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Changes in the hydraulic properties of a clay soil under long-term irrigation with treated wastewater☆

G. Bardhan, D. Russo, D. Goldstein, G.J. Levy *

Institute of Soil, Water and Environmental Sciences, Agricultural Research Organization (ARO), The Volcani Center, Bet Dagan, Israel

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ABSTRACT

Treated wastewater (TWW) is an important water resource, especially in semiarid and arid regions. However, there are concerns that irrigation with TWW could lead to degradation of soil physical and hydraulic properties. The objective of our study was to determine the effects of long-term (≥15 years) irrigation with secondary TWW on some basic and hydraulic soil properties of a clay soil. Undisturbed soil samples (cores) were taken to a depth of 4.5 m (in sections of 0.5 m) over a diagonal cross section of a five year old orchard irrigated with TWW. Samples were taken from five sites within the tree rows (i.e., representing soil directly affected by TWW; referred to as "within rows") and four sites between the rows of trees (i.e., the control treatment representing soil that was not directly subjected to the irrigation water; referred to as "between rows"). Soil analyses included an array of basic properties, determination of a continuous particle size distribution and measurement of the saturated hydraulic conductivity (HC). The latter two were used for the computation of soil characteristic curve, $\Theta(\psi)$, and the unsaturated HC curve, $K(\psi)$. Similar bulk density, moisture content, cation exchange capacity, pH and exchangeable sodium percentage (ESP) levels were observed for the TWW irrigated samples and the control ones. However, irrigation with TWW caused a significant reduction in the saturated HC, *Ks*. The computed $\Theta(\psi)$ curve at a given soil depth, averaged over the different sites, was similar for the TWW-irrigated samples and the control ones. On the contrary, the computed $K(\psi)$ curve at a given soil depth, averaged over the different sites, for the TWW-irrigated samples were lower than those for the control samples at matric potential ≥ -100 cm ($=$pF ≤ 2); similar $K(\psi)$ values were noted at pF > 2 for the two treatments. The observed differences in the hydraulic properties between the TWW-irrigated samples and the control ones in this specific matric potential range, albeit the similarity in their ESP, suggest that long term irrigation with TWW affected structural porosity via narrowing macro- and mesopores (>70 and 30–70 μm, respectively). It is further postulated that this adverse impact of irrigation with TWW on structural porosity might be associated with previously reported effects of TWW on the composition of the dissolved organic matter in the soil solution.

1. Introduction

The recognition of treated wastewater (TWW) as an important water resource is rapidly expanding in areas with a shortage of freshwater resources, such as semiarid and arid regions (Ben-Hur, 2004; Feigin et al., 1991; Hamilton et al., 2007). Irrigation with TWW can contribute a significant quantity of nutrients, and hence support the conservation of diminishing resources. However, irrigation with TWW is not free of risks both to crop production and the soil environment. Potential risks include reduction in yield due to elevated salinity and specific ion toxicity, migration of pollutants towards surface- and groundwater, and deterioration of soil structure. In Israel, after a long-term application of TWW, negative effects in terms of tree growth and yield were observed especially in clayey soils, in citrus and in avocado plantations (Assouline and Narkis, 2013). These observed negative effects, resulting from the long-term use of TWW for irrigation could be related, at least in part, to possible degradation of soil physical and hydraulic properties (Levy and Assouline, 2011).

Soil hydraulic properties, namely, the soil characteristic and the hydraulic conductivity curves, are key ingredients in the understanding of variably saturated flow and transport in porous media, and have therefore received much attention (e.g., recent review by Assouline and Or, 2013). These properties, and, especially, the hydraulic conductivity (HC), are also often employed to asses changes in the soil environment following variations in agricultural practices, such as irrigation management, drainage strategies, groundwater lowering, and measures to control runoff and soil erosion (Jones and Wagenet, 1984). Main properties that control soil HC are soil clay mineralogy, texture, type of

Abbreviations: TWW, treated wastewater; HC, hydraulic conductivity; PSD, pore size distribution; CEC, cation exchange capacity; ESP, exchangeable sodium percentage; EC, electrical conductivity; DOM, dissolved organic matter.

☆ Contribution from the Agricultural Research Organization (ARO), The Volcani Center, Bet Dagan, Israel.

* Corresponding author at: Institute of Soil, Water and Environmental Sciences, The Volcani Center, POB 6, Bet Dagan 50250, Israel.

E-mail address: vwguy@volcani.agri.gov.il (G.J. Levy).

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exchangeable cations, dry bulk density, as well as soil solution chemistry, i.e., ion concentration and composition (Bresler et al., 1982; Shainberg and Letey, 1984).

Reports concerning the effects of irrigation with TWW on soil saturated (*Ks*) and unsaturated HC are inconclusive. Some studies report the decrease of saturated and unsaturated HC as a result of irrigation with TWW (e.g., Assouline and Narkis, 2011, Cook et al., 1994, Coppola et al., 2004, De Vries, 1972, Goncalves et al., 2007, Magesan et al., 2000, Vinten et al., 1983). However, Levy et al. (1999) reported that TWW irrigation had no effect on the *Ks* of three different Israeli soil types (clayey grumusol, loamy loess, and sandy loam), while Mathan (1994) reported of an increase in *Ks* after more than 10 years of TWW irrigation. Magesan et al. (1999) did not detect changes in the unsaturated HC after 5 years of TWW irrigation of two New Zealand soils for which Cook et al. (1994) reported a 50% decrease in *Ks* after half the period of irrigation with the same TWW.

Albeit the effects of TWW application on the saturated and unsaturated HC are not fully understood, the changes in the pore system of the soil following use of TWW seem to be the dominant factor for the observed reduction in HC (Halliwell et al., 2001, Magesan et al., 1999). Irrigation with TWW could affect the soil pore system and thus harm soil hydraulic properties following its elevated sodicity levels which could enhance clay swelling and dispersion (Quirk and Schofield, 1955; Shainberg and Letey, 1984). The effects of sodicity on soil hydraulic properties and flow processes have been studied extensively (e.g., Bresler et al., 1982, Jury et al., 1991, Russo, 2005, Russo, 2013, Russo and Bresler, 1977a, 1977b, Russo et al., 2004). Although an exchangeable sodium percentage (ESP) value of 15 is generally considered to mark the transition from nonsodic to sodic soils (e.g., U.S. Salinity Laboratory Staff, 1954), it has been shown that internal swelling can occur at soil ESP as low as 5 (Mace and Amrhein, 2001); a value that could be reached in the soil after long-term irrigation with TWW (Levy et al., 2014a). The resulting pore clogging by the swelling induces a decrease in soil HC and changes in the soil water holding characteristics. This negative impact of irrigation with TWW on soil hydraulic properties could be exacerbated during the rainy season when the soil is exposed to low-electrolyte rainwater which presents favorable conditions for soil clay swelling and dispersion (Shainberg and Letey, 1984). Conceptual (Russo, 1988) and empirical (Suarez and Simunek, 1997) approaches were proposed to quantify the combined impacts of sodicity and salinity on soil hydraulic properties.

Most of the studies on the effects of irrigation with TWW on soil behavior focused on the upper soil layer (e.g., see review of Levy and Assouline, 2011 and references cited therein). Recently Levy et al. (2014a) noted that irrigation with TWW increased sub-surface (60–120 cm) soil sodicity to levels >8. Hence, in light of the above discussion the objective of the present study was to determine the effects of long-term (≥15 years) irrigation with secondary TWW on some basic soil properties including grain size distribution and the HC function of a 4.5 m deep profile of a clay soil.

2. Materials and methods

2.1. Experimental site and soil sampling

A 5 year old grapefruit orchard in Kibutz Mizra, the Yizre'el Valley, Israel, irrigated with secondary TWW was used for the study. The soil at the experimental site was clay, belonging to the subgroup Typic Chromoxererts (Dan et al., 1976; Soil Survey Staff, 1975). Prior to planting the grapefruit, the area of the orchard had been irrigated with TWW for ~15 years followed by growing of rainfed wheat for 5 years. The experimental area includes 18 rows with 24 trees per row. In the orchard, trees are placed 2 m apart within a row with a 5 m distance between rows. The trees are irrigated by a drip system, two drip lines for each row of trees.

Undisturbed soil samples (cores) were taken to a depth of 4.5 m (in sections of 0.5 m) over a diagonal cross section of the orchard on 21 November 2012. The undisturbed cores were taken from 5 sites within the tree rows (i.e., representing soil directly affected by wastewater from rows 2, 5, 11, 14 and 17; referred to as "within rows") and 4 sites between the rows of trees (i.e., representing soil that was not directly subjected to irrigation water from between rows 2 and 3, 5 and 6, 14 and 15, 17 and 18; referred to as "between rows"); sampling took place just next to the corresponding sampling point within a row. In each site one drilling was done.

2.2. Soil basic properties

Perspex tubes (0.5 m long, 0.025 m I.D.) were used for taking undisturbed soil cores. The undisturbed soil cores were brought to the laboratory and each was cut into half, to obtain two 25 cm sections. Some technical problems, associated probably with the vibrations of the drilling machine coupled with the looser structure of the soil in the upper 0.5 m, resulted in the soil sliding out from the tube during the process of pulling the tube out of the soil. Hence, analyses and reported results refer to samples from the depth of 0.5 to 4.5 m.

For each core, wet soil bulk density was immediately determined followed by the determination of soil moisture content using a 3 g soil sample. Thereafter, the samples were air-dried and passed through a 2 mm brass-sieve. Soil particle size distribution was determined by the Bouyoucos hydrometer method (Gee and Bauder, 1986), cation exchange capacity (CEC) by sodium acetate extract (Rhoades, 1986) and exchangeable sodium percentage (ESP) by ammonium acetate extract (Thomas, 1986). In addition, soil solution electrical conductivity (EC), pH and chloride concentration were determined in a 1:5 soil:water extract.

Soil particle size distribution was also determined using the laser diffraction (LD) technique (e.g., Eshel et al., 2004) because it provides a continuous particle size distribution which enables the determination the soil pore size distribution (PSD) (see Section 2.3.2 below). Soil samples from both "within rows" and "between rows" from four depths (0.75–1 m, 1.75–2 m, 2.75–3 m and 3.75–4 m) were used for this analysis. A Beckman-Couler LS-230 with a 750 nm laser beam (measures particles in the range of 0.45–2000 μm) was used together with software version 3.01 that employs the Mie theory for the optical model needed for the calculation of the particle size distribution. We followed the same analytical procedure as that described by Eshel et al. (2004).

2.3. Soil hydraulic properties

2.3.1. Saturated hydraulic conductivity (HC)

Saturated HC was determined using disturbed samples from both "within rows" and "between rows" from four depths (0.75–1 m, 1.75–2 m, 2.75–3 m and 3.75–4 m). Soil columns were prepared by packing 100 g of air-dried, crushed and sieved soil (<2.0 mm) into Perspex cylinders (5.4 cm internal diameter and 10.4 cm long) to a dry bulk density of 1.25 g cm^{-3}. The bottom of each cylinder contained 35 g (5.0 cm high) of acid washed sand over a fine metal sieve to facilitate drainage. A filter paper covered the soil surface to minimize disturbance during wetting and leaching. The soil columns were initially wetted from the bottom with a saline-sodic solution (electrolyte concentration of 40 meq L^{-1} and sodium adsorption ratio [SAR] of 6) at a rate of 5 mm h^{-1} using a peristaltic pump. After reaching saturation the columns were leached from the top with the same solution using a constant head device (Mariotte bottle) with a head of 55 cm. The leachate was collected continuously over fixed time intervals using a fraction collector and periodically analyzed for its EC. Cumulative flowing water volume (V), was monitored versus time (t), to provide data (together with soil column length [L], the hydraulic head [ΔH] and column cross section area [A]) necessary to calculate the saturated HC (K_s), on the