Irrig Sci
DOI 10.1007/s00271-014-0430-8

ORIGINAL PAPER

# Effects of irrigation using treated wastewater on table grape vineyards: dynamics of sodium accumulation in soil and plant

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Received: 4 March 2013 / Accepted: 7 February 2014


**Abstract** The effect of using treated wastewater for irrigation of table grapes (*Vitis vinifera* cv. Superior Seedless) was studied for six seasons. The experimental vineyard was grown on clay loam soil in a semi-arid area. Treated wastewater (5.83 meq $L^{-1}$ $Na^{+}$) with (TWW + F) and without (TWW) fertilizer, and fresh water with fertilizer (FW + F, 2.97 meq $L^{-1}$ $Na^{+}$), were each applied at three irrigation levels (80, 60 and 40 % of crop evapotranspiration before harvest). Root zone (0–60 cm soil depth) soil saturated paste extract $Na^{+}$ concentrations and sodium adsorption ratio (SAR) values fluctuated over the years, but generally decreased in the order TWW > TWW + F > FW + F for each irrigation level. Both $Na^{+}$ concentrations and SAR values developed faster and to a greater extent at higher irrigation. Adding fertilizer to TWW decreased $Na^{+}$ and SAR only at the high irrigation level. $Na^{+}$ concentrations in the trunk wood, bark and xylem sap of the TWW and TWW + F irrigated vines were significantly higher than those in the FW + F-irrigated vines. Leaf petiole $Na^{+}$ content increased with time and its maximum value in TWW and TWW + F irrigated vines exceeded 6,500 mg $kg^{-1}$, threefold higher than in FW + F irrigated vines. We conclude that in clay soils under relatively high irrigation, $Na^{+}$ may pose a greater potential risk to plants and soil rather than $Cl^{-}$ or salinity per se. However, significant effects on yield were not recorded during this six-year study probably due to the high salinity tolerance of the 'Paulsen' rootstock used in the experiment.

Communicated by R. Aragüés.

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## Introduction

Treated wastewater (TWW) is considered a valuable source of water for irrigation in many arid and semiarid regions throughout the world (Scheierling et al. 2011). The use of TWW is expected to rise with increasing water demand and concomitant decreases in water availability (Fuchs 2007). In 2010 about 40 % of irrigated agricultural land in Israel was irrigated using treated wastewater (Cohen et al. 2012; Kfir et al. 2012). The need to increase the use of TWW results from the increasing fresh water demand for domestic and industrial uses, due to population growth and increasing scarcity and fluctuations in annual precipitation. The consequences of using recycled wastewater were recently reviewed by Laurenson et al. (2012), discussing the effect of salinity on soil and vines.

Sodium ($Na^{+}$) is introduced into the water by anthropogenic activities and therefore $Na^{+}$ concentration and sodium adsorption ratio (SAR) in TWW are typically higher than in FW. TWW can harm plants indirectly by degrading soil structure which in turn negatively affects aeration and hydraulic conductivity (Tarchitzky et al. 1999;

Published online: 06 March 2014

Agassi et al. 2003; Bhardwaj et al. 2007; Levy 2011). High salinity as well as the specific solute composition of TWW constitutes a central problem, affecting crop performance and chemical and physical properties of the soil. TWW salinity results mainly from an increase in the concentrations of $Na^+$, $Cl^-$, and $HCO_3^-$ and to a lesser extent, $SO_4^{2-}$, $Ca^{2+}$ and $Mg^{2+}$, over background water concentrations. The standard procedures for secondary and tertiary treatment of wastewater do not reduce the concentration of most dissolved salts. Therefore, the only efficient way to reduce salt content is to control it at the source (Roland et al. 2000; Agassi et al. 2003; Laurenson et al. 2012) or to desalinate the water. When irrigating soils with water that has elevated $Na^+$ levels, the introduced $Na^+$ may replace other exchangeable cations on the soil's exchangeable complex. Exchanging $Ca^{2+}$ and $Mg^{2+}$ with $Na^+$ may lead to clay swelling and dispersion, decreased aggregate stability, impaired soil aeration, reduced soil permeability and infiltration rates, and increased runoff and soil erosion (Tarchitzky et al. 1999; Agassi et al. 2003; Levy 2011). SAR is a common measure used to evaluate the exchangeable sodium ratio in the soil's exchangeable cation complex and is commonly calculated from the cation composition in the soil solution: $SAR = [Na]/[Ca + Mg]^{1/2}$ (square brackets indicate cation concentrations in millimolar). In Israel, the SAR of FW is commonly about 2.5, but it ranges from about 5 to 8 by the time the water reaches the wastewater treatment facility (Feigin et al. 1991; Avnimelech 1993). Thus, local regulations for unrestricted irrigation use were set to a maximum SAR value of 5 (Inbar Committee 2003). This SAR value, when combined with low salinity such as that encountered during the rainy season, may result in clay dispersion and decreased infiltration rates. In clay soils, an increase in SAR from just 2 to 4 may result in increased surface runoff during rainstorms (Suarez et al. 2006).

Plant roots absorb essential nutritional elements such as N, P, and K, while to a certain extent exclude toxic elements such as Cl and Na. The efficiency with which agricultural crops exclude these ions determines their salt tolerance (Munns 1993). Reduced growth, early leaf senescence and the appearance of chlorotic and necrotic spots on leaves are external symptoms of salt stress (Greenway and Munns 1980; Tester and Davenport 2003). It is generally accepted that salt stress in plants has an osmotic component, in which growth is affected by reduced water uptake (Munns 1993, 2002; Munns et al. 2000; Shani and Ben-Gal 2005), and a slower, metabolic component, which is a result of specific ion toxicity stemming from, for example, the competition between $Na^+$ and $K^+$ for uptake pathways and binding sites in $K^+$-dependent metabolic and biosynthetic processes (Flowers and Yeo 1986; Munns 1993; Carden et al. 2003; Tester and Davenport 2003).

In Israel, large-scale use of TWW for irrigation has been applied in table grape vineyards for the past 8 years and as a consequence, an increase in visual salinity-like symptoms have appeared on the leaves; in some extreme cases, total collapse of yield-bearing vines has occurred.

Grapevines are defined as moderately salt-tolerant (Downton 1977b; Maas and Hoffman 1977; Maas 1990; Garcia and Charbaji 1993; Francois and Mass 1994). Salt tolerance in vines is affected by the scion-root combination, which also influences vine vigor (Yunusa et al. 1997). For grapevine, Maas and Hoffman (1977) set a threshold electrical conductivity (EC) of the saturated paste extract ($EC_e$) of 1.5 dS $m^{-1}$, with each 1 dS $m^{-1}$ above that value decreasing yield by 9.6 %. Following three field experiments conducted in Australia, Zhang et al. (2002) concluded that this value was too conservative. Their experiments exhibited a wide range of scion-related thresholds that ranged between 1.8 and 4 dS $m^{-1}$, with slopes ranging between 2.3 and 15 % yield reduction per 1 dS $m^{-1}$ increase. The rootstock 1,103 'Paulsen' (used in the present study) was the most salt-tolerant, exhibiting no yield reduction until the $EC_e$ exceeded about 4 dS $m^{-1}$ (Zhang et al. 2002). In the vines, a toxicity threshold for $Na^+$ concentration in the petioles at flowering was set at 5,000 mg $kg^{-1}$ (Nagarajah 1992; Prior et al. 1992; Reuter and Robinson 1997).

The ability of food crops to cope with increasing salinity and SAR in soils is highly important given the fact that of the current 230 million ha of global irrigated land, 45 million ha (19.5 %) are salt-affected soils (FAO 2008).

The objectives of the present research were to study the effects of irrigation with TWW on table grapes (*Vitis vinifera* cv. Superior Seedless) in a semiarid region. We tested the potential risk of $Na^+$-related damage from TWW irrigation, and whether TWW can be an appropriate substitute for FW in this crop. We examined the long-term (six seasons) dynamics of $Na^+$ accumulation in the soil, changes in soil SAR, changes in mineral content in the leaf and trunk, and effects on total fruit yield.

## Materials and methods

### Experimental site

A six-year study (2002–2007) was conducted in a 1-ha vineyard of table grapes *V. vinifera* cv. Superior Seedless (also called Sugraone), grafted onto 1,103 'Paulsen' rootstock, at the Lachish Agricultural Research and Development Station in southern Israel (lat. 31.6°N, long. 34.8°E). The vines were planted in April 1997. The Lachish region is one of the largest table grape-growing areas in the country. It is characterized by a semiarid Mediterranean climate with no summer rains. The soil is clay loam composed

**Table 1** Total annual winter precipitation, reference crop evapotranspiration ($ET_o$), and amount of water applied seasonally in the three irrigation levels (high, medium and low) during the 2002–2007 growing seasons (mm)

| | Precipitation[a] (mm) | $ET_o^b$ (mm season$^{-1}$) | High irrigation (mm) | Medium irrigation (mm) | Low irrigation (mm) |
|---|---|---|---|---|---|
| 2002 | 388 | 1,257 | 923 | 615 | 394 |
| 2003 | 509 | 1,232 | 815 | 544 | 348 |
| 2004 | 312 | 1,235 | 944 | 674 | 431 |
| 2005 | 382 | 1,238 | 903 | 647 | 392 |
| 2006 | 329 | 1,231 | 976 | 729 | 437 |
| 2007 | 314 | 1,219 | 996 | 712 | 398 |

[a] The rainy season of a given year begins on 1 Nov of the previous year and ends on 30 Mar. There were no summer rains during the experiment

[b] Calculated from meteorological data according to the Penman–Monteith equation as modified by the California irrigation management system from 1 April through 31 October

of 30 % sand, 28 % silt, and 42 % clay, with a cation-exchange capacity of 27.3 meq 100 g$^{-1}$, $CaCO_3$ content of 18 % and organic matter content of 0.6 %. The average winter precipitation was 372 mm during the 6-year trial (Table 1). Average reference evapotranspiration from April to October (calculated by the Penman–Monteith equation) was 1,272 mm.

## Irrigation treatments and vineyard structure

The effects of two factors were examined: irrigation water type and amount. Three water types were used: (1) fresh water with fertilizer (FW + F); (2) treated wastewater (TWW); (3) TWW with fertilizer (TWW + F). The TWW contained N, P and K at conventional levels (Table 3), thus treatment with TWW may supply these nutrients. Nevertheless, due to uncertainties farmers tend to add fertilizers as in treatment TWW + F. Each water type was supplied at three irrigation levels: high, medium, and low (nine treatments in all). Each treatment consisted of four replicates (36 plots in total) arranged in a randomized block design. Each treatment plot consisted of three rows with 14 vines per row. To minimize edge effects, only the 10 central vines from the middle row were sampled. Vine spacing was 2 m within rows and 3.5 m between rows. Rows were oriented from north to south and the vines were trained to a 2-m-high Y-shaped open-canopy gable system with six foliage wires on each side. Each vine was pruned to eight fruiting canes of 14 buds each. The canes were tied to the second- and third-lowest foliage wires supported by the Y-shaped cross-arms. Vine and row spacing, and training and trellis systems, were set according to standard practices for commercial table grape production in the area. Standard horticultural practices to control insects, fungi and weeds were employed throughout the experiment. A drip irrigation system with one line per row and in-line pressure-compensated 2.4 L h$^{-1}$ drippers was employed, with 0.5-m spacing between drippers (Netafim Ltd., Hatzerim, Israel).

The irrigation control unit (Talgil Computing & Control Ltd., Haifa, Israel) was set to three irrigation-amount treatments (high, medium and low) based on crop evapotranspiration under standard conditions ($ET_c$) as defined by Allen et al. (1998). In this study $ET_c$ represents the maximal evapotranspiration of the vines, while the actual water consumption of the field-grown vines was affected by various plant response mechanisms. The water amount for the high-volume treatment was set to satisfy 80 % of $ET_c$ before harvest and 60 % of $ET_c$ after harvest. In the medium-volume treatment, it was set to 60 and 40 % of $ET_c$ before and after harvest, respectively, slightly higher than the common agricultural practice in the region. In the low-volume treatment, it was set to 40 and 20 % $ET_c$ before and after harvest, respectively. The annual irrigation water amounts for each of the treatments are given in Table 1. Overall, the lowest annual irrigation volume was about 20 % lower than that of the common practice in this region. The daily irrigation amounts were determined on a 5-day basis according to the $ET_c$ data obtained from vines grown in 12 lysimeters located next to the vineyard and irrigated daily at 10–20 % excess consumption. A detailed description of the lysimeter setup and a discussion linking actual vine water consumption to its canopy dimensions and the $ET_c$ can be found in Netzer et al. (2009).

## Treated wastewater

Secondary treated municipal wastewater was used from a reservoir in Kibbutz Gat, located 2 km away from the experimental site. Municipal wastewater was treated by an activated-sludge process and left standing in the reservoir for a maximum of 180 days in June, and a minimum of 30 days in August. Chemical properties, determined by standard methods (Franson 1998), are presented in Tables 2 and 3. Water samples contained organic matter with 10–30 mg L$^{-1}$ biological oxygen demand (BOD) and 22–95 mg L$^{-1}$ chemical oxygen demand (COD). Fertilizer

**Table 2** Annual irrigation water parameters (final irrigation solution includes fertilizer): electrical conductivity (EC), sodium ($Na^+$) concentration and sodium adsorption ratio (SAR) of the three irrigation water quality treatments (Mean ± SE, $n = 8$)

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | Average |
|---|---|---|---|---|---|---|---|
| EC (dS $m^{-1}$) | | | | | | | |
| TWW | 2.04 ± 0.06 | 1.78 ± 0.09 | 2.25 ± 0.05 | 2.00 ± 0.13 | 1.88 ± 0.08 | 1.38 ± 0.10 | 1.83 ± 0.09 |
| TWW + F | 2.10 ± 0.05 | 1.96 ± 0.05 | 2.40 ± 0.06 | 2.19 ± 0.10 | 1.90 ± 0.07 | 1.45 ± 0.07 | 2.00 ± 0.07 |
| FW + F | 1.64 ± 0.04 | 1.41 ± 0.05 | 1.22 ± 0.05 | 1.47 ± 0.10 | 1.20 ± 0.03 | 0.9 ± 0.17 | 1.31 ± 0.07 |
| $Na^+$ (meq $L^{-1}$) | | | | | | | |
| TWW | 7.31 ± 0.07 | 6.16 ± 0.36 | 5.04 ± 0.06 | 5.33 ± 0.28 | 5.96 ± 0.08 | 5.19 ± 0.38 | 5.88 ± 0.21 |
| TWW + F | 7.37 ± 0.21 | 5.98 ± 0.36 | 5.06 ± 0.03 | 5.63 ± 0.28 | 5.98 ± 0.14 | 4.99 ± 0.51 | 5.83 ± 0.25 |
| FW + F | 3.66 ± 0.08 | 3.15 ± 0.03 | 3.27 ± 0.01 | 3.09 ± 0.10 | 2.15 ± 0.14 | 2.61 ± 0.08 | 2.97 ± 0.07 |
| SAR | | | | | | | |
| TWW | 4.87 ± 0.17 | 4.44 ± 0.25 | 3.37 ± 0.08 | 4.08 ± 0.20 | 4.36 ± 0.06 | 4.87 ± 0.66 | 4.33 ± 0.23 |
| TWW + F | 4.95 ± 0.18 | 4.22 ± 0.26 | 3.46 ± 0.07 | 4.02 ± 0.18 | 4.47 ± 0.14 | 5.04 ± 0.72 | 4.36 ± 0.26 |
| FW + F | 2.45 ± 0.03 | 2.35 ± 0.02 | 2.09 ± 0.02 | 2.44 ± 0.21 | 1.62 ± 0.08 | 2.37 ± 0.19 | 2.22 ± 0.09 |

TWW, treated wastewater; TWW + F, TWW with added fertilizer; FW + F, fresh water with added fertilizer

**Table 3** pH levels and chloride ($Cl^-$), potassium ($K^+$), calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$) and ammonium ($NH_4$-N) concentrations in the irrigation water for the period 2002–2007 (mean ± SE, $n = 50$)

| | pH | $Cl^-$ (meq $L^{-1}$) | $Ca^{2+}$ (meq $L^{-1}$) | $Mg^{2+}$ (meq $L^{-1}$) | $K^+$ (meq $L^{-1}$) | $NH_4$-N (meq $L^{-1}$) |
|---|---|---|---|---|---|---|
| TWW | 7.7 ± 0.1 | 8.58 ± 0.56 | 3.16 ± 0.06 | 2.52 ± 0.06 | 1.60 ± 0.05 | 2.34 ± 0.39 |
| TWW + F | 7.4 ± 0.1 | 8.50 ± 0.48 | 2.99 ± 0.05 | 2.42 ± 0.06 | 2.10 ± 0.07 | 3.51 ± 0.29 |
| FW + F | 7.3 ± 0.1 | 6.56 ± 0.31 | 3.04 ± 0.06 | 2.52 ± 0.06 | 1.09 ± 0.08 | 1.09 ± 0.11 |

For abbreviations see footnote to Table 2

(Gofer 4-2-6, Fertilizers and Chemicals LTD., Israel) was supplied daily through the irrigation water (fertigation) to the six fertilized treatments at a concentration of (mM): 0.87 $NO_3^-$, 1.06 $NH_4^+$, 0.87 K and 0.19 P. This fertilizer is comprised of $KNO_3$, $(NH_4)_2SO_4$ and $H_3PO_4$ with a $NO_3$-N to $NH_4$-N ratio of 45:55 and does not include $Na^+$. At the end of each drip line, a 50-cm tube led off the main line to a low-flow dripper (1 L $h^{-1}$) that was encapsulated in a sealed vial, and used for irrigation water sample collection. Irrigation water was collected every day, stored at low temperature (4 °C), and pooled into a sample that represented 30 days of water collection. These water samples were used to analyze EC, pH, and the concentrations of $Na^+$, $Cl^-$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, and $NH_4^+$.

## Soil sampling and analysis

Soil was sampled in March 2002, before the beginning of the experiment, for chemical and physical analysis. No significant differences were observed between plots (data not shown). After initiation of the experiment, the soil was sampled annually at the end of each irrigation season (October). Soil samples were taken by auger at depths of 0–30, 30–60, and 60–100 cm within the onion-shaped wetted soil volume at about 40 cm from the drip line, in the front of a dripper midway between two vines. Soils were rapidly oven-dried at 65 °C for preservation until analysis. The soil of this region is gypsum-free, thus no dehydration is expected by this drying pretreatment. Saturated paste extracts of dried soils were analyzed for EC, pH, $Na^+$, $Cl^-$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, and $NH_4^+$ according to Page et al. (1982).

## Leaf sampling and chemical analysis

From each replicate, 30 basal leaves opposite a bunch cluster were sampled at harvest (mid-July to mid-August) as suggested by Christensen (1969). Petioles, rather than whole leaves were analyzed following Downton (1977b), Prior et al. (1992) and Fisarakis et al. (2001). Petioles were rinsed three times in tap water then twice in distilled water to remove dust and pesticide residues, and oven-dried at 70 °C for 72 h. Samples were subsequently pulverized in an electric mill, and 150 mg of dry matter was digested with 5 ml of concentrated reagent-grade nitric acid at 130 °C. The digest was brought to a volume of 50 ml with double-distilled water and kept at 4 °C until analysis for $Na^+$ concentration by inductively coupled plasma-atomic emission spectroscopy (ICP-AES, Arcos, Spectro, Kleve, Germany).

### Wood samples

Core samples were taken 50 cm above ground using a 7-mm-diameter tree corer (Mattson, Mechaniska, AB, Mora, Sweden) from four vines in each plot and pooled (36 samples in total). Each core was separated into xylem and bark tissues, using a sharp blade, before drying for 72 h at 70 °C. Dry material was ground to a fine powder in an electric mill and digested by the same method as the leaves. Xylem sap was collected by connecting a plastic tubule to each hole in the trunk left by the wood corer (Fig. 1). Two sap collection devices were installed in each plot (72 in total) 2 weeks before bud break when root pressure was sufficient for sap extraction. In 22 out of 36 plots sap was collected successfully.

**Fig. 1** Xylem sap collection device attached to vine's trunk

### Yield data

The vineyard was usually harvested from mid-July to mid-August when the total soluble solids (TSS) of the grapes reached 15–15.5 °Brix. Fruit from each replicate of the different treatments was harvested and weighed separately.

### Meteorological data

Meteorological data, including precipitation data and data used for calculating reference crop evapotranspiration ($ET_o$, according to the Penman–Monteith equation) were obtained from an automatic weather station located at the Lachish research station, about 100 m from the experimental site. The station monitored solar radiation (CM-11, Kipp & Zonen, Delft, Netherlands), wind speed and direction (type 05103; R.M. Young, Traverse, MI), air temperature and relative humidity (type HMP 45C; Campbell Scientific, Inc., Logan, UT).

### Statistical analysis

The treatments in the vineyard were arranged in a factorial randomized block design. Data were analyzed using analysis of variance, and comparisons between means were determined according to the least significant difference (LSD) at $p \leq 0.05$. The software program JMP IN 5.1 (SAS Institute Inc., Cary, NC) was used for all statistical procedures.

## Results

### Irrigation water and precipitation

The amount of precipitation during winter fluctuated among the years of the experiment (Table 1): in 2004, 2006 and 2007, rainfall was below the annual average of 385 mm year$^{-1}$, while in 2003 it exceeded the average by 32 %. The average seasonal (spring to autumn) irrigation amounts during the 6 years of the experiment were 926, 653 and 400 mm for the high, medium and low irrigation levels, respectively (Table 1). No summer rainfall was recorded during the experiment.

The average EC of irrigation water applied in the FW + F treatment was 0.69 dS m$^{-1}$ lower than that in the TWW + F treatment. The fertilizer added on average 0.17 dS m$^{-1}$ to the EC of the irrigation water. The lowest EC value was obtained for FW + F in 2007, while the highest EC was recorded for TWW + F in 2004 (Table 2). $Na^+$ concentrations in TWW and TWW + F were similar and 1.8 times higher on average than in FW + F, resulting in about a 2-unit increase in SAR in the TWW and TWW + F (Table 2). The 2002–2007 mean pH of TWW + F was slightly lower than that of the TWW (Table 3) due to the acidity of the fertilizer solution (pH about 3.5). $Cl^-$ concentrations in TWW and TWW + F were about 30 % higher than in FW + F (Table 3). Only small and inconsistent differences were observed in the concentrations of $Mg^{2+}$ and $Ca^{2+}$ between the different water quality treatments. Addition of fertilizer to FW and TWW increased the concentrations of $K^+$ and ${NH_4}^+$ by about 0.51 and 1.14 meq L$^{-1}$, respectively (Table 3).

### Soil characteristics

The saturated soil paste extract electrical conductivity ($EC_e$) for all depths, treatments and years were usually below the threshold $EC_e$ of 2 dS m$^{-1}$ for grapevine (with exception of the upper soil layer in 2006) and did not show a trend of increasing salinity with time at any soil depth (Table 4). These $EC_e$ values do not indicate salinity hazards to vines grafted on the saline-tolerant 'Paulsen' rootstock used in the experiment. $EC_e$ was slightly higher in the 0–30 cm than in

**Table 4** Electrical conductivity (dS $m^{-1}$) of the saturated paste extract ($EC_e$) at soil depths of 0–30, 30–60, and 60–100 cm presented according to water quality treatments ($n$ = 72; 3 water amounts × 6 years × 4 replicates), irrigation treatments ($n$ = 72), and years ($n$ = 36)

| | 0–30 cm | 30–60 cm | 60–100 cm |
|---|---|---|---|
| $EC_e$ (dS $m^{-1}$) | | | |
| TWW | 1.84 A a | 1.69 A ab | 1.40 A b |
| TWW + F | 1.71 A a | 1.59 A a | 1.40 A a |
| FW + F | 1.50 A a | 1.15 B b | 1.22 A b |
| High irrigation | 1.96 A a | 1.72 A ab | 1.54 A b |
| Medium irrigation | 1.82 A a | 1.53 A ab | 1.34 A b |
| Low irrigation | 1.26 B a | 1.17 B a | 1.12 B a |
| 2002 | 1.49 B a | 1.21 BC a | 1.19 B a |
| 2003 | 1.54 B a | 1.29 BC ab | 0.97 B b |
| 2004 | 1.45 B a | 1.83 A a | 1.60 A a |
| 2005 | 1.43 B a | 1.65 AB a | 1.58 A a |
| 2006 | 2.65 A a | 1.87 A b | 1.65 A b |
| 2007 | 1.52 B a | 0.98 C b | 1.02 B b |

For abbreviations see footnote to Table 2. Values for each factor within a column followed by the same upper case letter and values within each row followed by the same lower case letter do not differ significantly ($p > 0.05$)

**Table 5** Sodium adsorption ratio (SAR) of the saturated paste extract at soil depths of 0–30, 30–60, 60–100 and 0–100 cm presented according to water quality treatments ($n$ = 72; 3 water amounts × 6 years × 4 replicates), irrigation treatments ($n$ = 72), and years ($n$ = 36)

| | 0–30 cm | 30–60 cm | 60–100 cm | 0–100 cm |
|---|---|---|---|---|
| SAR | | | | |
| TWW | 3.81 A b | 6.08 A a | 5.80 A a | 5.23 A |
| TWW + F | 2.51 B b | 4.53 B a | 5.15 AB a | 4.08 B |
| FW + F | 2.21 B c | 3.69 C b | 4.79 B a | 3.56 C |
| High irrigation | 3.62 A b | 5.64 A a | 6.02 A a | 5.12 A |
| Medium irrigation | 2.77 B b | 5.05 A a | 5.49 A a | 4.43 B |
| Low irrigation | 2.14 B b | 3.61 B a | 4.24 B a | 3.32 C |
| 2002 | 2.72 A b | 3.97 BC a | 4.31 B a | 3.67 B |
| 2003 | 2.31 A b | 3.33 C a | 3.79 B a | 3.15 B |
| 2004 | 2.24 A b | 3.95 BC a | 4.53 B a | 3.58 B |
| 2005 | 3.13 A b | 6.29 A a | 6.21 A a | 5.22 A |
| 2006 | 3.33 A b | 5.82 A a | 6.40 A a | 5.19 A |
| 2007 | 3.34 A b | 5.25 AB a | 6.25 A a | 4.95 A |

For abbreviations see footnote to Table 2. Values for each factor within a column followed by the same upper case letter and values within each row followed by the same lower case letter do not differ significantly ($p > 0.05$)

the 30–60 and 60–100 cm soil layers. The effects of water quality were minor as well. $EC_e$ in TWW was slightly higher than in FW + F, while intermediate values were found in TWW + F. Average $EC_e$ under the low irrigation treatment was significantly lower than in the other treatments at all soil depths. The saturated paste extract $Cl^-$ concentrations ranged from 5.4 to 10.9 meq $L^{-1}$ and were well correlated to $EC_e$ ($R^2 = 0.866$); these values are considered non-toxic for grapevines. A comparison of soil salt concentrations in autumn and spring showed that winter leaching resulted in 80–95 % $Cl^-$ decrease at 0–30 cm soil depth, and 73–93 % $Cl^-$ decrease at 30–60 cm soil depth, while for $Na^+$ these values were 41–66 % and 15–54 %, respectively (detailed data not presented), indicating lower $Na^+$ leaching.

Soil saturated paste extract SAR (Table 5) measured at 0–30, 60–90, and 60–100 cm depths, as well as the whole 0–100 cm profile, increased with time (2002, 2003, 2004 < 2005, 2006, 2007), treated wastewater (TWW > TWW + F > FW + F), and water amount (high > medium > low). SAR was significantly lower in the uppermost layer (0–30 cm) compared to the deeper layers (30–60 and 60–100 cm). In the following sections, we address the 0–60 cm layer, representing the active root zone, to describe these tendencies (Tables 6, 7).

After the first irrigation season, no differences were yet established in $Na^+$ concentrations under all irrigation treatments. In the high irrigation treatment, the 2002–2007 average $Na^+$ concentration was significantly higher with TWW (13.1 meq $L^{-1}$) than with the other two treatments (about 7.5 meq $L^{-1}$). A similar trend, but with lower absolute values and lower differences among treatments, was found in the medium irrigation level. In the low irrigation treatments, these differences were even smaller. Adding fertilizer to the TWW treatment decreases soil $Na^+$ concentration at high irrigation, but not at medium and low irrigation (Table 6). Multivariate testing for the effects of water quality, irrigation level, soil depth and years indicate that the main effect of irrigation level was significant: $Na^+$ concentrations were higher at high (9.42 meq $L^{-1}$) than at medium irrigation (8.02 meq $L^{-1}$), and the latter was higher than that at low irrigation (5.50 meq $L^{-1}$) ($p < 0.0001$; $n = 648$).

A similar pattern was found for SAR (Table 7). According to the multivariate test, the SAR of the soil under the different irrigation levels developed a distinct pattern with significant differences: FW + F < TWW + F < TWW ($p < 0.0001$; $n = 648$). Development of this pattern accelerated as irrigation level increased. From the second year (2003) on, significantly elevated average SAR values were recorded in TWW plots compared to FW + F plots under high irrigation, while SAR under FW + F did not differ significantly from TWW + F. At the two lower irrigation treatments no temporal trends were evident, but the average SAR of TWW was significantly higher than in the FW + F plots, while the two fertilized treatments were similar to each other (Table 7). The effect of irrigation amount on the average SAR under each water quality treatment (lower case

**Table 6** Annual $Na^+$ concentrations (meq $L^{-1}$) of the saturated paste extract at 0–60 cm soil depth under different levels of irrigation (high, medium and low) and water quality treatments

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | Average |
|---|---|---|---|---|---|---|---|
| High irrigation | | | | | | | |
| TWW | 17.77 A | 12.90 A | 10.26 A | 16.70 A | 13.03 A | 7.40 A | 13.10 A a |
| TWW + F | 7.72 A | 2.53 B | 5.71 A | 10.80 B | 11.85 A | 6.92 A | 7. 67 B a |
| FW + F | 11.73 A | 5.10 B | 4.58 A | 7.99 B | 7.68 B | 5.97A | 7.29 B a |
| Medium irrigation | | | | | | | |
| TWW | 12. 67 A | 11.75 A | 11.63 A | 6.03 A | 9.43 AB | 6.17 AB | 9.52 A b |
| TWW + F | 9.08 A | 3.65 A | 7.03 A | 7.78 A | 11.82 A | 8.36 A | 7.99 AB a |
| FW + F | 10.01 A | 4.41 A | 6.35 A | 6.62 A | 5.48 B | 4.06 B | 6.15 B a |
| Low irrigation | | | | | | | |
| TWW | 3.95 A | 3.28 B | 6.15 A | 4.20 A | 8.25 A | 9.32 A | 5.85 A c |
| TWW + F | 3.0 A | 5.18 A | 4.23 A | 8.07 A | 9.30 A | 4.53 B | 5.79 A a |
| FW + F | 3.49 A | 3.17 B | 3.36 A | 3.60 A | 5.28 A | 3.12 B | 3.68 B b |

For abbreviations see footnote to Table 2. Values within a column followed by the same upper case letter within an irrigation treatment, and 2002–2007 average values followed by the same lower case letter within a water quality treatment, do not differ significantly ($p > 0.05$)

**Table 7** Annual sodium adsorption ratio (SAR) values of the saturated paste extract at 0–60 cm soil depth under different levels of irrigation (high, medium and low) and water quality treatments

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | Average |
|---|---|---|---|---|---|---|---|
| High irrigation | | | | | | | |
| TWW | 6.15 A | 4.48 A | 4.83 A | 11.09 A | 8.05 A | 6.31 A | 6.90 A a |
| TWW + F | 2.56 B | 1.77 B | 2.50 AB | 5.91 B | 4.85 B | 4.69 AB | 3.76 B a |
| FW + F | 4.03 AB | 2.07 B | 1.98 B | 4.29 B | 4.26 B | 3.54 B | 3.42 B a |
| Medium irrigation | | | | | | | |
| TWW | 4.14 A | 5.26 A | 4.91 A | 4.02 A | 5.40 A | 4.75 AB | 4.74 A b |
| TWW + F | 2.64 A | 2.44 B | 3.31 A | 3.62 A | 4.66 A | 5.94 A | 3.79 AB a |
| FW + F | 3.97 A | 2.46 B | 3.11 A | 3.75 A | 3.56 A | 2.51 B | 3.23 B a |
| Low irrigation | | | | | | | |
| TWW | 2.54 A | 2.45 A | 2.91 A | 3.02 A | 3.21 A | 5.56 A | 3.30 A b |
| TWW + F | 1.84 A | 2.23 A | 2.33 A | 4.4 A | 4.38 A | 3.30 B | 3.11 AB a |
| FW + F | 2.23 A | 2.24 A | 1.95 A | 2.3 A | 2.82 A | 2.09 B | 2.28 B b |

For abbreviations see footnote to Table 2. Values within a column followed by the same upper case letter within an irrigation treatment, and 2002–2007 average values followed by the same lower case letter within a water quality treatment, do not differ significantly ($p > 0.05$)

letters in Table 7) was: high > medium and low in the TWW treatment, high = medium = low in the TWW + F treatment, and high = medium > low in the FW + F treatment.

## Plant characteristics

The maximum $Cl^-$ concentrations in the dry matter of leaf petioles sampled at harvest were 9,131 mg $kg^{-1}$ in TWW and 6,245 mg $kg^{-1}$ in FW + F. These values are below the toxic threshold values of 10,000 or 15,000 mg $kg^{-1}$ for grapevines (Nagarajah 1992; Prior et al. 1992; Reuter and Robinson 1997). Hence no further detailed $Cl^-$ data are presented hereafter.

$Na^+$ concentrations in the dry matter of leaf petioles sampled at harvest showed two distinct trends between the two TWW treatments and the FW treatment (Fig. 2). In 2002 and 2003, $Na^+$ concentrations were stable and similar in the three water quality treatments. From year 2004 onwards, $Na^+$ concentrations in TWW and TWW + F tended to increase with time, whereas $Na^+$ concentration in FW + W was quite stable, with a slight decrease from 2002 to 2006 followed by a slight increase in 2007. Overall, $Na^+$ concentrations were similar in TWW and TWW + F and higher ($p < 0.05$) than $Na^+$ concentrations in FW + F (Fig. 2; Table 8). For each water quality treatment, petiole $Na^+$ concentrations were higher ($p < 0.05$) at the high than

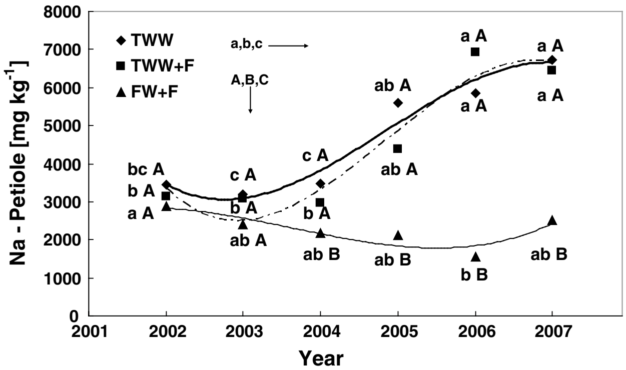


**Fig. 2** $Na^+$ concentrations in leaf petioles measured in each year and water quality treatment. Samples were collected at harvest. *Each data point* is an average of 12 plots (three irrigation level treatments × four replicates). *Different upper case letters* indicate significant differences ($p < 0.05$) between water quality treatments for a given year (*read vertically*). *Different lower case letters* indicate significant differences between years for each water quality treatment (*read horizontally*). TWW, treated wastewater; TWW + F, TWW with added fertilizer; FW + F, fresh water with added fertilizer

**Table 8** Six-year average $Na^+$ concentrations in leaf petioles for each irrigation level and water quality treatment

| | TWW | TWW + F | FW + F |
|---|---|---|---|
| $Na^+$ (mg $kg^{-1}$) | | | |
| High irrigation | 5,610 A a | 5,107 A a | 2,631 A b |
| Medium irrigation | 4,932 AB a | 4,811 AB a | 2,231 AB b |
| Low irrigation | 3,772 B a | 3,556 B a | 1,980 B b |

For abbreviations see footnote to Table 2. Samples were collected at harvest during years 2002–2007 ($n = 24$). Means within a column followed by the same upper case letter and means within each row followed by the same lower case letter do not differ significantly ($p > 0.05$)

at the low irrigation level, while values at the medium irrigation level did not differ from either (Table 8).

Mineral analyses of the xylem and bark tissues sampled from the main trunk of the vine in 2008 showed an overall accumulation of $Na^+$ in these perennial tissues. Samples from the TWW and TWW + F irrigated vines had similar $Na^+$ concentrations, and contained about 30–60 % more $Na^+$ in these tissues than their counterparts from the FW + F irrigated vines (Table 9).

Sap bleeding from the xylem in the spring, prior to bud break, collected by the device shown in Fig. 1, indicated significantly higher $Na^+$ concentrations in the TWW and TWW + F irrigated vines compared to the FW + F irrigated vines (Table 9). However, despite the significant differences in $Na^+$ concentrations among some of the treatments in the soil, leaf, xylem and bark, no significant differences between treatments were found in fruit yield during the experiment (Table 10).

**Table 9** $Na^+$ concentrations in xylem sap ($n = 22$) and in xylem and bark tissue ($n = 36$) for each water quality treatment

| | Xylem sap $Na^+$ (mg $L^{-1}$) | Xylem $Na^+$ (mg $kg^{-1}$) | Bark |
|---|---|---|---|
| TWW | 43.6 A | 821 A | 398 A |
| TWW + F | 48.6 A | 834 A | 476 A |
| FW + F | 21.7 B | 538 B | 298 B |

For abbreviations see footnote to Table 2. Samples were taken 2 weeks before bud break in 2008. Means within a column followed by the same letter do not differ significantly ($p > 0.05$)

## Discussion

In this study three water quality treatments combined with three irrigation amounts were used for irrigation of table grapes. We monitored salinity ($EC_e$) and a broad range of elements, including macronutrients, micronutrients, chloride, and heavy metals with the aim of determining their potential impact on soils and vines. Sodium ($Na^+$), with an average concentration in TWW and TWW + F that was double that in FW + F (Table 2), posed the greatest potential threat to soils and plants.

Soil $Na^+$ concentration in autumn, at the end of the irrigation season, is likely to be at its yearly maximum, reflecting the crop's ET-concentration effect and the balance between the amounts of salt added and leached by the irrigation water. $Na^+$ concentrations in spring are expected to be lower due to leaching with winter rainfall (Agassi et al. 2003). The autumn-to-autumn changes are affected by all components. For example, soil $Na^+$ was lower in eight out of nine treatments in autumn 2003 than in autumn 2002 (Table 6). This decrease was related to the reduction of $Na^+$ in TWW and FW during the 2003 irrigation season compared to the previous year (Table 2), and to the high 2003 winter precipitation (Table 1).

A multi-seasonal analysis of the different water quality treatments at different soil depths revealed that overall soil $Na^+$ concentration for the high irrigation treatment was significantly higher than that in the medium irrigation treatment, and the latter was significantly higher than that in the low irrigation treatment. It was previously suggested that when using saline water, increasing irrigation over actual evapotranspiration will promote salt leaching and will aid to maintain salinity under the threshold value for a given crop (Ayers and Westcot 1985; Bresler 1987; Dudley et al. 2008). This practice may help to maintain reasonable $Cl^-$ concentrations but, according to our results, elevated irrigation amounts led to a further increase in soil $Na^+$ concentrations. We conclude that in clay soils this practice may accelerate $Na^+$ accumulation and increase SAR in the soil. It should be noted that the amount of irrigation in our high and medium irrigation treatments exceeded the commonly

**Table 10** Yields of superior seedless grapes in the three water quality treatments

| | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | Average |
|---|---|---|---|---|---|---|---|
| Yield (t $ha^{-1}$) | | | | | | | |
| TWW | 34.9 | 19.0 | 40.6 | 15.2 | 47.4 | 20.0 | 29.5 |
| TWW + F | 32.7 | 22.1 | 43.4 | 10.3 | 44.4 | 20.1 | 29.0 |
| FW + F | 37.1 | 20.1 | 40.4 | 13.5 | 51.8 | 20.7 | 30.6 |

For abbreviations see footnote to Table 2. Means within each column do not differ significantly ($p > 0.05$, $n = 36$ for each treatment in each year)

used range of 350–550 mm per season for table grape vineyards in the Lachish region.

Soil $Na^+$ at 0–60 cm soil depth was noticeably higher in the TWW than in the TWW + F treatment under high irrigation, although only 2 years showed a significant difference. The differences in soil $Na^+$ concentrations between these treatments became less noticeable with time. In the multi-seasonal analysis with all irrigation levels and soil depths combined, the average soil $Na^+$ concentration in TWW (9.2 meq $L^{-1}$) was significantly higher than in TWW + F (7.5 meq $L^{-1}$), and the latter was significantly higher than in FW + F (6.2 meq $L^{-1}$) (analysis not shown). This was due to decreased SAR in the TWW + F treatment compared to the TWW treatment at the 0–60 depth in most years, especially in the high irrigation treatment (Table 7). This trend was more pronounced at the 30–60 depth and was significant for the whole 0–100 cm depth (Table 5). These results suggest that components within the added fertilizer affect soil $Na^+$ concentration. Since soils in this area contain a large percentage of clay (42 %), it is likely that cations contributed by the fertilizer compete with $Na^+$ for sites within the soil's exchangeable complex. $Ca^{2+}$ and $Mg^{2+}$ levels did not differ greatly among water quality treatments (Table 3), but $K^+$ and $NH_4^+$ concentrations were greater by 30 and 50 %, respectively, in the TWW + F than in the TWW treatment (Table 3). Another proposed indirect mechanism of exchangeable $Na^+$ displacement caused by the TWW + F irrigation water is related to the somewhat lower pH of this water (7.4) compared to the TWW (7.7) (Table 3). Further pH decreases may occur in the soil due to nitrification prompted by the high ammonium-to-nitrate ratio of the fertilizer. The lower pH would increase $Ca^{2+}$ and $Mg^{2+}$ concentrations in the $H_2O$–$CO_2$-calcite or dolomite system as found by Tamir et al. (2011, 2012). The $CaCO_3$ content of our soil was 18 %, and in agreement with this proposed mechanism the average Ca + Mg concentration in the saturated paste extract of the TWW + F soil samples increased by about 12 % over that in the TWW samples (data not shown). Thus, while TWW with relatively high $Na^+$ concentrations increased soil sodicity, $K^+$ and $NH_4^+$ in TWW + F plus increased $Ca^{2+}$ and $Mg^{2+}$ concentrations due to mineral dissolution substituted some of the $Na^+$ in the exchangeable complex of the soil, therefore decreasing soil sodicity in relation to that with TWW. Different studies have shown that compared to $Na^+$, not only divalent cations (e.g., $Ca^{2+}$ and $Mg^{2+}$), but also monovalent $K^+$ and $NH_4^+$ cations improve soil's structural stability and water permeability (Brooks et al. 1956; Chen et al. 1983; Rao and Mathew 1995). Thus, whether $K^+$, $NH_4^+$, $Ca^{2+}$ or $Mg^{2+}$ opposed the increased sodicity, the outcome would be an improvement in soil aggregate stability relative to soils with exchange sites dominated by $Na^+$.

While chemical composition of the soil reflects its long-term history, sampling at a fixed location (40 cm perpendicular to the dripper in our case) may introduce a certain bias due to differences in the volume of the onion-shaped wetted soil volume. The dimensions of the onion-shaped wetting pattern change during the season and between irrigation treatments. Conversely, the plant, which is exposed to the overall soil salinity gradients via its root system, may better represent the integrated root zone salinity.

The dynamics of $Na^+$ concentration in the leaves among treatments and seasons were less complex than the dynamics of $Na^+$ in the soil. As new leaves appear each spring, $Na^+$ concentration in the newly formed leaves is a measure of that in the soil solution during the growing season plus that stored in roots, trunk and canes. Significant differences in leaf petiole $Na^+$ concentrations were obtained between the TWW and TWW + F treatments compared to the FW + F treatment from the third year of the experiment (Fig. 2). Leaf petiole $Na^+$ remained relatively low in the FW + F irrigated vines, but increased with time in the TWW and TWW + F irrigated vines up to values of about 6,500 mg $kg^{-1}$ in year 2007. The concentration of $Na^+$ measured in the petioles at flowering is considered toxic above 5,000 mg $kg^{-1}$ (Nagarajah 1992; Prior et al. 1992; Reuter and Robinson 1997). Symptoms of salt toxicity appear as leaf chlorosis or burns on the leaf margins followed by early defoliation (Prior et al. 1992; Fisarakis et al. 2001; Paranychianakis and Angelakis 2008). Less severe visual symptoms of leaf chlorosis in our experiment appeared only in the TWW and TWW + F treatments after year 2005. Those mild chlorosis symptoms appeared sporadically from 3 weeks after bud break, and gradually disappeared toward veraison.

Irrespective of the water quality treatment, leaf petiole $Na^+$ concentrations were higher ($p < 0.05$) in the high than in the low irrigation treatment because of the corresponding higher $Na^+$ and SAR values in the soil. Despite the different dynamics of $Na^+$ accumulation in soil and leaves, the correlations between the two strengthened during the final 2 years of the trial ($R^2 = 0.335$–$0.502$).

At the end of the experiment, $Na^+$ concentrations in xylem and bark samples isolated from the trunk of the TWW and TWW + F irrigated vines nearly doubled those of the FW + F irrigated vines (Table 9). The perennial parts of the vine (roots, trunk and canes) probably provide an additional source of $Na^+$ that reaches the leaves with the transpiration stream during the growing season (Fisarakis et al. 2001).

Rootstock and scion varieties are important factors in vineyard success under salt-stress conditions (Groot Obbink and Alexander 1973; Downton 1977a; Laurenson et al. 2012). The use of different rootstocks produces variability in $Cl^-$ and $Na^+$ accumulation (Downton 1977a, 1985; Fisarakis et al. 2001; Paranychianakis and Angelakis 2008), but even rootstocks that are able to sequester $Cl^-$ differ in their ability to sequester $Na^+$ (Sharma and Upadhyay 2008). The 1,103 'Paulsen' rootstock used in this experiment is categorized as one the most salt-tolerant (Fisarakis et al. 2001; Zhang et al. 2002).

In early spring, the xylem vessels fill up with sap as a result of positive hydraulic pressure, also known as root pressure. This pressure results in xylem bleeding from the cut surfaces of pruned branches (spurs). The concentration of $Na^+$ in the xylem sap bleeding from the TWW and TWW + F irrigated vines were more than double that in the FW + F irrigated vines (Table 9). Since xylem sap was sampled in spring, before bud break, when soil $Na^+$ is at its lowest level, differences among treatments in sap $Na^+$ concentration may reflect differences in $Na^+$ concentrations in the soil as well as the $Na^+$ accumulated in the perennial parts of the vines during past seasons. $Na^+$ in the xylem tissues of both TWW and TWW + F treatments exceeded 800 mg $kg^{-1}$. In contrast, a nearby vineyard (Red-globe grafted on unknown salt-sensitive rootstock) that collapsed 3 years after shifting the water source from fresh to treated wastewater (similar to that used in our study) had a xylem $Na^+$ concentration above 2,000 mg $kg^{-1}$. Based on many xylem analyses, we consider that a xylem $Na^+$ concentration of about 800–1,000 mg $kg^{-1}$ is of marginal toxicity for grapevines. In accordance with these findings, grape yields were unaffected by the water quality treatments (Table 10). The pronounced yield differences observed between seasons were due to the alternate yield-bearing trait of cv. Superior Seedless. The ability of the vines to cope with high $Na^+$ concentrations is attributed to the salt-tolerant 'Paulsen' rootstock.

## Conclusions

Irrigation with TWW requires continuous monitoring to ensure that its salt components do not have adverse effects on soils and plants. Under our experimental conditions, high levels of $Na^+$ rather than $Cl^-$ in soil and vines emerged as the major potential problem related to TWW irrigation. Soil salinity ($EC_e$) was usually similar in the fresh and wastewater treatments and did not increase with time at any soil depth, but it was lower in the low than in the medium and high irrigation treatments. Soil $Na^+$ concentrations and SAR values fluctuated along the 6 years studied in accordance with those in the irrigation water and the amounts of winter precipitation, and were generally higher in the TWW irrigated plots. Adding fertilizer to the TWW moderated $Na^+$ accumulation and SAR increases in the high irrigation treatment, but not in the medium and low irrigation treatments. In contrast to previous studies which called for increasing the leaching fraction to decrease solute accumulation in soils, we found that increasing the leaching fraction by increasing irrigation amounts in a clay soil may accelerate the buildup of $Na^+$ and SAR in the root zone.

Vines exposed to continuous treated wastewater irrigation, with or without fertilizer, show a gradual $Na^+$ accumulation in perennial tissues, whereas $Na^+$ levels in vines irrigated with fresh water were low and stable along the six studied years. Unlike in the soil, addition of fertilizer to the treated wastewater did not diminish $Na^+$ accumulation in the plant. The deleterious effect of treated wastewater on $Na^+$ accumulation was more evident in the vine than in the soil because plants act as spatial and temporal integrator of the entire root zone. We propose the use of spring xylem sap and trunk wood analyses as additional indicators of salinity development to common soil criteria.

The yield of var. Superior table grapes grafted on the high salt-tolerant 'Paulsen' rootstock was not significantly affected by the water quality treatments during the 6 years of the experiment. Nevertheless, the observed trends of $Na^+$ accumulation in the vines exposed to TWW with or without added fertilizers may pose a potential risk in subsequent years under long-term use of treated wastewater.

**Acknowledgments** This research was supported by a grant from the Israeli Ministry of Agriculture (Project No. 826-47-02). The authors would like to thank Amram Hazan, Yosi Cohen, Carmit Lifshitz, Idith Dembak, Shiri Naftalyahu, and Tamar Weinberg for their assistance in field and laboratory work.

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