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Alteration of physical and chemical characteristics of clayey soils by irrigation with treated waste water

Mamoun A. Gharaibeh [a,*], Teamrat A. Ghezzehei [b], Ammar A. Albalasmeh [a], Ma'in Z. Alghzawi [a]

[a] Department of Natural Resources and Environment, Faculty of Agriculture, Jordan University of Science and Technology, P.O. Box 3030, Irbid 22110, Jordan
[b] Life and Environmental Sciences, University of California, Merced, United States

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ABSTRACT

The effect of irrigation with treated wastewater (TWW) on soil physico-chemical and hydraulic properties was evaluated in this study. Field treatments were: non-irrigated (rain-fed) plot (control), rain-fed plot for the first three years and irrigated with TWW for the last two years (2 yr) and plot irrigated with TWW for five years (5 yr). Soil samples were collected from two depth intervals (0–15 and 15–30 cm) in five replicates. Irrigation with TWW significantly increased aggregate stability (AS), exchangeable sodium percentage (ESP), organic matter (OM), and electrical conductivity (EC). Both hydraulic conductivity (HC) and cumulative infiltration (F(t)) were decreased significantly with TWW use and period of application. Moreover, reduction of HC at different tension revealed that pore clogging occurred at both, macro and micro scale. Scanning electron microscopy (SEM) images showed that soil pores were clogged partially and/or fully as a result of suspended particulates and organic matter. Enhanced AS of treated areas indicated that infiltration was more affected by pore clogging than soil dispersion and swelling.

1. Introduction

Water shortage is increasingly becoming one of the foremost global challenges. Declining water availability is approaching a level that could potentially lead to long-term crises in the Middle East and North Africa (Heidarpour et al., 2007). In Jordan, for example, chronic water shortage has been prevalent since the 1980s, and the severity of shortage is expected to escalate in the future (Gharaibeh et al., 2007). This chronic shortage of fresh water in arid and semi-arid regions has forced planners and decision-makers to seek non-conventional water sources and conservation solutions. In this regard, the use of treated wastewater (TWW) for irrigation holds a potential that has not been fully realized. The use of TWW has also the added benefit of having the lowest marginal cost among the non-conventional water resources such as seawater and brackish water desalination (Ammary, 2007). Moreover, TWW can be applied under controlled conditions where periodic monitoring of TWW as well as soil quality parameters are required.

The chemical and biological properties of TWW depend on the quality of the raw sewage water as well as on the level and mechanisms of treatment. Typical characteristics that distinguish TWW from conventional sources of irrigation water include sodium adsorption ratio (SAR), electrical conductivity (EC), suspended solids (SS), and dissolved organic matter (DOM). In some cases, the added constituents of TWW such as DOM and certain cations could improve soil quality and fertility (Mohammad and Mazahreh, 2003). Compared to fresh water; TWW contains higher concentrations of plant nutrients and organic matter needed for maintaining fertility and productivity of arid soils (Mohammad and Mazahreh, 2003). On the other hand, long-term use of TWW for irrigation may result in lasting adverse effects on soil quality (Levy and Assouline, 2011). Reduction in hydraulic conductivity has been generally attributed to physical clogging by suspended solids (Kumar et al., 1985; Magesan et al., 2000; Viviani and Iovino, 2004) and bioclogging facilitated by DOM (Bedbabis et al., 2014; Gharaibeh et al., 2007; Gonçalves et al., 2007). High-levels of sodium in TWW have also been linked with clay dispersion and subsequent clogging of pores (Levy and Assouline, 2011). In addition, it has been documented that DOM can promote clay dispersion at a magnitude that depends on its concentration, solution pH, and the type of exchangeable cation (Durgin and Chaney, 1984; Frenkeland and Levy, 1992; Tarchitzky et al., 1993; Tarchitzky et al., 1999). (Tarchitzky et al., 1999) explained this effect as attraction between negatively charged organic molecules and the positively charged edges of the clay particles which prevents the edge-to-face association of clay particles; thereby preventing clay flocculation.

The above brief review indicates that it is still uncertain whether the benefits of TWW as a source of irrigation water and nutrients outweigh its potential for long-term degradation of soil hydraulic characteristics. Therefore, it is crucial that long-term effects of TWW on hydrologic characteristics of agricultural soil are adequately understood and evaluated before its use for irrigation can be widely recommended.

* Corresponding author.
E-mail address: mamoun@just.edu.jo (M.A. Gharaibeh).

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Mechanistic understanding of its effects on soil properties is also imperative for development of effective counter measures to minimize the adverse effects.

This study aims to fill this much needed gap in our understanding of the long-term impacts of irrigation with TWW on physicochemical properties of soil. One of the defining features of this study is that it is based on multi-year field trials that accurately depict real world conditions and effects (Schacht and Marschner, 2015). Most previous studies have investigated the impact of irrigation with TWW on soil hydraulic conductivity using disturbed (repacked) samples, which may depart from real field conditions as a result of loss of antecedent soil structure; and portray inaccurate picture of the direction and magnitude of processes taking place in the field. Moreover, the hydraulic properties of the soil are directly affected by the quality of irrigation water. Thus, disturbing soil samples may result in alteration of flow patterns and equilibrium time with irrigation water. In this research, field conditions are maintained and unrealistic alteration of soil physical conditions are prevented, where the HC was measured directly in the field, and infiltration measurements were conducted using hood infiltrometer with increased tensions measured directly on soil surface. Moreover, to further support that irrigation with TWW causes clay swelling-dispersion and or pore clogging, the collective effects of TWW on soil physicochemical properties was investigated. Field and laboratory tests and imaging techniques (SEM) were employed for the first time up to the author knowledge to develop mechanistic understanding of TWW alter soil properties.

2. Materials and methods

2.1. Experimental design

Field experiments were conducted in 2013 in the agricultural field located at Jordan University of Science & Technology (JUST) (32 27′ 57.4″ N latitude, 35 57′ 54.4″ E longitude), 70 km north of Amman, Jordan. The fields have clayey soil texture (clay 48%, silt 37%, and sand 15%) after $CaCO_3$ removal and are classified as fine, mixed, thermic Typic Calcixerert with 15% $CaCO_3$ content. The mean annual precipitation in the area is below 150 mm, and average temperature ranges between 14 °C in winter to 33 °C in summer.

The study was conducted on three adjacent field plots (0.8 ha each) that were subjected to three-level experimental treatments for five years. The first treatment was non-irrigated (rain-fed) plot and served as control. (b) the second plot was rain-fed for the first three years and irrigated with TWW for the last two years. The third plot was irrigated with TWW for five years. In the remainder of this paper, these treatments are referred to as 0 yr, 2 yr, and 5 yr, respectively. The plots were generally vegetated with native shrubs *Diplotaxis erucoides*. The irrigated plots were also planted with alfalfa. The alfalfa was clipped eight times per year and the biomass was removed from the field, leaving behind stubble of approx. 5-cm height. Irrigation water was applied to the plots by basin flood irrigation at 2 days interval (3–4 times a week), each plot received a total amount of 172 m^3 per week (equivilent to 21.5 mm per week). The plots that were not irrigated were left to fallow.

The design of the experiments closely mimics the general practice of farmers in the area. This study was particularly focused to assess the sustainability of using TWW in areas that are left out of production because of shortage of suitable irrigation water. Irrigation with conventional water (e.g., stream water or groundwater) as a fourth treatment was not feasible to implement in this study.

2.2. Irrigation water quality

The TWW used for irrigation was generated by JUST wastewater treatment facility located in the campus. The facility treats about 2200 cm^3 of waste water per day using rotating biological contactors.

Table 1
Mean values of selected properties of the used TWW.

Parameter	Value	Unit
pH	7.8	–
EC[a]	1.6	dSm^{-1}
Na	359.4	
K	37.7	
Ca	97.0	mgL^{-1}
Mg	24.8	
Cl	297.8	
DOM[b]	70	
TSS[c]	30	
TDS[d]	1050	
SAR[e]	8.4	–

[a] Electrical conductivity.
[b] Dissolved organic matter.
[c] Total suspended solid.
[d] Total dissolved solid.
[e] Sodium adsorption ratio.

The key characteristics of the TWW are given in Table 1. The sodium adsorption ratio (SAR) of the TWW was calculated as

$$SAR = \frac{[Na^{+}]}{\{([Ca^{2+}] + [Mg^{2+}])/2\}^{1/2}}. \tag{1}$$

2.3. Soil physical and chemical properties

At the end of the five year field trials, composite soil samples (5 composite samples per each treatment and 4 subsample per each composite) were collected from the surface (0–15 cm) and subsurface (15–30 cm). Replicate samples were collected from randomly selected locations within each treatment. Soil samples were air dried after sampling and sieved to ≤2 mm. After sieving, all samples were labeled and stored for further chemical and physical analysis. Soil bulk density was determined using the core method as described by (Blake and Hartge, 1986). Soil samples were air-dried after collection and aggregate stability was determined immediately after sampling by the wet-sieving method (Kemper and Rosenau, 1986) using wet-sieving apparatus (Eijkelkamp Agrisearch Equipment, Giesbeek).

Soil pH and electrical conductivity (EC) were measured in saturated paste extract as described by (McLean, 1982; Rhoades, 1982), respectively. Cation exchange capacity (CEC) and exchangeable sodium were determined by substitution of the exchangeable cations with ammonium acetate method (Polemio and Rhoades, 1977; Thomas, 1982). Organic matter (OM) was measured using the loss on ignition (LOI) method described by (Nelson and Sommers, 1996). The exchangeable sodium percentage (ESP) was calculated as

$$ESP = \frac{[Na^{+}]_{\text{exchangeable}}}{CEC}. \tag{2}$$

Baseline soil characteristics collected prior to the start of the experiments are not available. However, the field is fairly homogeneous characterized by uniform texture and landform, and was under uniform management practices prior to the study. Therefore, any significant differences that resulted at the end of the study can only be attributed to the treatments.

2.4. In situ hydraulic properties

In situ infiltration measurements were conducted using hood infiltrometer (IL-2700, Umwelt-Geräte-Technik GmbH, Müncheberg, Germany) following (Schwärzel and Punzel, 2007). These measurements do not require preparation of the soil and therefore can be