – *Journal of Hydrology* 231-232: 4-32.
- [13] Dekker, L. W., Jungerius, P. D. (1990): Water repellency in the dunes with special reference to the Netherlands. – *Dunes of the European coasts* 18: 173-183.
- [14] Dekker, L., Ritsema, C. J. (2000): Wetting patterns and moisture variability in water repellent Dutch soils. – *Journal of Hydrology* 231-232: 148-164.
- [15] Dekker, L. W., Ritsema, C. J., Oostindie, K., Wesseling, J. G., Geissen, V. (2018): Effects of a soil surfactant on grass performance and soil wetting of a fairway prone to water repellency. – *Geoderma*: 10.1016/j.geoderma.2018.09.016.
- [16] Durgin, P. B., Chaney, J. G. (1984): Dispersion of Kaolinite By Dissolved Organic Matter From Douglas-Fir Roots. – *Canadian Journal of Soil Science* 64: 445-455.
- [17] Fortun, A., Fortun, C., Ortega, C. (1989): Effect of farmyard manure and its humic fractions on the aggregate stability of a sandy-loam soil. – *Journal of Soil Science* 40(2): 293-298.
- [18] Frenkel, H., Levy, G. J., Fey, M. V. (1992): Organic and Inorganic Anion Effects on Reference and Soil Clay Critical Flocculation Concentration. – *Soil Science Society of America Journal* 56(6): 1762-1766.
- [19] Halliwell, D. J., Barlow, K., Nash, D. (2001): A review of the effects of wastewater sodium on soil physical properties and their implications for irrigation systems. – *Australian Journal of Soil Research* 39(6): 1259-1267.

- [20] Jex, G. W., Bleakley, B. H., Hubbell, D. H., Munro, L. L. (1985): High Humidity-induced Increase in Water Repellency in Some Sandy Soils. – *Soil Science Society of America Journal* 49(5): 1177-1182.
- [21] Jiménez-Pinilla, P., Lozano, E., Mataix-Solera, J., Arcenegui, V., Jordán, A., Zavala, L. M. (2016): Temporal changes in soil water repellency after a forest fire in a Mediterranean calcareous soil: Influence of ash and different vegetation type. – *Science of the Total Environment* 572: 1252-1260.
- [22] Jordán, A., Zavala, L. M., Nava, A. L., Alanís, N. (2009): Occurrence and hydrological effects of water repellency in different soil and land use types in Mexican volcanic highlands. – *Catena* 79(1): 60-71.
- [23] King, P. M. (1981): Comparison of methods for measuring severity of water repellence of sandy soils and assessment of some factors that affect its measurement. – *Australian Journal of Soil Research* 19: 275-285.
- [24] Lado, M., Ben-Hur, M. (2009): Treated domestic sewage irrigation effects on soil hydraulic properties in arid and semiarid zones: A review. – *Soil and Tillage Research* 106(1): 152-163.
- [25] Letey, J. (1969): Measurement of contact angle, water drop penetration time and critical surface tension. – *Symposium on Water Repellent soils*, May 6-10, Univ. of California.
- [26] Leuther, F., Weller, U., Wallach, R., Vogel, H-J. (2018): Quantitative analysis of wetting front instabilities in soil caused by treated waste water irrigation. – *Geoderma* 319: 132-141.
- [27] Levy, G. J., Rosenthal, A., Tarchitzky, J., Shainberg, I., Chen, Y. (1999): Soil hydraulic conductivity changes caused by irrigation with reclaimed waste water. – *Journal of Environmental Quality* 28(5): 1658-1664.
- [28] Li, Y., Wang, X. F., Cao, Z. K., Si, B. C. (2017): Water repellency characteristic curve influenced by drying and wetting processes. – *Canadian Journal of Soil Science* 97(2): 226-240.
- [29] Liu, Z., Rahav, M., Wallach, R. (2019): Spatial variation of soil water repellency in a commercial orchard irrigated with treated wastewater. – *Geoderma* 333(7): 214-224.
- [30] Mataix-Solera, J., García-Irles, L., Morugán, A., Doerr, S. H., García-Orenes, F., Arcenegui, V., Atanassova, I. (2011): Longevity of soil water repellency in a former wastewater disposal tree stand and potential amelioration. – *Geoderma* 165(1): 78-83.
- [31] McGhie, D. A., Posner, A. M. (1980): Water repellence of a heavy-textured Western Australian surface soil. – *Australian Journal of Soil Research* 18(3): 309-323.
- [32] Misaghi, F., Delgosha, F., Razzaghmanesh, M., Myers, B. (2017): Introducing a Water Quality Index for Assessing Water for Irrigation Purposes: A Case Study of the Ghezel Ozan River. – *Science of the Total Environment* 589(C): 107-116.
- [33] Morales, V. L., Parlange, J. Y., Steenhuis, T. S. (2010): Are preferential flow paths perpetuated by microbial activity in the soil matrix? A review. – *Journal of Hydrology* 393(1-2): 29-36.
- [34] Nadav, I., Arye, G., Tarchitzky, J., Chen, Y. (2012): Enhanced infiltration regime for treated-wastewater purification in soil aquifer treatment (SAT). – *Journal of Hydrology* 420-421: 275-283.
- [35] Nadav, I., Tarchitzky, J., Chen, Y. (2012): Soil cultivation for enhanced wastewater infiltration in soil aquifer treatment (SAT). – *Journal of Hydrology* 470-471: 75-81.
- [36] Philip, J. R. (1957): The theory of infiltration: 4. Sorptivity and algebraic infiltration equations. – *Soil Science* 84: 257-264.
- [37] Piccolo, A., Pietramellara, G., Mbagwu, J. S. C. (1997): Use of humic substances as soil conditioners to increase aggregate stability. – *Geoderma* 75(32): 267-277.
- [38] Rye, C. F., Smettem, K. R. J. (2017): The effect of water repellent soil surface layers on preferential flow and bare soil evaporation. – *Geoderma* 289: 142-149.

- [39] Shakesby, R. A., Coelho, C. D. A., Ferreira, A. D., Terry, J. P., Walsh, R. P. D. (1993): Wildfire impacts on soil erosion and hydrology in wet mediterranean forest, Portugal. – *International Journal of Wildland Fire* 3(2): 95-110.
- [40] Shakesby, R. A., Doerr, S. H. (2006): Wildfire as a hydrological and geomorphological agent. – *Soil Science Society of America Journal* 74: 269-307.
- [41] Sheng, F., Wu, D., Zhang, L. (2016): Review on effect of reclaimed water irrigation on soil water movement in cropland. – *Transactions of the Chinese Society of Agricultural Engineering* 32: 46-51.
- [42] Singh, B., Sihag, P., Singh, K. (2017): Modelling of impact of water quality on infiltration rate of soil by random forest regression. – *Modeling Earth Systems and Environment* 3: 999-1004.
- [43] Stenstrom, T. A. (1989): Bacterial Hydrophobicity, an Overall Parameter for the Measurement of Adhesion Potential to Soil Particles. – *Microbiology* 55(1): 142-147.
- [44] Travis, M. J., Weisbrod, N., Gross, A. (2008): Accumulation of oil and grease in soils irrigated with greywater and their potential role in soil water repellency. – *Science of the Total Environment* 394(1): 68-74.
- [45] Vinten, A. J. A., Mingelgrin, U., Yaron, B. (1983): The effect of suspended solids in wastewater on soil hydraulic conductivity: II. vertical distribution of suspended solids. – *Soil Science Society of America Journal* 47(686): 408-412.
- [46] Vries, D. J. (1972): Soil filtration of wastewater effluent and the mechanism of pore clogging. – *Journal of the Water Pollution Control Federation* 44: 565-573.
- [47] Wallach, R., Ben-Arie, O., Graber, E. R. (2005): Soil Water Repellency Induced By Long-Term Irrigation with Treated Sewage Effluent. – *Journal of Environment Quality* 34(5): 1910-20.
- [48] Wallach, R., Jortzick, C. (2008): Unstable finger-like flow in water-repellent soils during wetting and redistribution - The case of a point water source. – *Journal of Hydrology* 351(1-2): 26-41.
- [49] Wallach, R. (2010): Effect of soil water repellency on moisture distribution from a subsurface point source. – *Water Resources Research* 46(8): 1-9.