

Water Resources Research

RESEARCH ARTICLE

10.1029/2020WR027781

Key Points:

- Soil hydraulic properties, infiltration, transpiration, and plant growth are affected by irrigation with treated wastewater
- Mixing treated wastewater with local freshwater can be one approach to mitigate adverse effects of effluent irrigation on soil properties
- The second approach can be adjusting irrigation management and design by reducing irrigation rate and increasing the wetted area per tree

Correspondence to:

S. Assouline,
vwshmuel@agri.gov.il

Citation:

Assouline, S., Kamai, T., Šimůnek, J., Narkis, K., & Silber, A. (2020). Mitigating the impact of irrigation with effluent water: Mixing with freshwater and/or adjusting irrigation management and design. *Water Resources Research*, 56, e2020WR027781. <https://doi.org/10.1029/2020WR027781>

Received 22 APR 2020

Accepted 10 AUG 2020

Accepted article online 14 AUG 2020

Mitigating the Impact of Irrigation With Effluent Water: Mixing With Freshwater and/or Adjusting Irrigation Management and Design

Shmuel Assouline¹ , Tamir Kamai¹ , Jiri Šimůnek², Kfir Narkis¹, and Avner Silber³

¹Department of Environmental Physics and Irrigation, Institute of Soil, Water and Environmental Sciences, A.R.O. - Volcani Center, Rishon LeZion, Israel, ²Department of Environmental Sciences, University of California, Riverside, CA, USA, ³Northern R&D, Kiryat Shemona, Israel

Abstract The use of treated wastewater (WW) for irrigation is steadily increasing worldwide. However, irrigation with WW requires special attention as it may alter soil hydraulic properties and, eventually, affect crop yields. The main goal of this study was to investigate two approaches that could mitigate this adverse impact: (i) mixing WW with local freshwater (FW) and (ii) adjusting the irrigation management and design to the deteriorated soil hydraulic properties. Four water qualities resulting from mixing FW and WW at different ratios for irrigation of an avocado orchard planted on a clayey soil were considered: FW, $M_{1/3}$ (2/3 FW – 1/3 WW), $M_{2/3}$ (1/3 FW - 2/3 WW), and WW. Increasing the WW component in the irrigation water reduces the soil's saturated hydraulic conductivity and infiltrability, and this reduction is depth dependent. It also reduces the transpiration of trees and their trunk growth. This is supported by numerical simulations that showed that irrigation with WW produced the reduction in plant transpiration relative to irrigation with FW. Numerical simulations indicated that irrigation management and design could be adjusted to improve plant water uptake and reduce the differences due to water quality. The results indicate that decreasing the irrigation rate and increasing the wetted area per tree could increase the water uptake in WW-irrigated soils to almost equal that in FW-irrigated soils. This can be achieved by using drippers with lower discharge and by using more drippers per dripline, more driplines per tree, and more drippers per tree (concentric loops of driplines around each trunk).

1. Introduction

The global demand for food is expected to double by 2050 (Tilman et al., 2011). Because of the limited potential for additional arable land and rapid dwindling of freshwater (FW) resources, this challenge is formidable (Falkenmark & Rockström, 2006; Famiglietti, 2014; UN Environment, 2019). One way to increase crop yields is to expand irrigated agriculture (Halliwell et al., 2001) and, therefore, to allocate new water sources previously considered “marginal” (saline, treated effluent, and desalinated water) to irrigation (Gleick, 2000; Grant et al., 2012; Grattan et al., 2015; Tal, 2006). However, this must be done carefully while considering potential long-term risks on the hydro-ecological functioning of soils (Assouline et al., 2015).

Irrigation with treated wastewater (WW) requires special attention as the use of WW may have drastic effects on soils due to its unique combination of organic matter (OM), mainly dissolved organic carbon (DOC), and high concentrations of sodium (Na^+). The high sodium concentration increases the sodium adsorption ratio (SAR) of water and soil solutions. This, in turn, increases the soil exchangeable sodium percentage (ESP) of the soil (Qian & Lin, 2019), causing to aggregate slaking, clay dispersion, and soil swelling (Rengasamy & Olsson, 1993). These processes induce an overall soil structure degradation (Basile et al., 2012), thereby reducing the soil saturated hydraulic conductivity, eliminating large pores, and shifting the water retention curve (WRC) toward smaller pores (Bresler et al., 1982; Russo & Bresler, 1977a, 1977b). Clay dispersion was found in many studies to be enhanced in the presence of DOC (Frenkel et al., 1992; Quirk & Schofield, 1955; Tarchitzky et al., 1993, 1999), and therefore, changes in soil properties are expected as a result of irrigation with WW (Assouline et al., 2015). These changes affect the main flow processes in the soil (e.g., infiltration, drainage, and evaporation) in the soil and, consequently, water and nutrient availability to plants. In addition, they were shown to reduce aeration and lower oxygen concentrations in the root zone (Assouline & Narkis, 2013).

Table 1
Soil Physical and Chemical Properties of Pristine Soil at the Experimental Site

Clay	Silt	Sand	Calcite	CEC	ESP	EC	pH
(%)	(%)	(%)	(%)	(meq/100 g)	(%)	(dS/m)	
46.7	24.5	28.8	9.8	48.6	0.84	0.5	8.0

Over the last two decades, studies have advanced knowledge regarding the impacts of irrigation with WW on soil properties. Long-term irrigation with WW of clayey soils was shown to cause significant deterioration of soil physical and chemical properties (Aiello et al., 2007; Assouline & Narkis, 2011; Assouline et al., 2016; Lado et al., 2005, 2012; Levy & Assouline, 2011). Soil ESP in WW-irrigated soils is often higher than the SAR of the soil solution (Assouline et al., 2016; Levy et al., 2014), implying

the need for developing new approaches that address this issue and improve our understanding of soil chemical processes (Sposito et al., 2016).

A detailed quantitative description of the changes in soil physical and hydraulic properties, and consequently infiltrability, of a clayey soil following long-term irrigation with WW can be found in Assouline and Narkis (2011), Coppola et al. (2004), and Aiello et al. (2007). An interesting finding in Assouline and Narkis (2011) was the depth-dependence of the extent of soil deterioration, suggesting that the long-term use of WW for irrigation will affect different zones in the soil profile differently, depending on soil properties, water quality, irrigation management, plant uptake, and climatic conditions.

The impact of long-term irrigation with WW on soil hydraulic properties, and consequently, on soil air and water regimes in the root zone, affects plant performances. Several studies reported (Assouline et al., 2015; Noshadi et al., 2013) or predicted (Phogat et al., 2020) a systematic decrease in yields of orchards irrigated with WW. Following more than 10 years of continuous irrigation with WW yields from drip-irrigated avocado and citrus orchards planted on clayey soils (~50% clay) dropped by approximately 20–30% relative to those from orchards irrigated with local FW (Assouline et al., 2015). Mechanisms explaining the loss of productivity under WW irrigation are yet unknown and likely involve multifaceted interactions between water quality and chemical, physical, and biological soil characteristics that affect plant functioning, including root uptake. To support the required expansion of irrigated agriculture and to ensure its sustainability and profitability when WW is used for irrigation, we need to seek for approaches that mitigate the adverse impacts of water quality on soil properties and yields. For example, Assouline (2019) has presented a simple physically based method that relies on the infiltration capacity curve to adjust irrigation rate and duration to changes in soil infiltrability, thus contributing to the design of efficient irrigation.

In this study, we propose to investigate two different approaches that mitigate the negative impact of WW use for irrigation. The first approach involves mixing WW with local FW to improve irrigation water quality. This mixing will allow continuing to exploit WW as an additional source of irrigation water while enhancing the sustainability and profitability aspects of the irrigated agriculture that will rely on this type of water. The second approach involves adjusting the irrigation management by considering the altered soil hydraulic properties affected by the long-term use of WW, especially on clayey soils. We present an analysis of the impacts of different mitigation approaches on soil properties and plant response relying on field data, laboratory experiments and analytical and numerical modeling and simulations.

2. Methodology

2.1. Experimental Site

The experimental site is an avocado orchard planted in 2010 (Haas grafted on Fairchild rootstock) located in the Western Galilee, Northern Israel (32.9821°N, 35.0830°E). The soil is grumusol, containing approximately 50% clay, mostly smectite. Information on soil mechanical and chemical analyses of a pristine soil is shown in Table 1. The climate is Mediterranean, with mild, wet winters followed by dry, hot summers. The rainfall season in the region is between October and May, with a mean annual precipitation of 580 mm.

The tree density is 417 trees per hectare, with 6 m between tree rows and 4 m between trees within rows. Each experimental plot comprised six rows (~100 trees), with the external rows considered as buffers. The experimental field design comprised four irrigation treatments involving high-quality local FW, local WW, and two mixing ratios between the two. The four treatments were as follows: FW, $M_{1/3}$ (2/3 FW – 1/3 WW), $M_{2/3}$ (1/3 FW – 2/3 WW), and WW. Chemical parameters of the resulting irrigation water in all four treatments during the 2017 summer are presented in Appendix A and shown in Table A1 and Figure A1.

The irrigation system in the field consisted of two driplines per row, located 25 cm on opposite sides of the trunk, with 1.6 L/hr pressure-compensated drippers (Netafim Inc., Israel) at a distance of 50 cm between drippers. The same total amount of water of 930 mm is applied in all four treatments during the irrigation season. Irrigation generally begins in May and ends in November, during the period where there is no rain in this region. Irrigation is applied every 2 days.

All horticultural treatments (e.g., pruning, pest and weed control, and fertilization) were performed uniformly in all treatments according to the recommendations of the Israeli Extension Service (Noy, 2006). The orchard was drip irrigated with WW since 2010. Treatments using different water qualities resulting from different mixing ratios between FW and WW began in April 2015.

3. Experimental Data

3.1. Field Data Collection

The soil at mid-distance between the trees was sampled at three depth ranges: 0–20, 20–40, and 40–60 cm. Sampling was carried out in April 2016, September 2017, and September 2019. To minimize the variability inherent in solute distribution around drippers, the soil below the drippers was sampled. Consequently, 10 locations along the rows were sampled assuming that it is enough to average soil variability and to obtain the required amount of soil needed to run all planned experiments using the same batch. This allowed a comparative analysis of the effects of irrigation water quality on soil properties. The disturbed soil samples were air-dried, crushed, and sieved. The soil fraction ≤ 2 mm of the aggregates was kept for the study.

Mechanical and chemical analyses were carried out at the Extension Service Laboratory of the Ministry of Agriculture at Neve Ya'ar (Western Galilee, Israel) using standard methods to provide the relevant soil characteristics (Methods of Soil Analysis, 1996). Dendrometers (PhyTech Ltd., Rosh Haayin, Israel) were installed in March 2017 to monitor the impact of water quality on the trees' growth rate.

Irrigation with WW affects the soil hydraulic properties, which can be estimated from infiltration experiments (Assouline & Narkis, 2011). The relative changes in these properties, resulting from the different water qualities, are thus estimated based on the analysis of infiltration experiments carried out on the soil samples from the different treatments. Subsequently, the estimated hydraulic properties are used as input in the numerical simulations for assessing the impact of irrigation water quality on water uptake.

3.2. Infiltration Experiments

Cylindrical columns, 13 cm long and 5.2 cm inner diameter, were used to conduct infiltration tests using a minidisk tension infiltrometer (Decagon Devices, Inc., Pullman, WA, USA). A weighted amount of air-dried soil was packed to attain a 10-cm thickness, at a bulk density of ~ 1.4 g/cm. A thin layer of 0.30 ± 0.05 cm of sand was put on the top of the soil surface to ensure good contact between the porous plate of the infiltrometer and the soil surface. The air was allowed to escape freely at the bottom of the soil column, and the experiment was stopped before the wetting front reached the bottom of the soil column. The infiltration experiments were run under a capillary pressure of $H_p = -0.5$ cm at the surface, to avoid flow along possible large voids resulting from packing or at the contact between soil aggregates and the wall of the column. Considering the tight fit between the cross sections of the column and the porous plate of the infiltrometer, we assume one-dimensional (1D) unsaturated flow conditions during infiltration. The cumulative volume of infiltrating water, V , was monitored versus time, t . The measured $V(t)$ curves were expressed in terms of the cumulative infiltration depth, $F(t) = \frac{V(t)}{A}$, where A is the cross-sectional area of the column. The infiltration experiments were run in two or three replicates. Tap water with EC of 0.3 ± 0.03 dS/m was used in all experiments.

3.3. Computations and Modeling

3.3.1. Analytical Expressions for Infiltration

Brutsaert (1977) proposed an approximate solution to the Richards equation (Richards, 1931) that has been shown to perform quite well in reproducing $F(t)$ curves (Selker & Assouline, 2017):

$$F(t) = tK_s + \frac{S^2}{\beta K_s} \left\{ 1 - \left[1 + \beta \left(\frac{t^{1/2} K_s}{S} \right) \right]^{-1} \right\} \quad (1)$$

where K_s and S are the soil saturated hydraulic conductivity and sorptivity, respectively, and β is a fitting parameter. The expression in Equation 1 was fitted to the measured $F(t)$ data of the 2017 soil sampling for estimating K_s by parameter optimization, thereby providing quantitative estimates of the effect of each treatment (FW, $M_{1/3}$, $M_{2/3}$, and WW) on each soil depth (0–20, 20–40, and 40–60 cm) in terms of K_s .

3.3.2. Parameter Optimization for Estimating Soil Hydraulic Properties

The Richards equation (Richards, 1931) describes accurately the infiltration process through soils, provided that the initial and boundary conditions and the soil hydraulic functions, namely, the WRC, $\theta(\psi)$, and the hydraulic conductivity function (HCF), $K(\psi)$, are known. Richards equation for transient, 1D vertical water flow, is

$$\frac{\partial \theta(\psi)}{\partial t} = \frac{\partial}{\partial z} \left\{ K(\psi) \left[\frac{\partial \psi}{\partial z} + 1 \right] \right\} - S(\psi, z, t) \quad (2)$$

where θ denotes the volumetric water content, ψ denotes the capillary head, z denotes the elevation (positive upward), t denotes the time, and S denotes the sink term accounting for water uptake by plant roots.

HYDRUS-1D (Šimůnek et al., 2005, 2016) solves Equation 2 numerically. To mimic the infiltration experiment with the infiltrometer, a constant capillary head was used as the upper boundary condition: ($\psi = H_p = -0.5$ cm; $t \geq 0$), free drainage was assumed as the lower boundary condition, $S(\psi, Z, t) = 0$ with no plant uptake, and the initial constant capillary head was applied to the whole profile ($\psi_i = -200$ cm; $t = 0$).

For estimating soil hydraulic properties, we used the Matlab optimization toolbox, iterating with HYDRUS-1D, to determine the WRC and HCF if the infiltration function $F(t)$ was known. This inverse procedure was applied, given the known initial and boundary conditions of the 1D infiltration tests and the measured $F(t)$ data of the 2017 soil sampling, to estimate the WRC of the soil after long-term exposure to irrigation with the four different water qualities.

HYDRUS-1D applies the model of van Genuchten (1980) for the WRC, with two shape parameters, α (L) and n ,

$$S_e(\psi) = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{[1 + (\alpha|\psi|)^n]^{(1-1/n)}} \right) \quad (3)$$

and estimates the unsaturated HCF $K(S_e)$ using the pore-size distribution model of Mualem (Mualem, 1976):

$$K(S_e) = K_s S_e^{0.5} \left[\frac{\int_0^{S_e} \frac{ds}{\psi}}{\int_0^1 \frac{ds}{\psi}} \right]^2 \quad (4)$$

where S_e is the saturation degree, θ_s represents the saturated water content, θ_r the residual water content, and K_s the saturated hydraulic conductivity.

The values of α and n , corresponding to each treatment (FW, $M_{1/3}$, $M_{2/3}$, and WW) were estimated by optimization. In the optimization procedure, K_s , θ_r , and θ_s were set constant. We used the K_s values estimated by Equation 1. The saturated water content, θ_s , was evaluated based on the bulk density of the packed soil column (Rogowski, 1971). The value of θ_r was estimated based on the specific surface area corresponding to the clay content in the soil, following the approach presented in Tuller and Or (2005).

3.3.3. 2D Numerical Simulation of Irrigation

The soil hydraulic properties determined from the infiltration tests were then applied to simulate the impact of long-term irrigation with FW and WW on the water regime and root water uptake at the

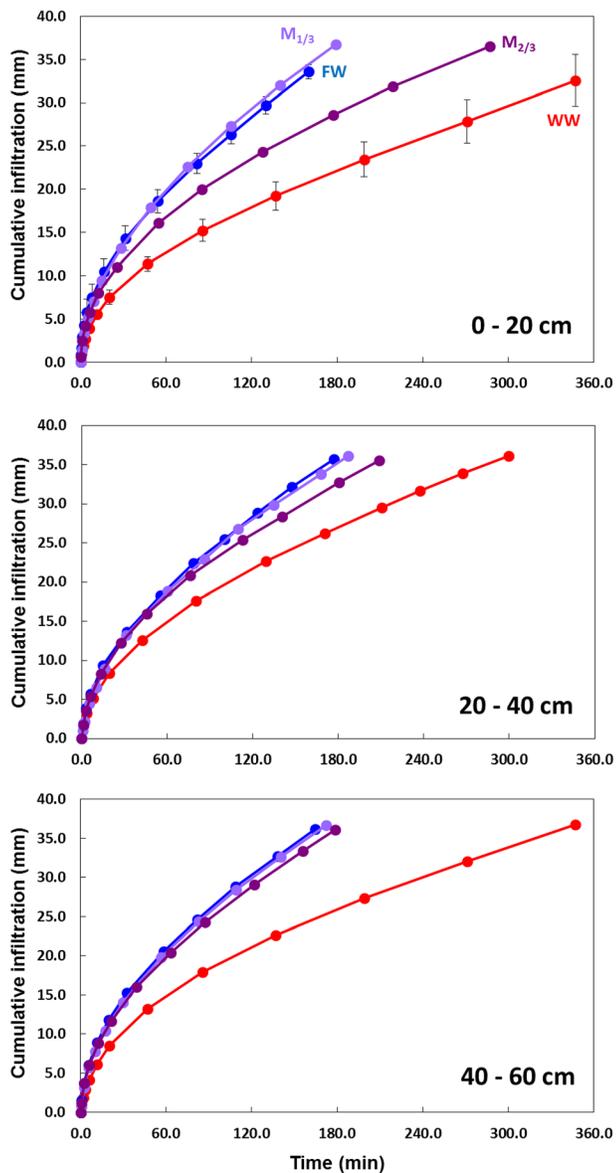


Figure 1. The effect of water qualities (FW, $M_{1/3}$, $M_{2/3}$, and WW) on infiltration in three soil profile depths (0–20, 20–40, and 40–60 cm) (soil sampling from September 2017).

avocado root zone scale under drip irrigation. The simulated results do not aim to reproduce real field conditions but rather focus on the aspect of soil hydraulic properties, their difference under drip irrigation with FW and WW, and their impact on water uptake and transpiration. Therefore, we chose not to account for the effects of salinity and related osmotic potential on root uptake and transpiration. This aspect of irrigation with WW was simulated and discussed in detail in several other studies (Assouline et al., 2015; Phogat et al., 2020; Russo et al., 2009), which showed that increased salinity in WW could contribute to reducing plant water uptake. Another simplifying assumption was that the irrigation water (FW and WW) did not affect the root zone spatial distribution. This simplification made it possible to study the impact of soil hydraulic properties under the same conditions in the domain (a similar irrigation amount and root uptake sink) and similar initial and boundary conditions.

The 2D module of HYDRUS (2D/3D) (Šimůnek et al., 2016) was used to simulate the flow regime in FW- and WW-drip-irrigated soil profiles during 1 month in the 2017 irrigation season from DOY 212 to DOY 243. The 2D version of Equation 2 was solved, this time considering the root water uptake term $S(\psi, z, t)$. The same irrigation dose was applied in all simulated scenarios. Potential transpiration was estimated based on the Penman-Monteith equation (Allen et al., 1998) using climatic data for the simulated period, assuming evaporation from the soil surface to be negligible, and setting most of the upper boundary condition to no flux. At the location of the drip line, the time-variable flux boundary condition was set equal to the dripper discharge rate divided by the length of this boundary. The bottom boundary condition at a depth of 200 cm was set to free drainage. A homogeneous soil profile was assumed, characterized by the soil hydraulic properties (WRC and HCF) corresponding to the 0- to 20-cm layer of the FW- and WW-irrigated plots, which is the layer that is most affected by the water quality at this stage of the experiment. An initial constant capillary head was applied to the whole profile ($\psi_i = -100$ cm; $t = 0$). Plant water uptake (transpiration), $S(\psi, z, t)$, was simulated following the option in HYDRUS that adopts the Feddes et al. (1978) stress function with parameters for avocado. We considered that the root system was distributed such that it spreads out to maximum 100 cm from the tree and penetrates to a maximum depth of 80 cm, with the maximum density at 25-cm depth. The numerical water balance error was up to 0.5% for the entire duration of the simulations.

The irrigation management and design in the experimental plots were chosen as the reference case: two drip lines per row (located 25 cm from the tree at both sides), irrigation every 2 days and dripper discharge of 1.6 L/hr (2 DL, 48 h, and 1.6 L/hr). The numerical model allowed investigating these management and design characteristics and adjusting irrigation according to altered soil hydraulic properties following the long-term use of WW. Specifically, we tested: (1) applying different irrigation rates (by changing the 1.6 L/hr dripper discharge rate by a factor of 2 to get 3.2 and 0.8 L/hr discharge rates) for the proportional (shorter or longer) duration, while achieving the same irrigation dose; (2) increasing the number of lateral drip lines per a tree row from 2 to 4, located 15 and 65 cm from the tree on both sides; and (3) changing the irrigation frequency from one irrigation every 2 days to daily irrigation. Different combinations were considered and are described in Table 3. The impact of these changes was expressed in terms of cumulative transpiration (root water uptake), which was considered to be directly related to yield.

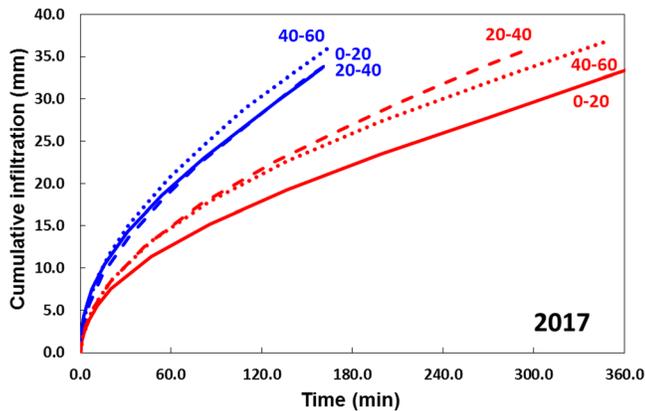


Figure 2. The effect of irrigation with FW (blue lines) and WW (red lines) on infiltration in three soil profile depths (0–20, 20–40, and 40–60 cm) (using soils from September 2017 sampling).

change as the period of consecutive irrigation seasons extends, because the effect of water quality with depth can increase with the duration of the low-quality water application.

The difference between the infiltration curves resulting from irrigation with FW and WW at the three depths along the soil profile is presented in Figure 2 to ease the comparison between the different curves. Two distinct groups of curves corresponding to two water qualities can be observed, indicating that water quality has a larger impact than the soil depth. In both cases, the upper 0- to 20-cm depth is more affected by water quality. However, these findings may vary depending on site characteristics. For example, Assouline and Narkis (2011) showed that under different conditions (an older avocado orchard, more prolonged exposure to irrigation with WW, and irrigation every 3 days), the most affected layer in the soil profile was the 20- to 40-cm layer.

The difference between the infiltration curves for the soil sampled in 2016, 2017, and 2019 from the upper soil layer (the 0- to 20-cm depth) resulting from irrigation with FW and WW are presented in Figure 3. These results, too, reveal two distinct groups of curves corresponding to two water qualities. Additionally, the results shown in Figures 2 and 3 indicate that the impact of water quality is stable over the seasons, thus characterizing the soil-plant system.

4.2. Impact of Irrigation Water Quality on Soil ESP and K_s at Different Depths

The depth distributions of ESP values corresponding to different soil profiles, as sampled in 2017, are shown in Figure 4 (left). An increase in the WW component in irrigation water leads to an apparent rise

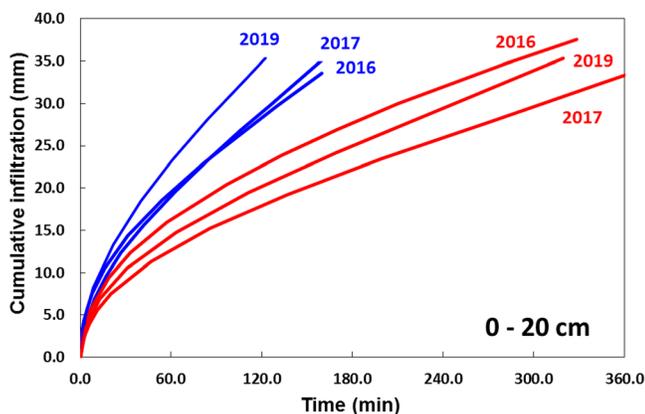


Figure 3. Infiltration curves for the FW- (blue lines) and WW-irrigated (red lines) soils sampled from the upper layer (0–20 cm) during 2016, 2017, and 2019.

4. Results and Discussion

4.1. Impact of Irrigation Water Quality on the Infiltration Curves

Figure 1 depicts the effect of irrigation water quality on the measured infiltration curves for four water qualities (FW, $M_{1/3}$, $M_{2/3}$, and WW) and three soil depths (0–20, 20–40, and 40–60 cm). The error bars on the FW and WW curves illustrate experimental standard deviations of the replicates in all the experiments. At all soil depths, soil infiltrability is reduced as the component of WW in the irrigation water increases and is significantly lower in the WW-irrigated soil. Mixing FW with 1/3 of WW ($M_{1/3}$) does not seem to have a significant effect on soil infiltrability, with similar infiltration curves for the FW and $M_{1/3}$ treatments at all depths. The mixing of FW with WW reduces the negative impact of WW on the infiltrability and, thereby, on soil hydraulic properties. The mixing effect is stronger in deeper layers of the soil profile. There is practically no difference between the infiltration curves of irrigation water that contain a component of FW at the 40- to 60-cm depth. This, of course, could

change as the period of consecutive irrigation seasons extends, because the effect of water quality with depth can increase with the duration of the low-quality water application. This trend was also simulated by Phogat et al. (2020) using the multicomponent major ion chemistry module UNSATCHEM integrated into the HYDRUS-1D software package (Šimůnek et al., 2016). For the FW dominated water, ESP also tends to increase slightly with depth. The impact of different water qualities on soil ESP is clear, and so is the beneficial effect of mixing. It seems that the FW component has a more significant impact on the upper soil layer (0–20 cm), while the effect of the WW component is more pronounced in the deeper layer (40–60 cm). In terms of ESP, the results show two distinct groups: FW and the $M_{1/3}$ soils in one group and $M_{2/3}$ and WW in another one.

The infiltration curves presented in Figure 1 were used to estimate saturated hydraulic conductivities, K_s , characterizing the soil profiles, by means of Equation 1. The results are shown in Table 2 and in Figure 4 (right). In the upper layer (0- to 20-cm depth), K_s is higher for the FW and $M_{1/3}$ irrigated soils than for the $M_{2/3}$ and WW soils. Interestingly, the K_s values of the deeper layer (40–60 cm) are more

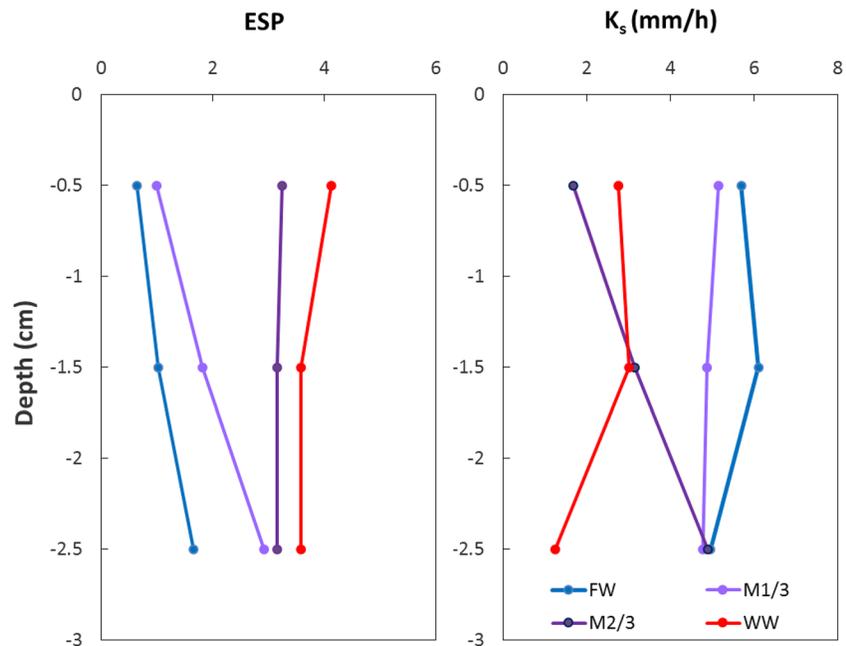


Figure 4. Depth distribution of soil ESP (left) and corresponding estimated K_s (right) for different water qualities (FW, $M_{1/3}$, $M_{2/3}$, and WW).

affected by the FW component compared to the ESP values, which are more affected by the WW component.

The relationship between K_s and ESP was found to be affected by the DOC concentration in the soil (Assouline & Narkis, 2011), and more specifically, K_s was related to the ratio of (ESP/DOC) (Assouline et al., 2016; Sposito et al., 2016). An empirical relationship was fitted to data from several earlier experiments with WW irrigation at different sites (Assouline et al., 2016). The data from this study are presented in Figure 5 along those reported previously, as well as the fitted relationship. The results from the mixing experiment correspond to these previously reported data, and the overall trend is well represented by the fitted dashed curve. This provides additional support to the insight that interactions between monovalent cations and organic molecules play a major role in determining the intensity of the impact of irrigation with WW on soil properties, and especially on K_s .

Table 2
Estimated van Genuchten (1980) Soil Hydraulic Parameters of Soil Irrigated With Four Water Qualities (FW, $M_{1/3}$, $M_{2/3}$, and WW) at Three Soil Depths (0–20, 20–40, and 40–60 cm)

Water quality	Soil depth	θ_s	θ_r	α	n	K_s
	(cm)	(cm^3/cm^3)	(cm^3/cm^3)	(1/cm)		(mm/h)
FW	0–20	0.47	0.15	0.034	1.70	5.68
	20–40			0.034	1.72	6.10
	40–60			0.025	1.74	4.96
$M_{1/3}$	0–20	0.47	0.15	0.026	1.74	5.14
	20–40			0.026	1.73	4.86
	40–60			0.023	1.76	4.76
$M_{2/3}$	0–20	0.47	0.15	0.027	3.03	1.68
	20–40			0.018	1.69	3.14
	40–60			0.026	1.74	4.89
WW	0–20	0.47	0.15	0.029	1.58	2.75
	20–40			0.023	1.64	3.01
	40–60			0.023	3.12	1.25

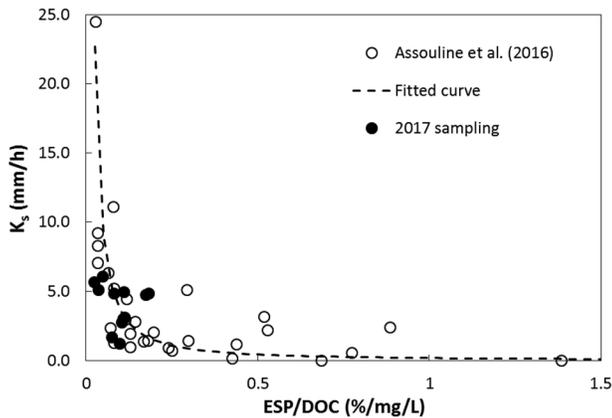


Figure 5. The K_s (ESP/DOC) relationship for the soil in the experimental site compared to previously reported data in Assouline et al. (2016) and the empirical relationship fitted to these data (dashed line).

4.3. Impact of Irrigation Water Quality on Soil Hydraulic Properties

The van Genuchten parameters for the soil WRC, α and n , for the different treatments (FW, $M_{1/3}$, $M_{2/3}$, and WW) were estimated based on the infiltration data. The K_s values previously determined using the analytical solution for cumulative infiltration (Equation 1) were used as prescribed values in the optimization procedure. The results are shown in Table 2. Increasing the WW component induces an increase in the air-entry value of the soil, as reflected by a smaller α value, and a decrease in n . A decrease of α with depth (increase in the air-entry value of the soil with depth) is also observable. In two cases, ($M_{2/3}$: 0–20 cm) and (WW: 40–60 cm), the resulting WRC are characterized by high n values (>3.0) that differ significantly from the relatively stable values in most of the layers. These two distinct values are correlated with the lowest two K_s values (<2.0 mm/hr). These high n values could result from the imposed low K_s values but could also result from local minima in the optimization procedures applied (for K_s and then for α and n). The resulting hydraulic functions,

$\psi(S_e)$ in Equation 3) and $K(S_e)$ in Equation 4, corresponding to the 20- to 40-cm layer are depicted in Figure 6 to illustrate the effect of water quality on soil hydraulic properties. Increasing the WW component in the irrigation water moves basically the $\psi(S_e)$ and $K(S_e)$ functions to the right, indicating that the exposure to WW induces a “heavier” soil. In terms of $K(S_e)$, and as shown previously for the ESP values and the infiltration curves, the results show a distinct group for the FW and the $M_{1/3}$ soils, and another one for the $M_{2/3}$ and WW soils.

An important point to bear in mind with regard to the impact of irrigation water quality on the soil hydraulic properties is the large intraseasonal and interannual variability that characterizes the quality of WW for irrigation (Figure A1). This water quality variability, coupled with high variability in annual rainfall, especially in semiarid regions, induces partial leaching of the root zone and indicates that precise simulations of chemical interactions between water components and the clay fraction are a challenge. This variability could explain why some studies reported that irrigation with WW had no detrimental effects on tree growth and productivity (Minhas et al., 2015; Morgan et al., 2008; Parsons et al., 2001) and soil physicochemical properties (Andrews et al., 2016). It is important to note that these studies are in full disagreement with

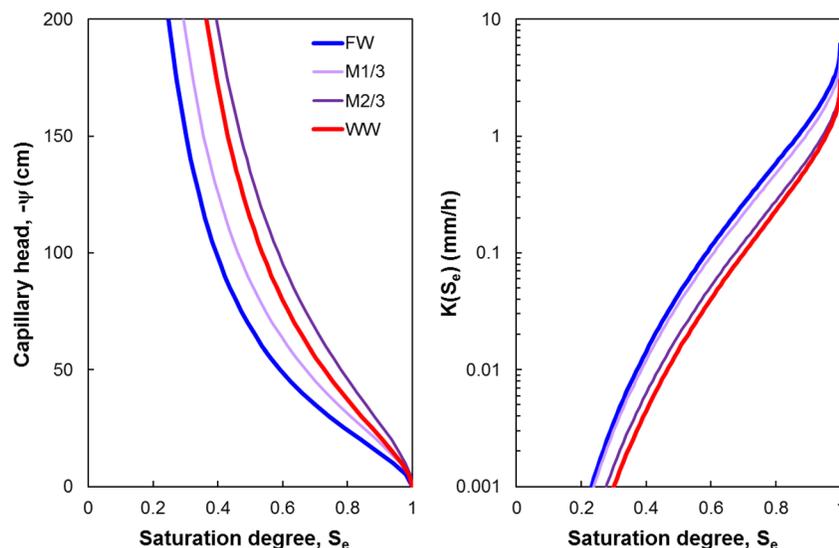


Figure 6. The water retention curves (left) and the hydraulic conductivity functions (right) for the 20- to 40-cm soil layer (corresponding to the parameters in Table 2) illustrating the impact of water qualities (FW, $M_{1/3}$, $M_{2/3}$, and WW) on soil properties, as estimated using the HYDRUS-1D inverse procedure.

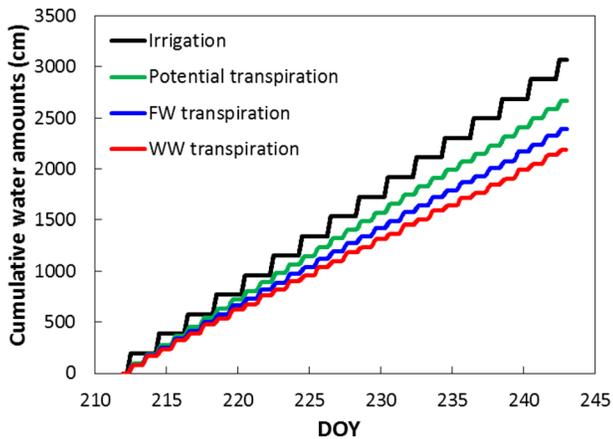


Figure 7. Simulation results in terms of actual transpiration (tree water uptake) for irrigation with FW and WW along with applied irrigation dose and estimated potential transpiration.

the results presented here and in previous studies (Assouline & Narkis, 2011, 2013; Assouline et al., 2016; Bardhan et al., 2016; Lado et al., 2012; Noshadi et al., 2013; Paudel et al., 2016; Phogat et al., 2020; Qian & Lin, 2019).

4.4. Simulated Water Regime in FW- and WW-Irrigated Soils

HYDRUS-2D was utilized to simulate the impact of irrigation with the two end members of the water quality range considered herein, FW and WW, on transpiration (plant water uptake) during 1 month in the irrigation season of 2017. The hydraulic properties representing the FW and WW soils at the 0- to 20-cm layer (Table 2), which is the layer that is most affected by the water quality at this stage of the experiment, were applied. The results are depicted in Figure 7 in terms of cumulative actual transpiration for the simulation period, along with a corresponding amount of applied irrigation water and estimated cumulative potential transpiration estimated based on climatic data at the site. The applied irrigation dose is higher than estimated potential transpiration, representing realistic irrigation management for uptake efficiency and salt leaching (not simulated here) from the root zone.

The transpiration in the FW-irrigated soil is higher than in the WW-irrigated soil by approximately 10%. This, as explained previously, illustrates only the impact of soil hydraulic properties (a capillary component) and does not account for additional effects of irrigation with WW on transpiration, such as salinity (an osmotic component) and spatial distribution of the root system (which can be assumed as additive effects).

Under field conditions, soil hydraulic properties, salinity, and the size of the root system have mutual and complex effects on the plant performance. The integral effect may be represented by the dendrometer readings. Measurements of trunk growth carried out using dendrometers installed on trees irrigated with different water qualities during 2019 (Figure 8) reveal a significant impact of water quality on tree performance. The trunk growth is maximal for irrigation with FW. Increasing the WW component in mixed irrigation water reduces trunk growth, which is minimal for irrigation with WW. Trunk growth was shown to be strongly related to tree transpiration and yield (Silber et al., 2019, 2013). The reduction in simulated actual transpiration due to changes in soil hydraulic properties induced by irrigation with WW indicates that such irrigation contributes to a decrease in tree performances and, consequently, to the drop in yield. The simulated decrease in actual transpiration of about 10% and an estimated additional decrease in actual transpiration due to higher osmotic pressure related to higher WW salinity (Assouline et al., 2015; Russo et al., 2009) could explain the drop in yields observed in avocado orchards after long-term irrigation with WW (Assouline et al., 2015; Phogat et al., 2020).

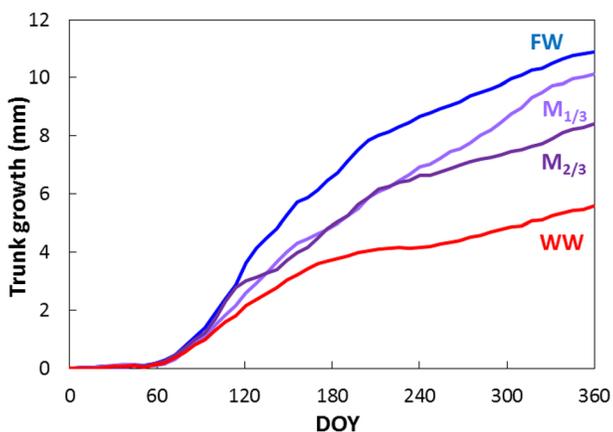


Figure 8. The impact of water qualities (FW, $M_{1/3}$, $M_{2/3}$, and WW) on trunk growth during 2019.

4.5. Adjusting the Irrigation Management

Based on the results presented above in terms of soil hydraulic properties, WW-irrigated soils act as “heavier” more clayey soils, although the amount of clay remained unchanged (compared to the FW-irrigated soils), displaying lower infiltrability, lower saturated hydraulic conductivity, and higher air entry value (lower α). These altered properties would normally necessitate to change the design of the irrigation system to adapt it to the “new soil.” The numerical solution of the flow equations via HYDRUS was further used to investigate the changes in irrigation management and design that could or should be made to mitigate the negative effects of WW irrigation on soil hydraulic properties and improve plant water uptake. Several irrigation designs and management parameters were considered: irrigation frequency, dripper discharge, and the number of drip lines per row. Seven irrigation schemes involving changes in these parameters were simulated (Table 3). In all the simulations, the same irrigation dose was applied. The results, expressed in terms of the ratio of

Table 3
Simulated Irrigation Scenarios

Irrigation scheme	Description
1. 2 DL; 48 hr; 3.2 L/hr	2 drip lines per row; irrigation every 48 hr; 3.2 L/hr dripper discharge
2. 2 DL; 48 hr; 1.6 L/hr (ref.)	2 drip lines per row; irrigation every 48 hr; 1.6 L/hr dripper discharge
3. 2 DL; 48 hr; 0.8 L/hr	2 drip lines per row; irrigation every 48 hr; 0.8 L/hr dripper discharge
4. 2 DL; 24 hr; 1.6 L/hr	2 drip lines per row; irrigation every 24 hr; 1.6 L/hr dripper discharge
5. 2 DL; 24 hr; 0.8 L/hr	2 drip lines per row; irrigation every 24 hr; 0.8 L/hr dripper discharge
6. 4 DL; 24 hr; 0.8 L/hr	4 drip lines per row; irrigation every 24 hr; 0.8 L/hr dripper discharge
7. 4 DL; 48 hr; 1.6 L/hr	4 drip lines per row; irrigation every 48 hr; 1.6 L/hr dripper discharge
8. 4 DL; 48 hr; 0.8 L/hr	4 drip lines per row; irrigation every 48 hr; 0.8 L/hr dripper discharge

actual transpiration (plant water uptake) relative to potential transpiration, are depicted in Figure 9. The reference scheme is the management in the experimental plots as described above: the (2 DL, 48 hr, and 1.6 L/hr) scheme (marked by a shaded rectangle).

The impact of the different schemes in terms of the spatial distribution of the water content in the simulation domain is illustrated in Figure 10 for the reference scheme (Scheme 2: 2 DL, 48 hr, and 1.6 L/hr) and for the one presenting the best result (Scheme 7: 4 DL, 48 hr, and 1.6 L/hr), for the FW and the WW soils properties. The water content distribution corresponds to the end of the application of the irrigation dose toward the end of the simulation period (DOY 240). The area limited by the dashed lines represents the root zone. For the reference scheme, the WW-irrigated soil is wetter (in agreement with the shift to a “heavier soil”), closer to saturation below the dripper, and more water drains below the root zone in that profile, compared to the FW-irrigated one. This indicates lower irrigation efficiency (as shown in Figure 9 in terms of the lower water uptake) and possible problems of aeration in the WW-irrigated profiles. Increasing the wetted area by doubling the number of driplines (Scheme 7) reduces the differences in the spatial distribution of the water content between the FW and WW treatments and improves the irrigation efficiency in the WW-irrigated treatment.

Several interesting and valuable insights can be gained from these results regarding approaches to adjust irrigation to the WW quality to reduce damages:

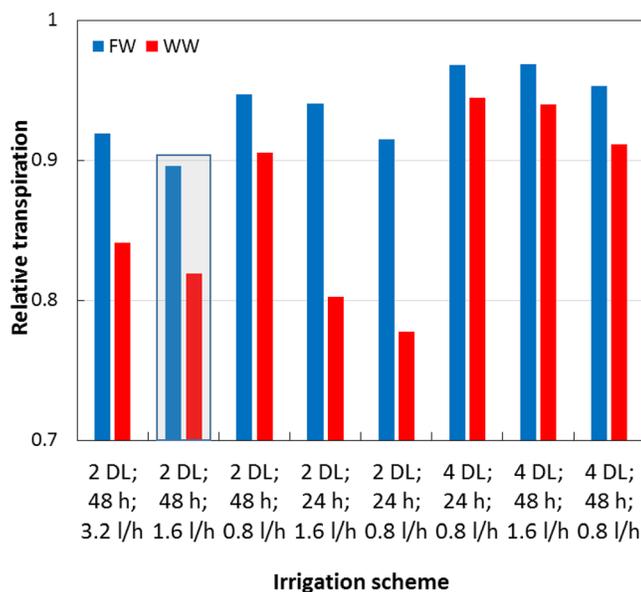


Figure 9. The effect of irrigation schemes and water qualities (FW and WW) on simulated relative (actual/potential) transpiration.

1. There is practically no gain in increasing the dripper discharge (Scheme 1 compared to Scheme 2, Figure 9) if the current setup of two drip lines and irrigating every 2 days is maintained. However, using drippers with a lower discharge increases transpiration and reduces the difference between FW- and WW-irrigated soils (Scheme 3 compared to Scheme 2, Figure 9), thus achieving some mitigating effect.
2. Increasing the irrigation frequency, namely, moving from one irrigation every 2 days to daily irrigation, has a significant negative impact, especially on the WW-irrigated soil (Schemes 4 and 5 compared to Scheme 2, Figure 9). The difference between actual transpiration in the FW- and WW-irrigated soils is maximal for this irrigation frequency (Schemes 4 and 5, 24 hr), independently of the dripper discharge used (1.6 L/hr in Scheme 4 and 0.8 L/hr in Scheme 5).
3. Increasing the number of driplines per row (here it was doubled, Schemes 6 through 8) provides the best result among the simulated cases: actual transpiration increases in both FW- and WW-irrigated soils, and the difference between the two is significantly reduced, achieving the strongest mitigating effect for the schemes under consideration. Practically similar results are obtained for Schemes 7 (4 DL, 48 hr, and 1.6 L/hr) and 6 (4 DL, 24 hr, and 0.8 L/hr).

Both the use of drippers with lower discharge rates and an increase in the number of driplines that increases the wetted area per tree tend to reduce

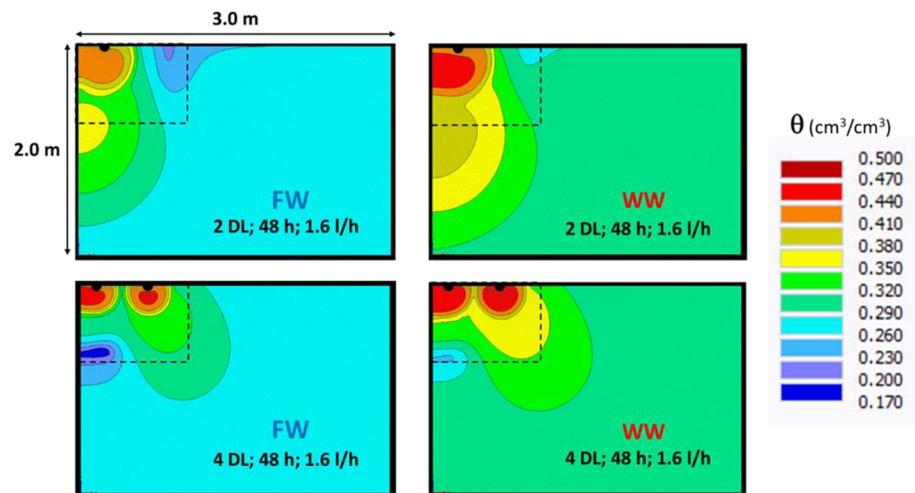


Figure 10. Spatial distribution of the water content in the simulation domain for the reference scheme (Scheme 2: 2 DL, 48 hr, and 1.6 L/hr) and for the one presenting the best result (Scheme 7: 4 DL, 48 h, and 1.6 L/hr), for the FW and the WW soils properties.

the local irrigation rate. This can also be achieved by increasing the number of drippers per line (drippers every 25 cm instead at every 50 cm as it is done currently) or by using concentric loops of driplines around the trunk. The promising results described above are in agreement with the physically based analysis presented in Assouline (2019).

From a practical point of view (the pressure available in the system and clogging risks in drippers), the use of drippers with higher discharge (1.6 L/hr) is preferable. Therefore, the design aiming at a lower irrigation rate by increasing the number of drippers per tree and widening the wetted area, such as by reducing the distance between drippers along a dripline, increasing the number of driplines per tree, or using concentric loops of driplines around each trunk, seems to be preferable. Therefore, we suggest this approach should be further investigated in future experimental studies evaluating irrigation managements and designs adjusted to the long-term effect of irrigation with WW on soil hydraulic properties.

5. Conclusions

Several insights can be gained from the above results:

1. On the one hand, the long-term use of WW for irrigation may deteriorate soil properties, especially if the clay content is relatively high. This, in turn, affects plant water uptake and lead to lower yields. On the other hand, we need to treat and recycle WW and use it whenever possible and appropriate. The results presented herein show that the $M_{1/3}$ water quality (mixing 2/3 FW with 1/3 WW) allows for using WW without causing damage to soil hydraulic properties that are evident after few years of irrigation and without significantly affecting plant uptake and plant growth. Mixing FW with WW at the $M_{1/3}$ ratio allows for benefiting from the use of WW, namely, by reducing FW demand, recycling nutrients, and minimizing the discharge of pollutants into waterways (Hanjra et al., 2012; Hassena et al., 2018) while preventing hazards.
2. The Shavei Tsion orchard was irrigated with WW before the experiment presented here was carried out. The infiltration experiments on soil samples from plots irrigated with FW or $M_{1/3}$ indicate that damages to soil hydraulic properties induced by irrigation with WW may be reversible. This needs to be investigated more thoroughly in the future.
3. It seems that the irrigation management and design can and should be adjusted to account for the changes in soil hydraulic properties

Table A1
Representative Range of Chemical Variables of FW and WW Irrigation Water Between June to September 2017

Parameter	FW	WW
pH	7.4–7.5	8.1–8.2
Cl ⁻ (ppm)	52–87	209–239
EC (dS/m)	0.8–1.0	1.5–1.6
Na ⁺ (ppm)	17–30	174–178
Ca ²⁺ + Mg ²⁺ (ppm)	73–132	113–126
SAR (-)	0.4–0.6	4.0–4.2

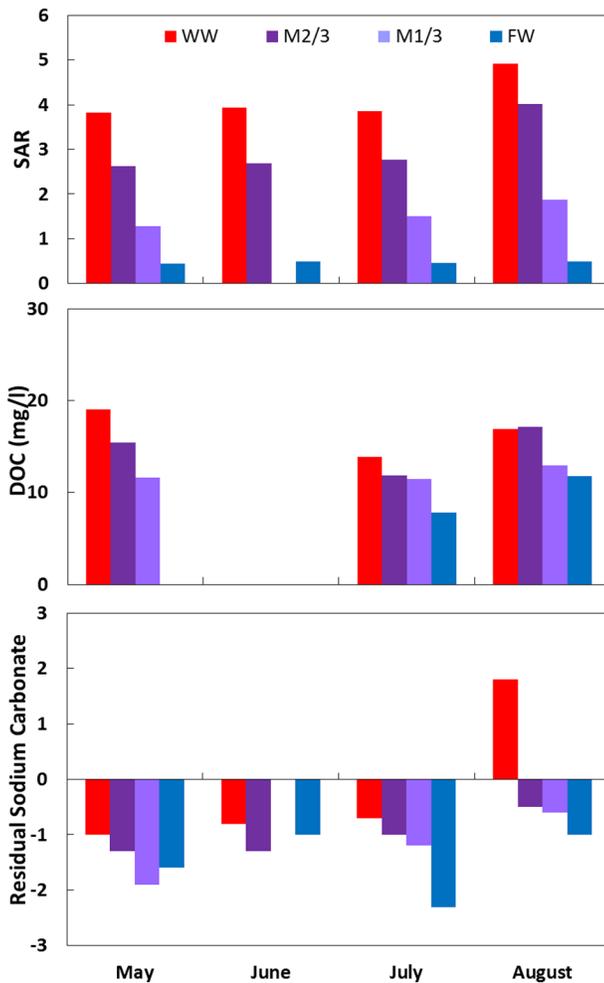


Figure A1. Parameters of water qualities (SAR, DOC, and RSC) for different irrigation waters (FW, $M_{1/3}$, $M_{2/3}$, and WW) during the irrigation season of 2016. The DOC data for irrigation water $M_{1/3}$ in June is missing.

Acknowledgments

The authors are grateful to Hadar Cohen, Rami Bar-Ziv, Menashe Levy, Yael Bar-Noy, and Nimrod Wolf, from the Acre Experimental Station and the Northern R&D, and the avocado team of Shavei Tsiyon orchard for their strong support and technical assistance. This research was partly supported by the Israeli Board of Avocado.

References

- Aiello, R., Cirelli, G. L., & Consoli, S. (2007). Effect of reclaimed wastewater irrigation on soil and tomato fruit: A case study in Sicily (Italy). *Agricultural Water Management*, 93(1-2), 65–72. <https://doi.org/10.1016/j.agwat.2007.06.008>
- Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). FAO Penman-Monteith equation. In *Crop evapotranspiration—Guidelines for computing crop water requirements*, FAO Irrigation and Drainage Paper 56 (chap. 2, pp. 1–281). Rome, Italy: Food and Agriculture Organization of the United Nations.
- Andrews, D. M., Robb, T., Elliott, H., & Watson, J. E. (2016). Impact of long-term wastewater irrigation on the physicochemical properties of humid region soils: “The living filter” site case study. *Agricultural Water Management*, 178, 239–247. <https://doi.org/10.1016/j.agwat.2016.10.001>
- Assouline, S. (2019). A simple method to design irrigation rate and duration and improve water use efficiency. *Water Resources Research*, 55, 6295–6301. <https://doi.org/10.1029/2019WR025221>
- Assouline, S., & Narkis, K. (2011). Effects of long-term irrigation with treated wastewater on the hydraulic properties of a clayey soil. *Water Resources Research*, 47, W08530. <https://doi.org/10.1029/2011WR010498>
- Assouline, S., & Narkis, K. (2013). Effects of long-term irrigation with treated wastewater on the root zone environment. *Vadose Zone Journal*, 12(2), 1, vzj2012.0216–10. <https://doi.org/10.2136/vzj2012.0216>
- Assouline, S., Narkis, K., Gherabli, R., & Sposito, G. (2016). Combined effect of sodicity and organic matter on soil properties under long-term irrigation with treated wastewater. *Vadose Zone Journal*, 15(4), 1–10.
- Assouline, S., Russo, D., Silber, A., & Or, D. (2015). Balancing water scarcity and quality for sustainable irrigated agriculture. *Water Resources Research*, 51, 3419–3436. <https://doi.org/10.1002/2015WR017071>
- Bardhan, G., Russo, D., Goldstein, D., & Levy, G. J. (2016). Changes in the hydraulic properties of a clay soil under long-term irrigation with treated wastewater. *Geoderma*, 264, 1–9. <https://doi.org/10.1016/j.geoderma.2015.10.004>

(especially in fine-textured soils) resulting from long-term irrigation with WW. The best approach seems to be to reduce the irrigation rate and increase the wetted area per tree. This can be achieved by using more drippers per dripline, more driplines per tree, more drippers per tree (concentric loops of driplines around each trunk), and drippers with lower discharge. Increasing the irrigation frequency leads to the worst performances in terms of plant water uptake.

Appendix A

The range of the main chemical characteristics representing the FW and WW irrigation water quality during the summer of 2017 is presented in Table A1.

The quality of the irrigation water that affect the soil properties in the context of WW irrigation is represented by the SAR, the dissolved organic content (DOC), and the residual sodium carbonate (RSC) (Hopkins et al., 2007), the latter evaluated as follows:

$$RSC = (\text{HCO}_3^- + \text{CO}_3^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+}) \quad (\text{A1})$$

RSC provides information about the potential of sodicity hazard. When RSC is positive, calcite is predicted to precipitate, lowering the Ca concentration in the soil solution and increasing SAR (Sposito, 2008). The SAR, DOC, and RSC values of the irrigation water along the irrigation season of 2016 are depicted in Figure A1. The effect of mixing on the irrigation water is evident, especially in terms of SAR. WW is characterized by an RSC that indicates the highest sodicity potential. This decreases gradually with the mixing, to be the lowest for FW. It is interesting to note the large variability in irrigation water qualities during the season. RSC for WW increased gradually during the season and reached the maximum value in August.

Data Availability Statement

The data from the experiments can be found in the Mendeley repository (<https://data.mendeley.com/datasets/5sm6tj3zgzk/draft?a=aba016b7-af0f-4c85-bace-28546032af6d>).

- Basile, A., Buttafuoco, G., Mele, G., & Tedeschi, A. (2012). Complementary techniques to assess physical properties of a fine soil irrigated with saline water. *Environment and Earth Science*, 66(7), 1797–1807. <https://doi.org/10.1007/s12665-011-1404-2>
- Bresler, E., McNeal, B. L., & Carter, D. L. (1982). *Saline and sodic soils: Principles-dynamics-modeling*. Adv. Agric. Sci. 10. Berlin: Springer-Verlag. <https://doi.org/10.1007/978-3-642-68324-4>
- Brutsaert, W. (1977). Vertical infiltration in dry soil. *Water Resources Research*, 13(2), 363–368. <https://doi.org/10.1029/WR013i002p00363>
- Coppola, A., Santini, A., Botti, P., Vacca, S., Comegna, V., & Severino, G. (2004). Methodological approach for evaluating the response of soil hydrological behaviour to irrigation with treated municipal wastewater. *Journal of Hydrology*, 292(1-4), 114–134. <https://doi.org/10.1016/j.jhydrol.2003.12.028>
- Environment, UN (2019). *Global Environment Outlook—GEO-6: Healthy planet, healthy people*. Nairobi. <https://doi.org/10.1017/9781108627146>
- Falkenmark, M., & Rockström, J. (2006). The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of Water Resources Planning and Management*, 132(3), 129–132. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2006\)132:3\(129\)](https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129))
- Famiglietti, J. S. (2014). The global groundwater crisis. *Nature Climate Change*, 4(11), 945–948. <https://doi.org/10.1038/nclimate2425>
- Feddes, R. A., Kowalik, P. J., & Zaradny, H. (1978). *Simulation of field water use and crop yield*, Simulation Monographs. Wageningen, The Netherlands: Pudoc.
- Frenkel, H., Fey, M. V., & Levy, G. J. (1992). Organic and inorganic anion effects on reference and soil clay critical flocculation concentration. *Soil Science Society of America Journal*, 56, 1762–1766.
- Gleick, P. H. (2000). The changing water paradigm, A look at the twenty-first century water resources development. *Water International*, 25, 127–138.
- Grant, S. B., Saphores, J. D., Feldman, D. L., Hamilton, A. J., Fletcher, T. D., Cook, P. L. M., et al. (2012). Taking the “waste” out of “wastewater” for human water security and ecosystem sustainability. *Science*, 337(6095), 681–686. <https://doi.org/10.1126/science.1216852>
- Grattan, S. R., Diaz, F. J., Pedrero, F., & Vivaldi, G. A. (2015). Assessing the suitability of saline wastewaters for irrigation of *Citrus* spp.: Emphasis on boron and specific-ion interactions. *Agricultural Water Management*, 157, 48–58. <https://doi.org/10.1016/j.agwat.2015.01.002>
- Halliwell, D. J., Barlow, K. M., & Nash, D. M. (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. <https://doi.org/10.1071/SR00047>
- Hanjra, M. A., Blackwell, J., Carr, G., Zhang, F., & Jackson, T. M. (2012). Wastewater irrigation and environmental health: Implications for water governance and public policy. *International Journal of Hygiene and Environmental Health*, 215(3), 255–269. <https://doi.org/10.1016/j.ijheh.2011.10.003>
- Hassena, A. B., Zouari, M., Trabelsi, L., Khabou, W., & Zouari, N. (2018). Physiological improvements of young olive tree (*Olea europaea* L. cv. *Chetoui*) under short-term irrigation with treated wastewater. *Agricultural Water Management*, 207, 53–58. <https://doi.org/10.1016/j.agwat.2018.05.024>
- Hopkins, B. G., Horneck, D. A., Stevens, R. G., Ellsworth, J. W., & Sullivan, D. M. (2007). *Managing irrigation water quality for crop production in the Pacific Northwest*. A Pacific Northwest Extension Publication. Oregon State University, University of Idaho, Washington State University.
- Lado, M., Bar-Tal, A., Azenkot, A., Assouline, S., Ravina, I., Erner, Y., et al. (2012). Changes in chemical properties of semi-arid soils under long-term secondary treated wastewater irrigation. *Soil Science Society of America Journal*, 76(4), 1358–1369. <https://doi.org/10.2136/sssaj2011.0230>
- Lado, M., Ben-Hur, M., & Assouline, S. (2005). Effects of long-term effluent irrigation on seal formation, infiltration and interrill erosion. *Soil Science Society of America Journal*, 69(5), 1432–1439. <https://doi.org/10.2136/sssaj2004.0387>
- Levy, G. J., & Assouline, S. (2011). Chapter 9: Physical aspects. In G. J. Levy, et al. (Eds.), *Use of treated waste water in agriculture: Impacts on the soil environment and crops* (pp. 1–306). Oxford, UK: Wiley-Blackwell.
- Levy, G. J., Fine, P., Goldstein, D., Azenkot, A., Zilberman, A., Chazan, A., & Grinhut, T. (2014). Long term irrigation with treated wastewater (TWW) and soil sodification. *Biosystems Engineering*, 128, 4–10. <https://doi.org/10.1016/j.biosystemseng.2014.05.004>
- Methods of Soil Analysis (1996). *Soil Science Society of America Book Series*. Madison, WI: ASA and SSSA.
- Minhas, P. S., Yadav, R. K., Lal, K., & Chaturvedi, R. K. (2015). Effect of long-term irrigation with wastewater on growth, biomass production and water use by Eucalyptus (*Eucalyptus tereticornis* Sm.) planted at variable stocking density. *Agricultural Water Management*, 152, 151–160. <https://doi.org/10.1016/j.agwat.2015.01.009>
- Morgan, K. T., Wheaton, T. A., Parsons, L. R., & Castle, W. S. (2008). Effects of reclaimed municipal wastewater on horticultural characteristics, fruit quality, and soil and leaf mineral concentration of citrus. *Horticultural Science*, 43(2), 459–464. <https://doi.org/10.21273/HORTSCI.43.2.459>
- Mualem, Y. (1976). A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12(3), 513–522. <https://doi.org/10.1029/WR012i003p00513>
- Noshadi, I., Salahi, A., Hemmati, M., Rekabdar, F., & Mohammadi, T. (2013). Experimental and ANFIS modelling for fouling analysis of oily wastewater treatment using ultrafiltration. *Asia-Pacific Journal of Chemical Engineering*, 8(4), 527–538. <https://doi.org/10.1002/apj.1691>
- Noy, M. (2006). *Recommendations for growing of avocado*. Israel: Extension Service, Ministry of Agriculture.
- Parsons, L. R., Wheaton, T. A., & Castle, W. S. (2001). High application rates of reclaimed water benefit citrus tree growth and fruit production. *Horticultural Science*, 36(7), 1273–1277. <https://doi.org/10.21273/HORTSCI.36.7.1273>
- Paudel, I., Cohen, S., Shaviv, A., Bar-Tal, A., Bernstein, N., Heuer, B., & Ephrath, J. (2016). Impact of treated wastewater on growth, respiration and hydraulic conductivity of citrus root systems in light and heavy soils. *Tree Physiology*, 36(6), 770–785. <https://doi.org/10.1093/treephys/tpw013>
- Phogat, V. D., Mallants, D., Cox, J. W., Šimůnek, J., Oliver, D. P., Pitt, T., & Petrie, P. R. (2020). Impact of long-term recycled water irrigation on crop yield and soil chemical properties. *Agricultural Water Management*, 237, 106167. <https://doi.org/10.1016/j.agwat.2020.106167>
- Qian, Y., & Lin, Y. (2019). Comparison of soil chemical properties prior to and five to eleven years after recycled water irrigation. *Journal of Environmental Quality*, 48(6), 1758–1765. <https://doi.org/10.2134/jeq2019.03.0132>
- Quirk, J. P., & Schofield, R. K. (1955). The effect of electrolyte concentration on soil permeability. *Journal of Soil Science*, 6(2), 163–178. <https://doi.org/10.1111/j.1365-2389.1955.tb00841.x>
- Rengasamy, P., & Olsson, K. A. (1993). Irrigation and sodicity. *Australian Journal of Soil Research*, 31(6), 821–837. <https://doi.org/10.1071/SR9930821>

- Richards, L. A. (1931). Capillary conduction of liquids through porous medium. *Physics*, *1*(5), 318–333. <https://doi.org/10.1063/1.1745010>
- Rogowski, A. S. (1971). Watershed physics: Model of soil moisture characteristics. *Water Resources Research*, *7*(6), 1575–1582. <https://doi.org/10.1029/WR007i006p01575>
- Russo, D., & Bresler, E. (1977a). Effect of mixed Na-Ca solutions on the hydraulic properties of unsaturated soils. *Soil Science Society of America Journal*, *41*, 714–717.
- Russo, D., & Bresler, E. (1977b). Analysis of the saturated-unsaturated hydraulic conductivity in a mixed Na-Ca soil system. *Soil Science Society of America Journal*, *41*(4), 706–710. <https://doi.org/10.2136/sssaj1977.03615995004100040017x>
- Russo, D., Lafer, A., Silber, A., & Assouline, S. (2009). Water uptake, active root volume, and solute leaching under drip irrigation: A numerical study. *Water Resources Research*, *45*, W12413. <https://doi.org/10.1029/2009WR008015>
- Selker, J. S., & Assouline, S. (2017). An explicit, parsimonious, and accurate estimate for ponded infiltration into soils using the Green and Ampt approach. *Water Resources Research*, *53*, 7481–7487. <https://doi.org/10.1002/2017WR021020>
- Silber, A., Naor, A., Cohen, H., Bar-Noy, Y., Yechieli, N., Levi, M., et al. (2019). Irrigation of 'Hass' avocado: Effect of constant vs. intermittent water stress on yield. *Irrigation Science*, *37*(4), 451–460. <https://doi.org/10.1007/s00271-019-00622-w>
- Silber, A., Naor, A., Israeli, Y., & Assouline, S. (2013). Combined effect of irrigation regime and fruit load on the patterns of trunk-diameter variation of 'Hass' avocado at different phenological periods. *Agricultural Water Management*, *129*, 87–94. <https://doi.org/10.1016/j.agwat.2013.07.015>
- Šimůnek, J., van Genuchten, M. T., & Šejna, M. (2005). *The HYDRUS-1D software package for simulating the movement of water, heat, and multiple solutes in variably saturated media, version 3.0, HYDRUS Software Series* (Vol. 1, pp. 1–270). Riverside, Riverside: Department of Environmental Science, University of California.
- Šimůnek, J., van Genuchten, M. T., & Šejna, M. (2016). Recent developments and applications of the HYDRUS computer software packages. *Vadose Zone Journal*, *15*, 25.
- Sposito, G. (2008). *The chemistry of soils*. New York: Oxford University Press.
- Sposito, G., Oster, J. D., Smith, C. J., & Assouline, S. (2016). Assessing soil permeability impacts from irrigation with marginal-quality waters. *CAB Reviews*, *11*(15), 1–7. <https://doi.org/10.1079/PAVSNRR201611015>
- Tal, A. (2006). Seeking sustainability: Israel's evolving water management strategy. *Science*, *313*(5790), 1081–1084. <https://doi.org/10.1126/science.1126011>
- Tarchitzky, J., Chen, Y., & Banin, A. (1993). Humic substances and pH effects on sodium and calcium montmorillonite flocculation and dispersion. *Soil Science Society of America Journal*, *52*, 1449–1452.
- Tarchitzky, J., Golobati, Y., Keren, R., & Chen, Y. (1999). Wastewater effects on montmorillonite suspensions and hydraulic properties of sandy soil. *Soil Science Society of America Journal*, *63*(3), 554–560. <https://doi.org/10.2136/sssaj1999.03615995006300030018x>
- Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(50), 20,260–20,264. <https://doi.org/10.1073/pnas.1116437108>
- Tuller, M., & Or, D. (2005). Water films and scaling of soil characteristic curves at low water contents. *Water Resources Research*, *41*, W09403. <https://doi.org/10.1029/2005WR004142>
- van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Science Society of America Journal*, *44*(5), 892–898. <https://doi.org/10.2136/sssaj1980.03615995004400050002x>