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ORIGINAL PAPER

Impact of treated wastewater irrigation on water repellency of Mediterranean soils

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Abstract Irrigation with treated wastewater (TWW) is gaining importance due to declining water availability in dry regions. TWW irrigation has various potential adverse effects on soil quality such as hydrophobic effects on soil surfaces, reducing initial sorptivity and promoting the formation of preferential flow paths. In May and June 2010, in situ infiltration measurements using mini disk tension infiltrometer were deployed in five different orchard plots in Israel to assess the impact of different irrigation water qualities on the soil water repellency index *R*. In most plantations, long-term test sites were accessed to compare adjacent plots irrigated with fresh water (FW) or TWW. Topsoil samples were analyzed for selected physical and chemical characteristics. The mean *R* values increased at all TWW sites, from +15 up to +55 % compared with FW sites. The water drop penetration time (WDPT) increased up to 30 fold at three of five TWW sites compared with FW sites. Subsequent *U* tests and multilevel analysis indicated an impact of the type of irrigation water on *R* and WDPT. Moreover, soil electrical conductivity and exchangeable sodium percentage were consistently higher at all TWW sites. These results show that irrigation water quality clearly influences physical and chemical properties of the soil.

Introduction

Treated wastewater (TWW) is considered as a reliable source of water for agricultural irrigation because of its constant availability throughout the year (Friedler 2001). Its importance will continue to increase with reduced freshwater (FW) availability and rising severe water stresses for the eastern Mediterranean. This region will be under considerable stress due to enhanced water withdrawal, higher annual mean temperatures and decreased annual precipitation because of climatic change (Smiatek et al. 2011; Milano et al. 2012). TWW use in agriculture in FW scarce regions can help to alleviate the pressure on available natural water resources, as it allows higher quality water to be available for other purposes. Israel is considered to be world's leading in using TWW for agricultural irrigation (Hamilton et al. 2007). According to the Israel Water Authority (2012), 37.7 % of Israel's FW consumption in 2010 (1,259.7 hm^3 in total) was used for agricultural purposes and 54.7 % for domestic purposes. Within the total agricultural water consumption for Israel in 2010 (1,099.8 hm^3), FW makes up 43.2 %, TWW 37.7 %. Additional water resources for irrigation were saline water (SW) (15.0 %) and flood water (4.1 %). As Israel's national policy calls for further gradual replacement of FW, higher TWW use rates are expected with improved standards and regulations for TWW reuse in irrigation to be enforced (Inbar 2007; Provizor 2009). Until 2020, it is expected that almost all municipal wastewater will be treated and reused, mainly for agricultural irrigation (Brenner 2012).

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Treated wastewater contains higher concentrations of nutrients (e.g. N, P, K), but also of soluble salts (which contain e.g., Cl, Na, Ca, Mg), organic substances and inorganic and organic pollutants compared with FW (Feigin et al. 1991). TWW irrigation was found to have various side effects on the environment, like enhanced levels of soil salinity, sodicity and nitrate leaching to the groundwater (Bond 1998).

Schacht et al. (2011) defined the current most important soil-related agricultural risks associated with TWW irrigation in the Jordan River region and pointed out that these environmental risks mainly depend on the local soil properties and the TWW quality. TWW quality depends on its original water source, the "pickup" during usage, treatment technology and dilution of the TWW after treatment; thus, it is regionally variable. One of the described risks associated with using TWW is hydrophobicity, measured by soil water repellency (SWR). Tarchitzky et al. (2007) observed narrower subsurface wetting zones in TWW-irrigated soils. The resulting undesired non-continuous wetting conditions along tree rows have prompted research toward water repellency in Israel (Levy and Assouline 2011). Reasons for concern are given, as increased rates of SWR, and thereby decreased rates of water infiltration, could lead to greater runoff, less water retention and the development of preferential flow paths. This has the potential to reduce soil water efficiency and impose severe implications to the environment and food security (Hallett et al. 2011).

Tarchitzky et al. (2007) identified changes in water distribution patterns in TWW-irrigated orchards in Israel, discussed the occurrence of soil water repellency (SWR) on TWW-irrigated sites and linked it to the differences in the soil organic carbon (SOC) characteristics of the topsoil. Nadav et al. (2013a, b) proceeded with this evaluation, characterization and quantification of SWR following irrigation with TWW. Using lysimeters consisting of different soils and applying different water qualities, the effects of irrigation water quality on SWR were found to be dependent on the specific surface area of the respective soil texture (Nadav et al. 2013a). In a further field study at a test site within an avocado plantation, higher SWR and different soil wetting behavior were reported in TWW-irrigated soils compared with FW-irrigated soils (Nadav et al. 2013b). Furthermore, differences in quantity and quality of SOC between the two treatments were observed between treatments (Nadav et al. 2013b). Assouline and Narkis (2011) took soil samples from the same test sites, and their results proved differences in soil chemical and hydrological properties between the treatments.

Soil water repellency is a wide spread phenomenon which has been described in various regions, climates, soils and land uses (Doerr et al. 2000; Ritsema and Dekker 2003). It is commonly caused by organic compounds derived from living or decomposing plants or microorganisms which can coat the mineral surfaces and aggregates. Because of this, coarse-textured soils tend to be more susceptible to SWR due to their lower specific surface area (Doerr et al. 2000). However, severely repellent grassland soils with clay contents >55 % have also been reported (Dekker and Ritsema 1996). SWR exhibits a nonlinear behavior with soil water content. In general, soils are wettable close to saturation, becoming increasingly repellent up to a maximum as the soil water content decreases. From this maximum onward, repellency diminishes monotonically or rises again to a second local or absolute maximum nearby the dried soil state (de Jonge et al. 1999; Goebel et al. 2004; Regalado and Ritter 2005).

One of the common methods for measuring the persistence of SWR in the field is the 'water drop penetration time' (WDPT) test, introduced by Wander (1949) and Krammes and Debano (1965). It consists of placing one drop of distilled water on the soil surface and measuring the time for its complete infiltration in seconds (Letey 1969). As hydrophobicity decreases with time, the delay in droplet infiltration reflects the time the surface tension of the soil remains higher than that of the droplet and how long hydrophobicity persists (Doerr 1998). If the soil is perfectly wettable, the droplet would infiltrate immediately and the soil's WDPT would be 0. According to Dekker et al. (2009), the WDPT test is the only suitable test for assessing the persistence of SWR on field-moist samples at present due to unreliable results of other methods.

Lichner et al. (2007) adapted the method introduced by Tillman et al. (1989) and estimated the soil sorptivity for water and ethanol to define the so-called soil water repellency index (R) from the cumulative infiltration versus time relationship measured with a Decagon mini disk infiltrometer (MDI, Decagon Devices, Inc.). Hunter et al. (2011) compared a MDI with a 4.5-cm-diameter disk and the standard tension disk infiltrometer with a 20-cm-diameter disk and found that the mini disk infiltrometer is well suited for in situ measurements of the degree of soil water repellency. Wallis et al. (1991) explained that the ratio of soil sorptivities using ethanol (S_e), and water (S_w), expressed as the repellency index $R = 1.95\ S_e/S_w$, is more sensitive for soil water repellency testing than the WDPT test. Clothier et al. (2000) stated that R would seem to be better to describe the degree of repellency. Lichner et al. (2007) showed that the adapted method was well suited to estimate R in the field for R values from interval 0.28–360. The values of R are open for interpretation regarding hydrophobicity effects on soil surfaces. A perfectly wettable soil has an R value of 1 (Hallett and Young 1999). Higher R values generally indicate a higher SWR.

As Graber et al. (2006) have shown, the use of disturbed soil samples for the evaluation of SWR is not representative

Table 1 Properties of the different irrigation waters at the five test sites

Test site	AK		HM		RP		YO		NE	
Crop	Avocado		Avocado		Pear		Mango		Date	
Treatment	FW	TWW	FW	TWW	FW	TWW	FW	TWW	SW	TWW
Sampling date	17.05.2010		2010		2010	2006–2010	2010		20.05.2010	
EC (mS cm^{-1})	0.98	1.59	0.77–0.90	2.4–2.8	0.61	1.31	0.49	0.88	3.02	2.69
SAR	0.74	3.23	0.3–0.5	1.3–1.5	0.62	4.31	0.90	3.29	7.42	5.02
pH	6.9	8.2	nd	nd	7.2	7.9	6.5	8.4	7.4	7.3

FW freshwater, *TWW*-treated wastewater, *SW* saline water, *EC* electrical conductivity, *SAR* sodium adsorption ratio, *nd* not determined

of measurements for undisturbed soil samples and that the extent of deviation in absolute WDPT values is very large and unpredictable. As in most SWR studies, the use of disturbed samples is common practice (Levy and Assouline 2011) and there is a need to improve methods for the estimation of SWR under undisturbed conditions in the field.

The objective of this study was to assess the impact of TWW irrigation compared with FW irrigation on soil water repellency and chemical properties in orchards in Israel. For this purpose, the method of Lichner et al. (2007) was used. Hence, long-time agricultural test sites were accessed and soil properties (i.e., soil sorptivity, water repellency index *R* and WDPT) were measured.

Materials and methods

Description of test sites

The test sites were located in the central and northern districts of Israel. Except for the orchard Neve Eitan, all test sites were situated in long-term agricultural experimental orchards, which provided replicate plots irrigated with either FW or secondary or tertiary TWW. The test site Neve Eitan is a date plantation irrigated either with saline spring water (SW) or primary TWW. At all test sites, irrigation was ceased several days before conducting of the measurements in order to achieve similar soil water contents. Irrigation water properties were provided by the operators of the orchards. For the site Neve Eitan, their analyses were commissioned (Table 1). On all test sites, TWW shows higher electrical conductivity (EC), higher sodium adsorption ratio (SAR) and higher pH compared with FW. At the orchard Neve Eitan, SW exhibits higher EC, SAR and pH values than TWW. Soil types are described based on the Israeli soil classification (Dan et al. 1972) and translated into the FAO/WRB classification according to Krasilnikov and Arnold (2009).

The test site Akko (AK) is located in an avocado plantation east of Akko city (32°55′51″N, 35°06′19″E). It is the same plantation in which the studies of Assouline and Narkis (2011) and Nadav et al. (2013b) were performed. The avocado trees were about 15 years old and planted on parallel mounds in rows. Within the experimental site, the tree rows are irrigated with TWW or FW by drip irrigation systems at 2 mm day^{-1} in spring and up to 4 mm day^{-1} in summer. The litter was removed regularly. The clayey soil was classified as an alluvial brown Grumusol (WRB: Vertisol). The infiltration tests were carried out in the area of the adjacent tree rows 15 (FW) and 16 (TWW). The different treated and observed spots were approximately 20–40 m apart. Several drip irrigation spots in-between the trees were dried out either using special cramps to seal the drip irrigation holes or by moving the irrigation tubes aside. The topsoil of the spots was allowed to dry for six subsequent days before the measurements were taken.

The test site Ha Ma´apil (HM) is located in an avocado plantation close to the equally called kibbutz (32°22′52″N, 34°58′34″E). The test site, comparing FW and TWW irrigation, was established with planted trees in 1991. The litter was not removed regularly and accumulated up to 15 cm in depth. Depending on the given rainfall, the irrigation season starts in March at a rate of 3–4 mm day^{-1} of water applied by drip irrigation. The soil type is Hamra, a red sandy soil (WRB: Chromic Luvisol). The measurements were taken 7 days after ceasing irrigation, allowing the top soil to dry. The different test spots were approximately 40 m apart. The litter was carefully removed by hand, and the mineral soil surface was cleaned using a hand broom.

The test site in the pear plantation close to Rosh Pina (RP, 32°57′42″N, 35°33′47″E) was established in 2004 to evaluate the effects of the change in irrigation water on the soil and the trees due to the construction of a new wastewater treatment plant close to the plantation. Except for the FW section of the test site, the whole plantation was henceforth irrigated with TWW. The pear trees in this plot were about 40 years old and are planted on mounds. The litter of the trees is removed regularly. In the dry season, the trees were irrigated 2–3 times a day with a rate of 7–9 mm day^{-1}. The total annual irrigation amount is about 750 mm. The clayey soil was classified as an alluvial brown Grumusol (WRB: Vertisol). The infiltration tests were conducted 6 days after ceasing irrigation by blocking the drip irrigation holes with special cramps or aside movement of the drip irrigation tubes. The different observation spots were approximately 10–12 m apart.

The mango plantation Yonatan (YO) is located in-between the Sea of Galilee and Ma´ale Gamla (32°53′55″N, 35°39′51″E). The test site was established in 1998. The clayey soil, a Basaltic Protogrumusol (WRB: Vertic Leptosol), is relatively shallow with a depth of soil development of 0.6–0.8 m. The tests were conducted after 7 days of drying of the topsoil by putting the mini drip irrigation tubes aside. Shrinking of the soil led to small cracks of the topsoil at the dried plots. The different observed spots were approximately 10–15 m apart.

Five single test spots in three different date plantations close to the kibbutz Neve Eitan (32°29′32″N, 35°31′32″E) were chosen for performing the infiltration tests and are referred to in general as test site Neve Eitan (NE). The water used for irrigation was TWW from a settling pond close to the kibbutz and saline water (SW) from nearby springs. Three plots irrigated with SW were chosen in total (SW 1, SW 2 and SW 3). Two of them were situated in a plantation approximately 700 m west from the kibbutz (SW 1, SW 3) and one at the kibbutz's northern boundary (SW 2). The two TWW-irrigated plots were in the date plantation at the kibbutz's western boundary (TWW 1, TWW 2). The maximal distance between two observation spots (SW 3–TWW 1) was 1.7 km. Irrigation with TWW was established about 20 years before. The age of the date trees varied between 15 and 40 years. The soils were characterized as calcareous serozem (WRB: Hypercalcic Calcisol). The date trees are irrigated with mini sprinklers. Water samples were taken directly from the sprinklers and were subsequently analyzed. The test spots were chosen in the area wetted by the mini sprinklers. The sites were carefully cleaned to avoid disturbances to the soil surface. The infiltration measurements were taken at least 6 days after translocation of the mini sprinklers to the other side of the tree, opposing and not affecting the measurement plot itself.

Measurement of repellency index with the mini disk infiltrometer

The MDI consists of a polycarbonate tube and has two chambers: a water reservoir and a bubble chamber. Both chambers are connected via a Mariotte tube, which provides a constant water pressure head for different suction rates (0.5–6 cm). The bottom elastomer of the MDI contains a porous sintered steel disk. After placing the filled tube on the soil, surface water infiltrates into the soil according to its sorptivity and hydraulic conductivity. For this study, a pressure head of −2 cm was chosen according to Decagon Devices Inc. (2012).

As it is known that SWR varies with soil moisture, it was attempted to minimize the uneven effect of different soil water contents of the particular test sites on the MDI measurements and the resulting R values by homogenizing the location preconditions. To achieve this homogeneity, irrigation was ceased or the irrigation equipment within each test site spots was set aside at least 5 days before the measurements, so that the single spots could air dry. No rainfall events occurred during the whole test period. All single measurements at a test site were taken on the same day. Only undisturbed spots were chosen. Overlying leaves or loose plant residues were removed, but no potential soil crusts were harmed. To reduce the influence of spatial heterogeneity of soil properties, closely neighboring spots were compared. For that, the MDI measurements were collected in at least seven pairwise arrangements within every test site and treatment. In each repetition, a pair of MDI was used, filled either with tap water or ethanol. The pair was placed simultaneously on the soil surface approximately 20 cm apart; as preliminary tests showed that this spacing was sufficient to ensure no overlapping of the particular subsurface wetting zones. On uneven surfaces, a thin layer of medium-textured, non-hydrophobic sand was applied to ensure good contact between the MDI and the soil surface. During the measurement, the volume of the water in the reservoir chamber was noted in regular intervals every 15 s. Only readings from 0 to 180 s were used for the determination of the soil sorptivity for water (S_w) and ethanol (S_e) in order to exclude time dependent drops in repellency observed by many researchers in infiltration studies (Clothier et al. 2000; Hallett et al. 2004).

The S_w and S_e values were estimated from the linear trend line of the plot of the values of cumulative infiltration (I) versus the square root of time ($t^{1/2}$) (Clothier et al. 2000). The R value was computed from each MDI measurement pair as described by Wallis et al. (1991) using the equation:

$$R = 1.95\,(S_e/S_w) \quad (1)$$

where the constant 1.95 equates the differences in surface tension and viscosity between ethanol and water (Hallett et al. 2004).

WDPT tests

Concomitantly to the estimation of R, the WDPT test was conducted with at least seven replicate measurements at each test site and treatment using a Gilson Micropipette, applying a drop of 60 µl distilled water on the soil surface and recording the time for the droplet to penetrate completely.

Analysis of soil properties

Composite samples were taken from the top soil at all test sites and particular treatments from a depth of 0–10 cm

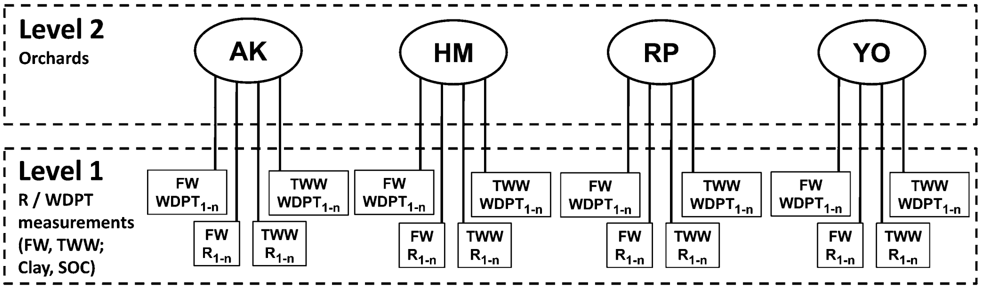

Fig. 1 Sketch of the two-level linear multilevel analysis model. The *first level* are the particular measurements (*R*/WDPT), the *second level* the four orchards (*FW* freshwater, *TWW*-treated wastewater, *R* repellency index, *WDPT* water drop penetration time, *SOC* soil organic carbon)

using a gouge auger. The samples were air-dried after sampling and sieved to ≤2 mm. The soil particle size distribution was determined by sieving and sedimentation (ISO 11277: 1998) with the exception of not degrading carbonates. Gravimetric water content (WC) was calculated from cores taken with steel sample rings (0–5 cm) concurrent to the respective MDI measurements by weighting the fresh and oven-dried cores (105 °C for 24 h). Total carbon and nitrogen content was quantified using a C/N-Analyzer (Elementar Vario EL). $CaCO_3$ content was determined by measuring the release of CO_2 after H_3PO_4 addition using a DIMATOC 2000 C-Analyzer (Dimatec, Germany). Exchangeable sodium percentage (ESP) was measured and calculated from the SAR of the saturated soil-paste extract after Rhoades and Miyamoto (1990) and U.S. Salinity Laboratory Staff (1954). Soil salinity was determined as the electrical conductivity at 25 °C in the saturated paste extract (EC_e).

Statistical analysis

The mean and standard deviation of the *R* index and the WDPT measures were calculated for every test site. To check for differences between irrigation water types, the Mann–Whitney *U* test for independent samples was conducted for each of the two parameters *R* and WDPT for every orchard. For the orchards AK, HM, RP and YO, the *U* test was calculated for FW irrigation versus TWW irrigation. For the orchard NE, differences between SW and TWW irrigation were tested.

Since the influencing factors on *R* and WDPT might be complex, a multivariate regression model was chosen to analyze multiple effects on the outcome measures. Because of the nested and hierarchical data structure, a linear multilevel model was chosen. The single observations are nested within the test sites; the single observations in one orchard are probably more alike than observations between orchards (Schielzeth and Nakagawa 2013). Multilevel modeling gives the opportunity to analyze hierarchical data and is described in more detail elsewhere (Goldstein 1987; Snijders and Bosker 2012). Multilevel models have been mostly applied in social sciences and health research, but have received growing popularity in geography and environmental sciences (e.g. Neumann et al. 2011). For this paper, a two-level linear model with random intercept was chosen for the comparison of the four FW/TWW-irrigated orchards. The first level is the particular measurements (94 × *R* or 165 × WDPT, respectively), the second level the four orchards (Fig. 1). For each outcome, the first model only measures the impact of irrigation. The model follows the equation:

$$Y_{ij} = \beta_{0j} + \beta_{1j}x_{ij} + \beta_2 z_j + r_{ij} \tag{2}$$

with β_0 as the intercept, β_1 as the coefficient of x (the level 1 measurements) and β_2 as the coefficient for the orchard level z. r is the residuals for both levels (Snijders and Boskers 2012).

Since a random intercept model is analyzed, the β_0 can be expressed as:

$$\beta_{0j} = y_{00} + U_{0j} \tag{3}$$

with y_{00} as the average intercept and U_{0j} as the group-dependent effects (Snijders and Boskers 2012). In this case, U_{0j} stand for the orchard deviation on *R* and WDPT. In an additional second multivariate model, it was also adjusted for soil parameters to be known to affect SWR (SOC and clay percentage). Through this, the characteristics of the orchards and their influence on the irrigation method are taken into account.

Since the test site NE had different irrigation patterns than the other observation sites, the site was not included in the multilevel analysis. Due to the low number of total observations within NE, it was not feasible to perform a separate multivariate regression only for NE.

Because of the relatively low total number of observations per site, the level of significance (p) for all analyses was set to $p < 0.10$.

All statistical analyses were conducted with Microsoft Excel 2007, SPSS (version 20) and SAS (release 9.2).

Table 2 Selected physical and chemical properties of the soils at the five test sites and treatments (FW freshwater, TWW-treated wastewater, SW saline water)

Soil property	Test sites and treatments												
	AK		HM		RP		YO		NE				
	FW	TWW	FW	TWW	FW	TWW	FW	TWW	SW 1	SW 2	SW 3	TWW 1	TWW 2
WC (%)	14.6	14.4	5.0	8.0	20	23.2	28.8	31.1	21.8	13.2	17.7	23.5	20.1
Sand (%)	11.3	12	76.5	83.5	2.9	2.1	6.1	5	28.2	20.3	28.2[a]	21.2	13.7
Clay (%)	50.7	47.3	15	7.7	53.3	55.5	59.2	56.7	26.3	33.6	26.3[a]	41.3	33.6
$CaCO_3$ (%)	1.8	2.4	0.1	0.9	0.9	0.9	0.4	2.9	71.8	64.2	70.5	55.6	55.8
SOC (%)	1.15	1.27	1.12	1.32	1.28	0.82	2.16	1.8	2.16	2.03	2.33	1.94	2.03
N (%)	0.14	0.18	0.12	0.15	0.14	0.1	0.24	0.21	0.27	0.25	0.25	0.37	0.27
pH	7.7	7.8	7.0	7.4	7.6	7.7	7.3	7.7	7.7	7.7	7.8	7.4	7.6
EC_e (mS cm^{-1})	1.73	3.27	2.53	4.41	0.49	0.95	0.82	1.0	2.76	2.83	3.91	2.99	1.85
ESP	2.09	16.2	2.82	14.46	1.4	15.6	2.3	9.19	14.35	15.92	15.75	10.9	12.02

For AK, HM, RP and YO, values are from composite bulk samples taken at the sites. For NE, data from the five plots are given separately

WC refers to the soil water content of the particular test site at the time of test procedure

WC water content, *$CaCO_3$* calcium carbonate, *SOC* soil organic carbon, *N* nitrogen, *EC_e* electrical conductivity of the saturated paste extract, *ESP* exchangeable sodium percentage

[a] SW 3 is in the same plantation as SW 1. Therefore, soil texture for SW3 was not determined separately

Results

Soil properties

For all the studied test sites, allowing the topsoil to dry led to homogeneous water contents. The differences in water contents within the TWW and FW treatments were not relevant (between 0.2 and 3.2 %). At the test site NE, differences were higher, but below 10.5 %. However, heterogeneity between the test sites textures was observed. AK, RP and YO had clay contents >45 %, HM in contrast had a sand percentage >75 %. All aforementioned test sites had $CaCO_3$ contents <3 %. In contrast to that, NE with its carbonate content >55 % exhibited very different properties. These very high carbonate contents constitute highly to the soils composition itself; thus, dissolving the carbonates prior to texture analysis would have led to unrealistic results. Selected soil properties for all test sites and plots are given in Table 2.

The distribution of SOC and N contents at the FW and TWW-irrigated orchards was uneven and did not show any general trend, although the TWW plots showed slightly higher pH values. Related to that, the $CaCO_3$ contents were similar or higher at the TWW-irrigated sites. On the TWW sites, the electrical conductivity of the saturated paste extract (EC_e) was increased 1.2–1.9 times that observed in the FW-irrigated plots. In addition, the exchangeable sodium percentage (ESP) values in the TWW-irrigated plots reached 4–11 times the level of the FW plots.

R and WDPT

The *R* and WDPT observations revealed differences between test sites and treatments. A Mann–Whitney *U* test for independent samples was conducted for each orchard comparing *R* and the WDPT between FW and TWW treatments to determine the significance of these differences (Table 3). The same was done for NE separately, comparing SW and TWW treatments. None of the four orchards that were irrigated with FW and TWW showed significant differences for *R*. However, an overall trend was visible, as for all orchards, the mean of *R* is higher in TWW sites compared with FW sites (test sites AK, HM, RP and YO) and in the TWW sites compared with SW sites in NE (Fig. 2). In contrast, WDPT showed not to be dependent on the type of irrigation water. For all orchards, except for AK, the WDPT differed significantly between plots irrigated with FW and TWW. But the effect was not consistent in its direction. While in HM and YO, the WDPT was significantly higher when irrigated with TWW (HM + 2,945 %; YO + 418 %), the orchard RP shows a reverse effect (−68.4 %). Here, the WDPT was higher in the plots irrigated with FW. As for AK, both treatments showed WDPT of 0. At NE, both *R* and WDPT were significantly correlated with the type of irrigation water. Both measures are higher at the TWW-irrigated sites compared with the SW sites (Table 3).

To check for correlations, WDPT was plotted against *R* for all test sites and treatments (Fig. 3). With the exceptions of AK and RP for reasons discussed above, it is visible that the TWW treatments showed higher *R* and WDPT values

Table 3 Means and standard deviation of repellency index (*R*) and water drop penetration time (WDPT) values for all orchards and treatments, comparing freshwater (FW) and treated wastewater (TWW) treatments (above) and saline water (SW) and TWW treatments at the test site NE (below)

Test site	*R*					WDPT				
	FW		TWW		*p*	FW		TWW		*p*
AK	2.08	±0.56	2.8	±1.44	0.456	0	–	0	–	–
HM	5.02	±1.73	7.78	±5.94	0.414	0.44	±1.01	13.4	±22.87	0.001
RP	1.54	±0.65	1.77	±0.70	0.721	0.79	±0.54	0.25	±0.45	0.011
YO	2.34	±1.11	2.85	±1.26	0.383	0.22	±0.44	1.14	±0.38	0.005
	SW		TWW		*p*	SW		TWW		*p*
NE	2.06	±0.98	7.12	±4.03	0.000	1.03	±1.64	8.52	±7.23	0.000

The *p* values are for *U* tests conducted

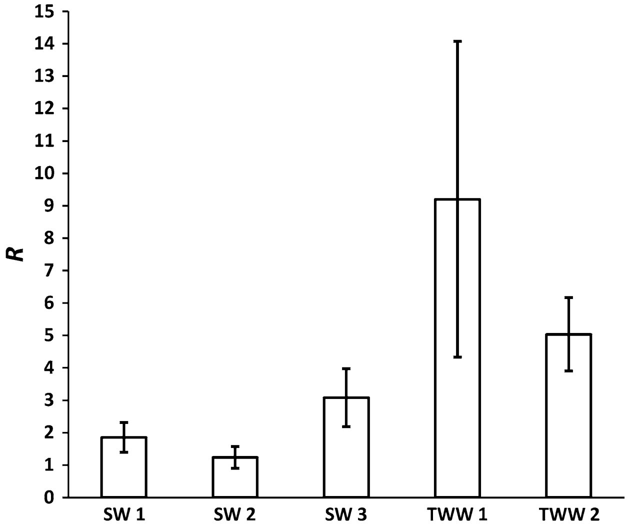

Fig. 2 Mean values of repellency indices (*R*) at the test site NE from plots irrigated with SW and TWW. *Error bars* show standard deviations for the seven replicate measurements

compared with the FW or SW treatments. However, no trend is visible.

Multilevel analysis

Since the standard deviations are high due to the small sample size per orchard and to account for the hierarchical data structure, a multivariate multilevel analysis was conducted to include all measurements in one model (Table 4). Through this, FW irrigation can be compared with TWW irrigation for all sites measurements. When all values are considered in one model, both *R* and WDPT are significantly dependent on the irrigation water type (Table 4, model 1). When irrigated with TWW, *R* is about 1.05 times higher than when irrigated with FW. The effect for WDPT is stronger, showing that TWW irrigation results in an almost three times higher WDPT than in places irrigated with FW.

Since the irrigation water type is not the only factor that might influence both *R* and WDPT, a multivariate multilevel model was conducted (Table 4, model 2). In this, certain soil properties known to affect SWR were included. As the WC was harmonized between irrigation types on all test sites as a condition of this study, this value was not included in the analysis. The second model accounts for the effect of SOC and clay content at each test site and treatment (see Table 2). Including these variables in the multilevel analysis with the irrigation water type gives the opportunity to simultaneously account for all factors while taking the local specifics of each orchard into account. This shows that the significant effect of the irrigation water type was no longer statistically significant. Both clay content and SOC show a strong correlation with *R*, and clay content also with WDPT (see Table 4). This correlation is strong enough that through the inclusion of those characteristics into the analysis, the irrigation water type does no longer have a significant influence on either outcome. When accounting for all attributes together, a positive significant effect is displayed on *R* for SOC content and a negative most significant effect on *R* and WDPT is obtained for clay; showing that a higher percentage of SOC results in higher *R* and a lower percentage of clay results in higher *R* and higher WDPT.

Discussion

The effect of TWW irrigation increasing SWR compared with FW irrigation was further supported by the results of this study, even when taking the spatial heterogeneity within the orchards into account, and agrees with previous studies by Tarchitzky et al. (2007) and Nadav et al. (2013b). Comparing the FW- and TWW-irrigated treatments, the irrigation water type seems to have an influence only on WDPT

Fig. 3 Relationship between water drop penetration time (WDPT) and repellency index (*R*) showing mean values and standard deviations

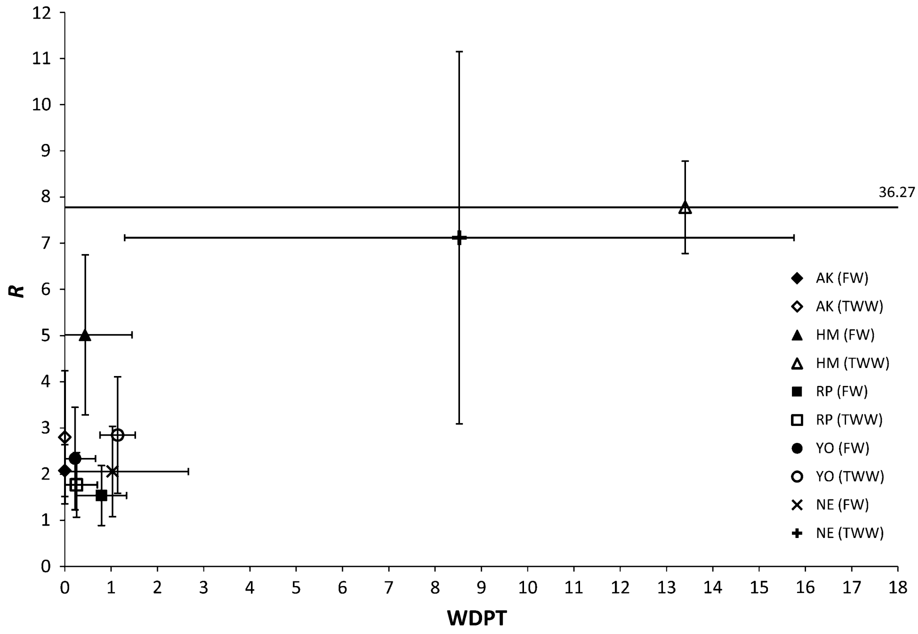

Table 4 Multilevel analysis of the impact of irrigation water type on *R* and WDPT for the freshwater (FW)- /treated wastewater (TWW)-irrigated test sites (model 1)

Effect	*R*		WDPT	
	Estimate	*p*	Estimate	*p*
Model 1				
TWW (FW)	1.046	0.0864	2.976	0.096
Res log-likelihood	270.9		757.3	
Model 2				
TWW (FW)	0.965	0.1078	2.674	0.140
SOC	1.442	0.0714	2.828	0.271
Clay	−0.105	<0.0001	−0.191	0.0002
Log-likelihood	266.0		747.5	

Model 2 also considers other relevant soil properties. The estimate states the degree of difference between exposure variables; *p* gives the error tolerance for the estimate

and not on *R*. Although the *U* tests revealed no significant differences between the FW and TWW treatments, the comparison of mean *R* values from the FW and TWW treatments and from the SW and TWW treatments at the same test sites show higher *R* values when irrigated with TWW. These findings should be re-evaluated with a higher number of measurements to improve statistical power for parametric tests. Also, while the effect of irrigation on the WDPT is significant throughout the orchards, the effect is contrasting to that found at the test site RP. All these results could point to a too small sample size for reliable results. Therefore, the multilevel analysis was conducted, resulting in the expected significant influence of TWW irrigation on higher values in both *R* and WDPT. However, when corrected for covariance with specific soil attributes, this effect is no longer visible. This can have various reasons. *R* might have been affected by TWW irrigation, but happened to be correlated with SOC and clay content even though they did not actively influence *R*. Maybe the chosen orchards were too diverse, so that no correlation could be seen. The effect could also be a result of a small sample size, either the measurements per orchard or the number of orchards. Or—interpreting the results directly—water repellency depends more on the soil attribute variation within the test sites than on the irrigation water type and quality, a result not found in previous studies that most often lacked to control for soil attributes.

The most pronounced differences in *R* and WDPT are seen for the site NE, which was irrigated with SW and TWW, reflected in the results of the *U* test shown in Table 3. Unfortunately, these results could not be tested in simultaneous control of the soil attributes due to multicollinearity. To prove the consistency of these results, even when controlled to other soil attributes, this should be tested in a more intense, single-site study.

The impact of TWW irrigation on the magnitude of the observed *R* and WDPT values itself might appear low. All WDPT values, even those for the TWW treatment, indicate wettable or only slightly water repellent conditions (Dekker and Ritsema 1994). The *R* values of this study were comparable to those reported by Hallett et al. (2001) from aggregates from a range of soil management practices in northern Europe and those given by Fischer et al. (2010) for biocrusts on sand dunes from Germany. Lichner et al. (2007) show much higher *R* values of up to 360 on sandy pine forest soils in Slovakia. Even in forest glade soils covered with biocrusts, Lichner et al. (2013) estimated *R* values of up to 140. It is noteworthy, that the highest *R* values from this study were measured on the most sandy test site in HM. This finding is in agreement with that of Doerr et al. (2000) that coarse-textured soils have higher susceptibility to develop water repellency. The shift to higher SWR when irrigating with TWW is associated with a reduced soil wetting behavior as well as enhanced preferential flow, which may increase leaching and reduce water use efficiency. In a region where water is scarce, especially the latter is essential to preserve.

Nadav et al. (2013b), working on adjacent plots of the test site AK, measured similar WDPT values for the FW sites, but observed WDPT values >60 s on TWW-irrigated plots. However, their measurements took place in August 2008, 2 months further into the irrigation season from the measurements of this study. It could be concluded that SWR had built up over the season, an effect also observed by others (Chan 1992; Dekker and Ritsema 1994; Greiffenhagen et al. 2006; Lemmnitz et al. 2008) and that WDPT values are thus greater than those reported in the present study.

Comparing the orchards individually, the influence of the irrigation water quality showed a positive trend, indicating that TWW irrigation induces higher SWR when looking at the means of *R* and WDPT. When controlling for impacts of irrigation on *R* and WDPT in a multilevel model, it was demonstrated that this effect might be masked by SWR influencing effects of organic matter and clay contents. Taking this into account, further studies are necessary using statistical multilevel analysis methods to investigate potential multicausal interrelationships of soil properties on SWR. Regarding this, laboratory studies for providing controlled preconditions might be an option. But this remains a challenge, as it is proven that the applicability of results gained from disturbed soil samples to field conditions is restricted (Graber et al. 2006).

The MDI method for measuring *R* under field conditions has been shown to be very applicable already in previous studies (Hunter et al. 2011). But similar to the WDPT method, it provides results with high variances, which actually displays the field variability. Its disadvantage is the increased time for each measurement and the requirement of more equipment compared with the WDPT method, but this might be redeemed by its higher sensitivity, which has to be proven by further studies, particularly. However, this study could contribute to develop field methods for estimating SWR under field conditions and to their interpretation.

Conclusion

The results of this study indicate that irrigating with TWW enhances soil water repellency and affects soil chemical parameters that are important for soil quality. TWW-irrigated soils showed higher *R*, ECe and ESP values compared with adjacent FW-irrigated soils, whereas the findings of the WDPT tests were not consistent. Multilevel analysis evaluation of the results indicated an additive effect of TWW on *R*, but if clay content and SOC are additionally included that the effect is no longer visible. Further studies on this are recommended. As mismanagement of TWW irrigation poses a risk for sustainable agriculture and food security, control of TWW quality is essential for safe utilization of TWW. To conclude, site-specific irrigation water management appears to be crucial.

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