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Impact of treated wastewater irrigation on long-term soil water retention

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ABSTRACT

This paper analyzed the impact of treated wastewater irrigation on long-term soil water retention. Irrigation with treated wastewater (TWW) constitutes a strategic opportunity for development of agriculture in semi-arid regions. For the sustainable management one of the challenges is evaluating its effect on the soil. The results of the current study indicated that TWW-irrigation leads to increased soil salinity at a depth of 0–0.20 m. In terms of the soil's ability to retain water, at the mid-period use (8 y), the TWW retention was reduced by 33% capacity at a depth of 0.10 m compared to soil irrigated by freshwater. The decrease was less significant (24% of retention) in the long term. The surface layer of the soil (0–0.10 m) irrigated by TWW retained less water than when irrigated by fresh water. Regarding the soil water retention curve, the impact of TWW becomes important at very high suction pressures (i.e., VHP > 1,000 cm) compared to lower suction pressures (i.e., HP: 10–1,000 cm). The results suggested that the use of TWW decreased the water retention at field capacity and wilting point values.

Keywords: Irrigation; Soil proprieties; Salinity; Treated wastewater; Water retention

1. Introduction

The use of alternative resources, such as treated wastewater (TWW) can help to alleviate the global water shortage problem particularly in arid regions. While this helps to improve agricultural financial gains, it can also have negative effects by modifying the soil physical and chemical properties [1,2]. The reuse of treated wastewater (TWW) for irrigation is a widespread practice in regions of the world affected by water shortages, particularly in arid and semi-arid regions such as Northern Africa.

Currently, treated wastewater (TWW) irrigation is performed on more than 20 million hectares worldwide. This amount will significantly increase over the coming decades as water stress intensifies [3]. In the Mediterranean region, the practice of TWW-irrigation is particularly pertinent due a shortage of available freshwater resources [4]. However, the effects of such practices on soil proprieties needs to be well understood to prevent not only land degradation, but also to alleviate environmental and human health impacts. Recently authors have reported on the consequences of wastewater quality on irrigated soils under various periods of application [5,6].

Effective management of water resources is crucial to be able to deal with water shortages due to climate change in arid regions such as the Mediterranean especially during

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periods of drought [7]. Understanding the problem is thus vital. In one specific study, Oliveira et al. [7] deduced that an increase of exchangeable sodium (Na^{2+}) in the soil is a major problem associated with TWW-irrigation, since Na^{2+} is present in high concentrations in wastewater. In the long term, the increase in percentage of exchangeable sodium affects soil structure and hydraulic properties, including water retention and hydraulic conductivity [8,9]. Impacts of TWW on the latter have been investigated by Sepaskhah and Sokoot [10] for different soil textures. Results showed that a reduction in hydraulic conductivity mainly occurred near the surface at soil depths of 0–50 cm. This effect was more prominent in clay-loam soil than in loam and sandy-loam soils. Tarchouna et al. [11] reported a significant decrease in hydraulic conductivity in sandy textured soil under long term TWW-irrigation. However, conductivity remained sufficient to reduce soil salinization. Many researchers have reported that TWW irrigation decreases soil saturated hydraulic conductivity (Ks) across different soil types and textures [8–10,12–17].

Bardhan et al. [15] disclosed that TWW affects structural porosity via narrowing of macro and mesopores (>70 and 30–70 μm) respectively. Physical structure of the soil is not the only concern of TWW-irrigation. Physicochemical and microbiological parameters can also be influenced [15,18] by water retention [19,20]. Tarchitzky et al. [21] demonstrated that soil irrigated from TWW had an increased water retention capacity due to organic matter buildup. Specific factors related to the composition of treated wastewater (TWW), such as mineral elements (e.g., metallic trace elements, microorganisms, organic matter) and high concentrations of soluble salts can lead to intolerable soil salinity levels for most plants or landscape crops, particularly in heavy textured soils [22–25]. Suspended solids and organic matter also should be considered [1].

The likely risks of adverse changes in soil structural stability and hydraulic properties following TWW irrigation can come from high levels of dissolved organic matter, suspended solids, sodium adsorption rates and water salinity [26]. Paudel et al. [27] have shown that TWW contains high concentrations of saline components and suspended organic and inorganic particles compared to fresh water this can lead to soil structure degradation, increased osmotic potential and reduced aeration, root growth and hydraulic conductivity. Furthermore, soil salinity increases from sandy to clay soil, which has a direct impact on plants. This outcome will be intensified when using non-conventional water, such as TWW. It would have an impact on the soil's water retention and would play a significant role in a farmer's irrigation management decision making.

The aim of this study was to quantify the impact of treated wastewater on soil proprieties of three semi-arid sites using as a case study the province of Boumerdes in Algeria. In addition, the effects of treated wastewater (TWW) and freshwater irrigation on soil water retention properties in the mid to long-term were assessed and compared.

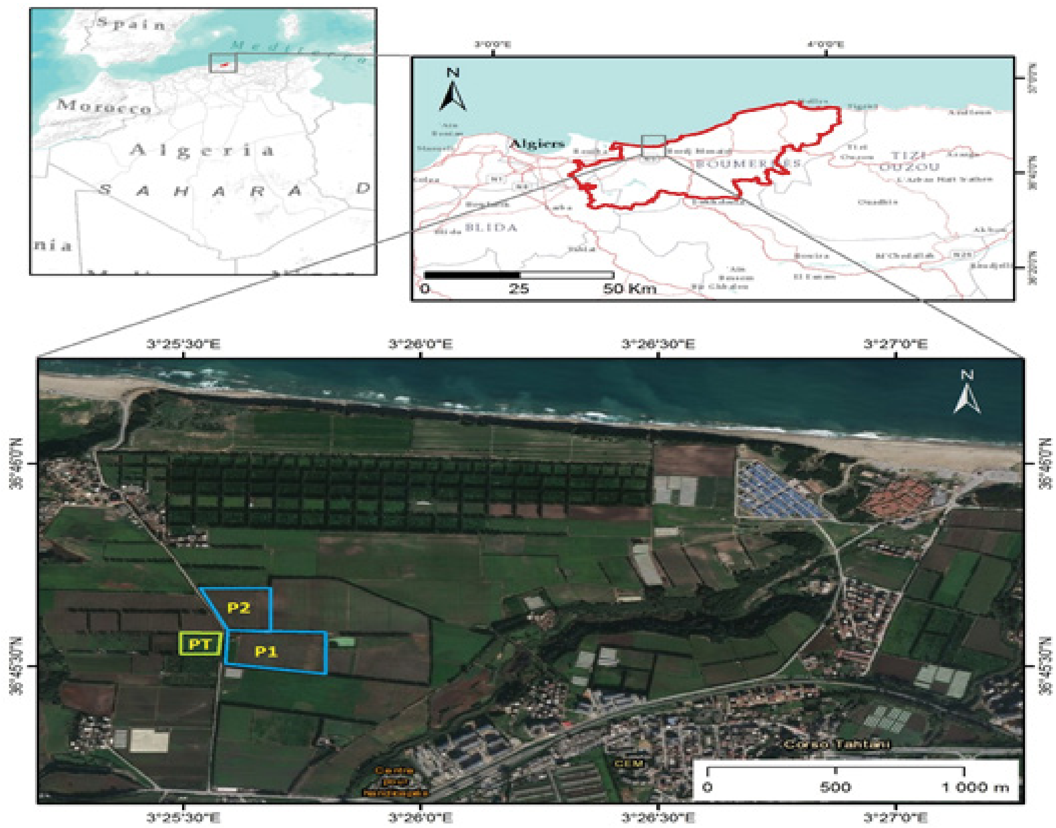

Fig. 1. Experimental site.

2. Materials and methods

The study was conducted in the province of Boumerdes (36.76° N, 3.42° E), in northeastern Algeria. This region is 26 m above sea level and has a sub-humid Mediterranean climate (Fig. 1). The annual rainfall ranged between 500 and 1,300 mm and the annual average temperature was 18°C. The main cultivated crops were grapes, citrus fruits, and animal fodder.

The treated wastewater (TWW) employed in this experiment was provided by the wastewater treatment station of Boumerdes. Monthly monitoring of water quality showed that the TWW utilized met local and international standards for agricultural reuse (Table 1). The experimental site included three agricultural plots: P1, irrigated by TWW for 8 y (mid-term), P2, irrigated by TWW for 13 y (long term) and control plot (PT) irrigated by fresh water. Physicochemical analysis was carried out for each plot (granulometry and bulk density) and for each depth (pH water, pH KCl, total calcium carbonate content and organic matter).

2.1. Soil water retention sampling

For each plot, systematic soil sampling was performed at 30 cm from the dripper at depths of 0–10 cm, 10–20 cm, and 20–60 cm. To characterize the water retention curve in the study site plots, water retention values were obtained according to the Richard's method [28] at soil matric potentials of 1, 4, 7, 10, 30, 70, 100, 500 and 1,500 kPa.

The model of the soil water retention curve (SWRC) is defined as follows by Eq. (1) [29]:

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \tag{1}$$

where h is the matrix potential in (cm). θ_r and θ_s are the residual and saturated soil water content (cm^3/cm^3), respectively, and α (cm^{-1}) and n are the form factors of the SWR function. The parameter 'm' was calculated by $m = 1 - 1/n$.

2.2. Statistical study

To determine whether a significant difference between the different plots existed and, if so, which plot was more influenced by TWW-irrigation. The values of soil water retention at soil matric potentials of 1, 4, 7, 10, 30, 70, 100, 500 and 1,500 kPa were used for each plot selected in this study. Multiple pairwise comparisons were performed following two-factor ANOVA. This procedure was implemented to separate the averages of the soil water retentions at alpha levels of 0.05%, 0.01% and 0.001% using the Tukey Test (HSD).

3. Results and discussion

3.1. Soil physicochemical characterization

Soil analysis indicated a similar texture for the three plots, dominated by sand and silt, while the clay proportion was weak. According to USDA triangle [30], texture is defined as sandy-silty. There was no major difference in bulk density (i.e., 1.45, 1.45, and 1.40 g/cm^3) as a function of depth for P1, P2, and PT respectively (Table 2).

The result of the soil physiochemical proprieties (Table 3) showed that the pH (KCl) values had a slight tendency towards soil acidity. Last level of depth for control plot indicates the lowest value of 6.17 while for P1 and P2, they are, respectively, 5.80 and 6.50. Regarding the total calcium carbonate content ($CaCO_3$ T), values were very low in the three levels of depth for all plots and did not exceed 0.17%. This rate was consistent with the absence of HCl effervescence and indicated the non-calcareous nature of the soils.

3.1.1. Organic matter

The organic matter content (OM) was predominant in the first depth level for all three soils and the highest value was reached in plot P1 (Table 3). The OM rate decreased with depth, except for the control plot (PT) where it appeared very high in the second level.

These results suggested that TWW-irrigation does not systematically lead to an accumulation of organic matter in the soil. Due to their high nutrient and trace element content, TWW stimulates soil microbiological activity [31,32], thus promoting soil organic carbon mineralization. When

Table 1
Parameters of TWW used for irrigation

	Values	Standards
TSS (mg/L)	12.11	30
BOD_5 (mg/L)	8.34	30
COD_5 (mg/L)	33.84	90
$N–NO_3$ (mg/L)	5.845	30
pH	7.295	6.5–8.5
T (°C)	20.15	–
EC (µS/cm)	1,254.95	3,000

TSS: Total suspended solids; BOD_5: Biological oxygen demand for 5 days; COD_5: Chemical oxygen demand for 5 days.

Table 2
Physical characteristics of soil

Soil origin	Granulometry (%)			Bulk density (g/cm^3)
	Sand (%)	Silt (%)	Clay (%)	
Plot P1	48	30	16	1.45
Plot P2	50	28	17	1.45
Control plot PT	45	33	17	1.40

conditions are favorable, this results in a decrease of the OM level in the soil [33,34].

3.1.2. Soil salinity

For the three plots, electrical conductivity (EC) results indicated a low salinity so that the measured EC did not reach the limit of 4 mS/cm for which soils are considered as moderately saline [35]. Electrical conductivity of TWW-soil that had been irrigated for 8 y increased by 0.77 mm hos/cm in the first depth level, while the lowest value was observed in plot P2 (Fig. 2). At mid-term, TWW-irrigation led to a slight increase in salinity at 0–20 cm depth. These results were in line with Kaboosi [22] who reported that, in comparison to conventional water, the use of TWW for 8 y caused a slight rise in soil salinity. The increase in salinity was mainly due to salt-laden treated wastewater.

3.1.3. Impact of TWW irrigation on soil water retention curve

The ANOVA results matched the water retention curves profiles (Fig. 3) and indicated a very high significant difference ($p < 0.001$) between the three plots in terms of water retention capacity (Fig. 4a).

Analysis of the differences between the modalities with a 95% confidence interval of the two-by-two plots determined by The Tukey Test (HSD) showed a high significant difference between the control plot (PT) and both P1 (0–10 cm) and P2 (0–10 cm). However, no significant variation was recorded between P1(10 cm) and P2 (10 cm).

The 8 y irrigation by TWW caused a 33% reduction in the soil water retention *r* at the soil horizon surface 0–10 cm compared to freshwater irrigation. This reduction was less significant (24%) after 13 y application. These outcomes can be related to the grapevine's root system which was, at this depth, better developed around the wet bulb of the dripper for the 13-year-old grapevine compared to the 8-year-old one.

Roots play a key role in improving soil structure and structural stability. Keith [36] suggested that root-influenced soils (i.e., rhizosphere soils) are less porous due to increased aggregation. Furthermore, the use of TWW can induce a high accumulation of salts and organic components in the 0–20 cm (Fig. 2, Table 3). Indeed, these concentrations can have potentially negative effects on soil quality, such as reducing hydraulic conductivity and stability of the soil aggregate, particularly in the upper 10 cm layer of silty soil [37].

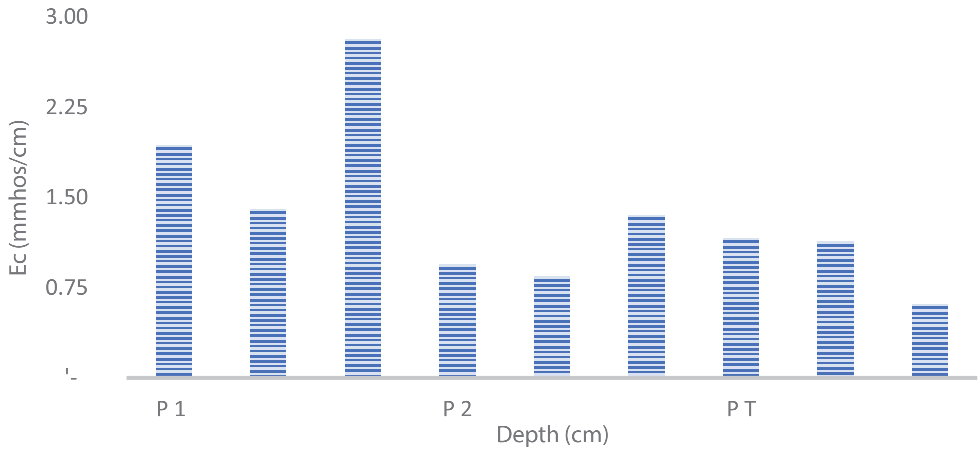

Fig. 2. Variation of electrical conductivity in plots.

Table 3
Chemical properties of soil

Plots	Depth (cm)	pH (water)	pH (KCl)	$CaCO_3$ *T*(%)	OM (%)
	0–20	6.70	6.49	0.17	2.17
P1	20–40	6.83	6.60	0.17	0.72
	40–60	6.73	6.50	0.17	1.38
	0–20	6.66	6.03	0.17	1.31
P2	20–40	6.50	5.88	00	0.55
	40–60	6.38	5.80	00	0.26
	0–20	6.92	6.45	0.17	1.29
PT	20–40	6.75	6.25	0.17	1.93
	40–60	6.71	6.17	00	0.88

$CaCO_3$ *T*%: total calcium carbonate content; OM (%): organic matter.

For both plots P1 and P2, the impact of TWW-irrigation became more significant at very high suction pressures (VHP > 100 hPa) and high suction pressures (HP: 1–100 hPa) (Fig. 4b). At mid-term, the most important impact in the upper layer (0–10 cm) occurred for the pressure range 0–100 hPa, while for the longer term, the reduction in water retention capacity was much more significant at very high pressure VHP (Fig. 4b).

The long-term application of TWW-irrigation involved two impacts on the soil water retention curve (SWRC). The SWRC for the surface layer (0–10 cm) in TWW-irrigated plots showed less water retention capacity and indicated that the upper soil layer retained less water than when it was irrigated by fresh water. On the other hand, findings showed that the 0–10 cm layer in plot P2 had a higher water retention capacity that could be explained by the effect of TWW irrigation long duration on micro porosity. However, the results of this study indicated that the use of TWW on 0–10 cm horizon at mid-term may have opposing effects compared to long term TWW application. This can be associated with an increase in the medium pore radius for the 0–10 cm surface soil horizon for the duration of irrigation and suggested that additional factors that influence the properties of soil water retention, such as pore size and connectivity and pore sealing, could also be affected [38,39].

The TWW from the Boumerdes plant had an acceptable salinity for agricultural irrigation. However, results of experimentation showed that TWW-irrigation caused a slight increase in soil salinity in the surface region. To avoid the risk of soil salinization, recycling of TWW must be regularly monitored and standards must be respected. Moreover, application of insecticides or fungicides must be carried out in a reasonable manner and in accordance with specific standards and rules to protect the soil. Therefore, additional studies are recommended to improve site-specific irrigation water quality and leaching management. This is crucial to avoid a deterioration in soil quality due to irrigation with TWW, especially if this practice becomes widespread in the context of resource scarcity.

3.1.4. Impact of TWW irrigation on saturated water content, field capacity, wilting point and available water

The field capacity (FC) is defined as the "water content at which the thermodynamic forces between soil and water are much higher than the gravitational forces to a point where the water flux out of soil medium is negligible" [39,14]. In the current investigation it was expected that water retention at field capacity (FC, proposed at pF 2.5) should have significatively changed after mid and long term TWW irrigation on surface horizon (0–10 cm). However, the impact of TWW irrigation at mid-term decreased FC compared to the 10 cm horizon with long term use (Fig. 4c). After 13 y application of the TWW, results suggested that the FC increased compared to 8 y use. That could be explained by the organic matter accumulation on the first horizon (0–10 cm) due to irrigation. Additionally, the soil electric salinity values in this research indicated that they are more significative after 8 y application than at 13 y.

The wilting point (WP), also called the permanent wilting point, may be defined as the amount of water per unit weight or per unit bulk volume in the soil, expressed in percentage, that is, held so tightly by the soil matrix that roots cannot absorb this water and a plant will wilt [40]. The results indicated a significant change in P1 and P2 compared to the freshwater application (Fig. 4c). It can be argued that the decrease in FC and WP for the horizons of 0–10 cm could have been the consequence of flocculation stemming from the salinity of the irrigation water. This could have increased soil aggregate stability with decreased infiltration, as found by other researchers [41–44].

Finally, available water capacity is the difference between FC and WP, such that:

$$\text{AWC} = W_{\text{FC}} - W_{\text{WP}} \tag{2}$$

The AWC in Eq. (2) for the horizon 0–10 cm was not significantly impacted by TWW irrigation. This result was like that reported by Loy et al. [14]. A decrease in FC and WP and the difference between them for the two plots (P1, P2) suggest that the impact on soil water retention properties is very similar in horizon 0–10 cm.

4. Conclusions

The increasing demand for conventional water, the lack of it, and the irregularity of precipitation makes treated wastewater (TWW) an attractive source of water for irrigated agriculture in semi-arid countries, such as Algeria.

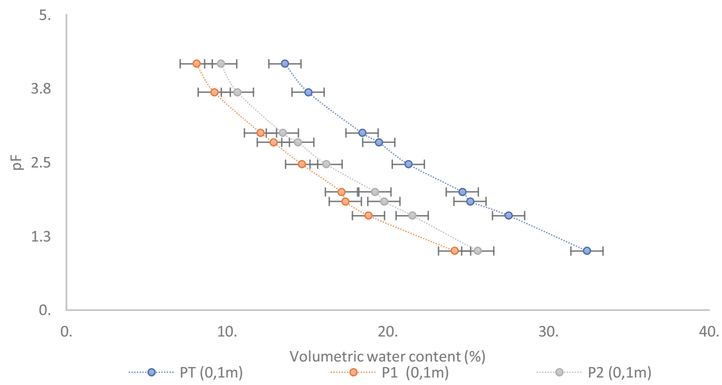

Fig. 3. Soil water retention curves for the three experimental plots (PT, P1 and P2).

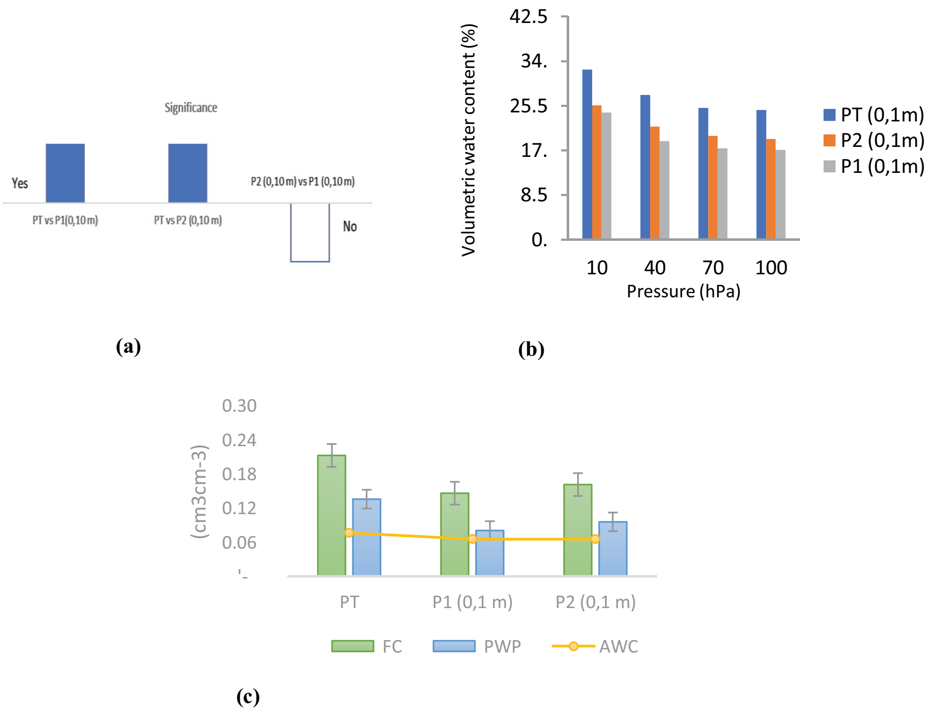

Fig. 4. (a) Analysis of differences between modalities with a 95% confidence interval/Tukey Test analysis (HSD). (b) Variation of water retention in HP (0–100 hPa) and (c) graphical representation of field capacity, permanent wilting point, and available water capacity for each horizon (0, 10 m).

According to the current study treated wastewater produced the best results for the farmer in semi-arid regions, in terms of profitability. The treated wastewater (TWW) has an acceptable salinity for agricultural irrigation. However, its reuse in the long and medium term led to an increase in salinity in the surface horizons of the soils studied. The soils of the plots examined were very poor in organic matter. The higher levels found in the surface suggested an accumulation of organic matter due to TWW irrigation.

In comparison with the results observed on the plot irrigated with drilling water, the water retention capacity of the plots irrigated by TWW was reduced in the upper layers (0–10 cm). The application of TWW irrigation after 8 y caused a reduction of 33% in soil water retention in the soil surface (0–10 cm). In the long term the reduction impact was estimated at 24% compared to the control plot (PT). The capacity to retain water in soil irrigated by conventional water was strong. Treated wastewater irrigation at mid and long-term decreased soil water retention at field capacity and wilting point, and consequently the available water capacity.

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Conflicts of interest

The authors declare no conflict of interest.

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