An Assessment of Treated Municipal Wastewater Used for Irrigation of Grapevines with Respect to Water Quality and Nutrient Load

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Submitted for publication: September 2022
Accepted for publication: October 2022

Key words: grapevine, irrigation, municipal, nutrients, toxicity, wastewater

The impact of treated municipal wastewater (TMW) irrigation on soil and grapevines was assessed under field conditions in vineyards in the Coastal region of South Africa. Grapevines were irrigated using TMW from the City of Cape Town uninterruptedly over a period of 11 years. Grapevines were either rain fed, irrigated with TMW via a single dripper line, or received twice the volume via double dripper lines. The quality of the TMW used for vineyard irrigation was acceptable, and below the minimum criteria stipulated by the General Authorisations to irrigate up to 500 m^3 per day in terms of pH, EC$_w$ and SAR. Mean Na$^+$ concentration in the TMW exceeded the critical value of 100 mg/ℓ for irrigating grapevines in South Africa. The Cl$^-$ levels in the TMW were well below the threshold value of 700 mg/ℓ at which toxicity in grapevines might occur. Consistently high P concentrations measured in the TMW could lead to the formation of algal blooms in water storage facilities and bio-fouling of irrigation equipment. The low N content in the TMW could not supply the annual N requirement of grapevines. The annual amount of P applied *via* the single dripper lines was slightly below grapevine requirements, whereas double the TMW irrigation applied excessive amounts of P. Amounts of K$^+$ applied via TMW irrigation was in excess of annual grapevine requirements, which could affect wine quality negatively. The amount of Ca^{2+} and Mg^{2+} applied *via* the TMW also exceeded annual grapevine requirements.

INTRODUCTION

The climate of the Western Cape is particularly suitable for the production of grapes and supports a very productive wine industry (Du Plessis & Schloms, 2017). However, fresh water resources are generally limited in the grape growing districts. Consequently, sustainable grape production in the province is highly dependent on winter rainfall and the application of irrigation in drier regions. In this regard, inconsistent rainfall and periodic droughts can severely impact the wine industry. During the 2014 to 2017 hydrological years, the province experienced its worst drought since 1904 (Botai *et al*., 2017). The City of Cape Town (CoCT) introduced level 6B water restrictions in February 2018 under which daily domestic water consumption was limited to 50 ℓ per person per day. The agricultural sector in the province also had to reduce its consumption by an average of 60% of its normal water quota. Some regions were more severely affected, *e.g.* producers in the Lower Olifants River region only received 13% of their normal allocation (World Wildlife Foundation, 2018). Furthermore, the South African wine grape harvest amounted to *ca*. 1.2 million tonnes in 2018, which was 15% less than in 2017 and the smallest crop in more than ten years (Vinpro, 2018). Conserving water and improving water use efficiency is therefore of cardinal value to the wine industry. The reuse of effluents and wastewater may present a potential solution to relieve pressure on fresh water sources and provide alternative irrigation water during drought periods.

Low annual rainfall, limited supply of fresh water that can be stored on farms, as well as water restrictions imposed by the authorities have emphasised the need for alternative irrigation water sources. Many arid and semi-arid countries use treated municipal wastewater (TMW) as an alternative source of irrigation water. For example, *ca*. 50% of Israel's irrigation water consists of TMW (Levy *et al*., 2014). It is particularly suitable as an irrigation water source in Mediterranean countries that have limited fresh water supplies during the warmer months and high rainfall during winter months that can facilitate the leaching of salts applied *via* wastewater irrigation. Thus far, the feasibility of using

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Acknowledgements: Messrs. Pierre Blake for permission to work in his vineyard, and Egbert Hanekom for managing the vineyard and technical assistance. Staff of the Soil and Water Science Division at ARC Infruitec-Nietvoorbij for technical support

TMW for vineyard irrigation under South African conditions has not been assessed. Despite this, it is reported that *ca*. 2 000 ha of vineyards in the Swartland region are irrigated with TMW (Myburgh, 2018). The CoCT and the Malmesbury municipality, respectively, supply this wastewater.

Using TMW for irrigation has a number of potential benefits. As a source of additional water it can improve and sustain crop production. Since domestic wastewater often contain high amounts of macro-elements, essential nutrients such as nitrogen (N), phosphorous (P) and potassium (K^+) can be recycled if applied *via* the irrigation water. In addition, the presence of organic compounds in TMW may have positive effects on soil structural stability. Furthermore, reusing large volumes of wastewater in a beneficial and environmentally responsible way can be a sustainable waste disposal management strategy. This will also limit the pollution of natural water bodies where wastewater is often deposited.

On the negative side, TMW usually have high salt contents that can affect the physical, chemical and biological properties of the soil. Sodium (Na^+) and K^+ are particularly detrimental in terms of soil structural stability and increasing soil salinity, which in turn affects crop water availability. The presence of large amounts of monovalent cations may result in clay dispersion that can subsequently clog soil pores and limit water movement into and throughout the soil. In addition, irrigation using K^+-rich wastewaters may lead to excessive K^+ uptake by grapevines that can potentially have a negative effect on wine quality (Laurenson *et al*., 2012). Furthermore, corrosive metals such as iron (Fe^{2+}) and manganese (Mn^{2+}) are often present in municipal wastewater due to an influx of industrial wastewater and can lead to the clogging of irrigation equipment. The presence of heavy metals, pathogens and pharmaceutical compounds may also limit the use of TMW, since some of these elements can accumulate in plants and ultimately enter the biological food chain. Most of the information generated with regard to wastewater originated from laboratory studies with either municipal wastewater or simulated wastewater. No studies have yet investigated the impact of irrigation of grapevines with TMW under field conditions in South Africa.

The objectives of this study were to assess the quality of TMW used for irrigation of commercial vineyards, and to quantify the amount of plant nutrients applied *via* TMW irrigation. This study formed part of a long-term project to assess the sustainability of using TMW for vineyard irrigation in the Coastal region of the Western Cape.

MATERIALS AND METHODS

Site selection and vineyard characteristics

The field trial was carried out in full bearing, commercial vineyards on a farm near Philadelphia in the Coastal region of the Western Cape (-33.40°, 18.35°) from the 2006/07 until 2017/18 seasons. The farm is located 12.2 km from the Atlantic Ocean, situated 132 m above sea level and has a mean February temperature of 21.6°C (Mehmel, 2010). The region has a Mediterranean climate and is classified as a class III climatic region according to its growing degree days from September to March (Winkler, 1974). Given the hilly landscape where the vineyards were irrigated using TMW, three experiment sites were selected in different landscape positions. The first site was in a *Vitis vinifera* L. cv. Sauvignon blanc vineyard located on the shoulder of a hill (Fig. 1), and was planted in 2000. The second and third sites were in two *V. vinifera* L. cv. Cabernet Sauvignon vineyards situated on a back- and a footslope, respectively. The vineyard on the footslope was planted in 2001, whereas the one on the backslope was planted in 2002. All grapevines were grafted onto 99Richer, and planted in a NS direction at a spacing of 2.75 m × 1.2 m. The grapevines were trained onto a five strand lengthened Perold trellis with moveable wires. Vertical shoot positioning was carried out to prevent a sprawling canopy. The vineyards were managed according to the grower’s normal viticultural practices in terms of cover crop, fertiliser and irrigation management.

Irrigation treatments and application

Each of the three main experiment sites consisted of three treatment plots. These plots consisted of one row of 15 experiment grapevines, as well as a buffer row on each side and at least two buffer grapevines at each end of the experiment rows. In one treatment, the grapevines were rain fed, *i.e.* grown under dryland conditions. It was included to compare soil and grapevine responses upon irrigation with TMW. Consequently, the rain fed treatment was not applicable to the present study. Determining soil and

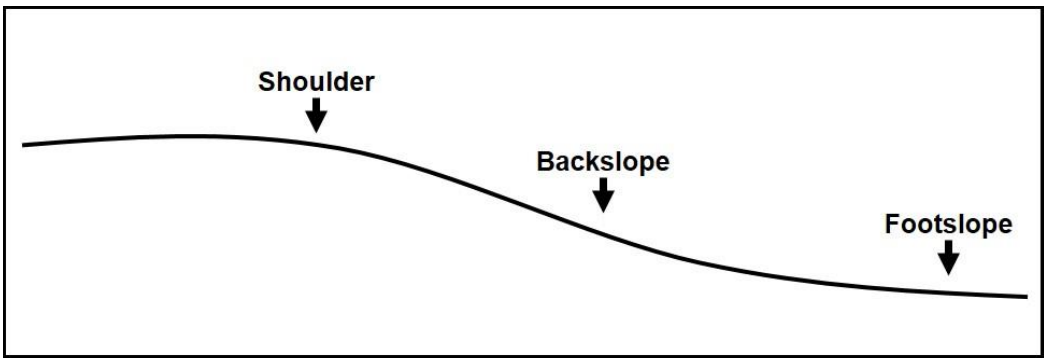

FIGURE 1
Diagram to illustrate the landscape position of the experiment sites near Philadelphia.

grapevine responses to irrigation with TMW compared to rain fed conditions is part of an ongoing study. Grapevines of the second treatment were irrigated with TMW *via* a single dripper line (SLD) which is the standard industry norm. Drippers were spaced 1 m apart in the grapevine row and had a flow rate of 2.3 ℓ/h. Irrigation frequency and volumes of water were applied according to the grower's irrigation schedule. Grapevines of the third treatment received irrigation *via* double dripper lines (DLD) which doubled the volume of wastewater compared to SLD. The purpose of the DLD was to accelerate any possible effects of the wastewater on the soil and grapevines. Irrigation volumes of the SLD plots were measured by means of water meters from the beginning of the study period. Since the lengths of the DLD plots were exactly the same as the SLD plots, it was assumed that grapevines in the DLD plot received double the volume of irrigation compared to those in the SLD plots. Rainfall was also measured for the duration of the study.

Irrigation water origin and quality

The TMW was sourced from the Potsdam wastewater treatment works (WWTW) near the CoCT. The wastewater was supplied to the farm *via* an extensive irrigation scheme that serves *ca.* 1000 hectares under grapevines. This particular WWTW uses the activated sludge method in combination with chlorination, as well as an ultraviolet disinfection stage to treat raw municipal wastewater to achieve chemical standards that allow the safe use of the wastewater for irrigation of crops (Olujimi *et al*., 2016; www.aurecongroup.com/projects/water/potsdam-wastewater-treatment-works). A sample of the TMW was collected annually on the farm at the beginning of each year since the 2006/07 season. Wastewater samples were analysed by a commercial laboratory for pH, electrical conductivity (EC_w), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), P, K^+, calcium (Ca^{2+}), magnesium (Mg^{2+}), Na^+, chloride (Cl^-), bicarbonate (HCO_3^-) and sulphate (SO_4^{2-}) according to methods described by Clesceri *et al*. (1998). The sodium adsorption ratio (SAR) was calculated as follows:

$$SAR = Na^+ \div [(Ca^{2+} + Mg^{2+}) \div 2]^{0.5} \quad \text{(Eq. 1)}$$

where Na^+, Ca^{2+} and Mg^{2+} are the sodium, calcium and magnesium concentrations (mmol/ℓ), respectively. Likewise, the potassium adsorption ratio (PAR) was calculated as follows:

$$PAR = K^+ \div [(Ca^{2+} + Mg^{2+}) \div 2]^{0.5} \quad \text{(Eq. 2)}$$

where K^+ is the potassium concentration (mmol/ℓ). Total nitrogen (total-N) was the sum of the NH_4-N and NO_3-N concentrations. From the 2007/08 season onwards, the TMW was also analysed for trace elements, *i.e.* boron (B^{3+}), Fe^{2+}, copper (Cu^{2+}), Mn^{2+} and zinc (Zn^{2+}), according to methods described by Clesceri *et al*. (1998). The heavy metals, *i.e.* arsenic (As^{3+}), cadmium (Cd^{2+}), chromium (Cr^{3+}), lead (Pb^{2+}) and mercury (Hg^{2+}), were also analysed according to methods described by Clesceri *et al*. (1998). It must be noted that the heavy metal concentrations were only determined from 2007/08 until 2012/13. Assessment of the microbial status in the TMW was beyond the scope of the study.

Amount of elements applied

Annual amounts of elements applied *via* TMW irrigation were calculated as described by Howell (2016). The amounts of elements present in the TMW were assumed to be relatively constant throughout the year. Therefore, the annual element content in the wastewater and total irrigated volume were used to calculate the amounts of elements applied during each season.

RESULTS AND DISCUSSION

Rainfall

At Philadelphia, rainfall is considerably lower compared to Stellenbosch, which is further inland and closer to the mountain ranges that border the Coastal region (Fig. 2). Mean annual rainfall only amounts to 259 mm at Philadelphia compared to 728 mm at Stellenbosch. Given the low summer

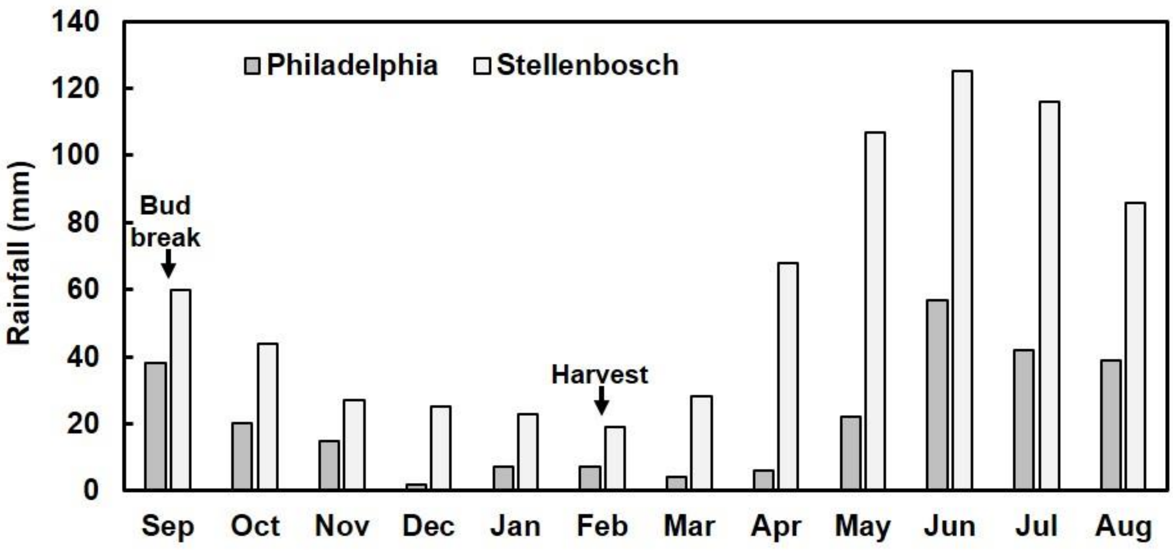

FIGURE 2
Mean monthly rainfall at Philadelphia (11 years) and Stellenbosch (9 years).

DOI: https://doi.org/10.21548/43-2-5466

rainfall, it is evident that grape production will benefit from irrigation, and be more sustainable compared to rain-fed grapevines. The low rainfall implies that accumulation of salts or harmful chemicals applied *via* irrigation with TMW is more likely to occur at Philadelphia than at Stellenbosch. Consequently, the risk of using wastewater for irrigation of vineyards will be greater at Philadelphia.

Irrigation volumes

On average, grapevines in the backslope and footslope sites received comparable volumes of irrigation, whereas those in the shoulder plot received slightly less (Table 1). Due to limited water resources, vineyards in the Coastal region generally receive relatively low irrigation volumes compared to regions such as the Breede and Olifants River. In the latter regions, more water can be abstracted from large irrigation schemes along the rivers. It was previously shown that 129 mm per year was sufficient for drip irrigated wine grapes near Wellington (Myburgh, 2011a; Myburgh, 2011b). This indicated that the grapevines at Philadelphia received adequate irrigation. On the other hand, it implied that grapevines in the DLD plots were indeed over-irrigated for the purpose of the study.

TABLE 1
Mean volume of TMW applied annually for grapevine irrigation by means of single dripper lines near Philadelphia from 2006/07 until 2017/18.

Landscape position	Irrigation (mm)
Shoulder	160±71
Backslope	168±70
Footslope	172±68

Irrigation water quality

pH: The pH range of the TMW varied between 6.7 and 8.0 throughout the 11-year study period (Table 2). This was within the range of 6.2 and 9.8 previously reported for TMW in Australia (Stevens, 2009). However, the pH tended to be lower than values of 8.5 to 9.0 reported for secondary treated municipal effluents in Botswana (Emongor & Ramolemana, 2004). The pH variation was within the range of 6.5 to 8.4 which is recommended for irrigation water (Howell & Myburgh, 2013 and references therein). Irrigation water with a pH outside of this range may result in nutritional imbalances, or may contain toxic ions (Ayers & Westcot, 1985). The pH of the TMW was within the legislated limits to irrigate up to 500 m^3 of wastewater per day as prescribed by the General Authorisations as indicated in Table 3 (Department of Water Affairs, 2013).

Electrical conductivity: The EC_w of the TMW (Table 2) was well within the range of 0.2 dS/m to 2.9 dS/m (Stevens, 2009) and similar to values of 0.9 dS/m to 1.6 dS/m reported by Laurenson *et al*. (2012). However, the mean EC_w slightly exceeded the critical value of 0.8 dS/m which is the salinity threshold for water used to irrigate grapevines (Van Zyl, 1981). The EC_w range measured for the irrigation water fell within the range of 0.7 dS/m to 3.0 dS/m at which salinity problems in terms of crop water availability might occur in sensitive crops (Ayers & Westcot, 1985). However, no notable reduction in vegetative growth of grapevines is expected at the maximum measured EC_w, *i.e.* 1.2 dS/m (Ayers & Westcot, 1985). Similar to pH, the EC_w was within the legislated limits (Table 3).

TABLE 2
The pH and electrical conductivity (EC_w) of the TMW used for vineyard irrigation near Philadelphia from 2006/07 until 2017/18.

Parameter	Minimum	Maximum	Mean
pH	6.7	8.0	7.1±0.3
EC_w (dS/m)	0.7	1.2	0.9±0.2

TABLE 3
General Authorisations for legislated limits for pH, electrical conductivity (EC_w), chemical oxygen demand (COD), faecal coliforms (FC) and sodium adsorption ratio (SAR) for wastewater used for irrigation in South Africa (Department of Water Affairs, 2013).

Parameter	Maximum irrigation volumes (m^3/day)		
	< 50	< 500	< 2 000
pH	6-9	6-9	5.5-9.5
EC_w (dS/m)	2	2	0.7-1.5
COD (mg/ℓ)	5 000	400	75
FC (per 100 mℓ)	1 000 000	100 000	1 000
SAR	< 5	< 5	Other criteria apply

Nitrogen and phosphorus: The mean total-N value measured over the course of the study period (Table 4) was considerably lower than the range of 8.0 mg/ℓ to 30.7 mg/ℓ reported previously (Laurenson *et al*., 2012). The maximum of 16.0 mg/ℓ was a result of high NH_4-N levels in the wastewater during the 2011/12 growing season (data not shown). However, the NH_4-N levels of the irrigation water was on average low (Table 4). Similarly, NO_3-N levels were well below values of 6.7 mg/ℓ to 29.3 mg/ℓ previously reported for secondary treated municipal effluent (Emongor & Ramolemana, 2004). As a result, the mean total-N level was below the critical value of 5 mg/ℓ at which crops sensitive to N (such as grapevines) might be affected (Howell & Myburgh, 2013 and references therein). Therefore, an over-supply of N through treated wastewater irrigation was not a concern. The level of P in the TMW ranged between 0.1 mg/ℓ and 9.5 mg/ℓ (Table 4) and was similar to the range of 2.7 mg/ℓ to 12.8 mg/ℓ reported by Laurenson *et al.* (2012). However, the P concentration in the wastewater consistently exceeded the long-term critical value of 0.05 mg/ℓ which demarcates a risk for algal blooms and bio-fouling of the irrigation equipment (Howell & Myburgh, 2013 and references therein).

Calcium and magnesium: Levels of Ca^{2+} in the wastewater varied between 33.4 mg/ℓ and 67.3 mg/ℓ throughout the 11-year study period (Table 5). This range was considerably higher than values of 6 mg/ℓ to 16 mg/ℓ reported by Chen *et al*. (2013), but it was comparable to values of 31 mg/ℓ to 70 mg/ℓ reported by Andrews *et al*. (2016). There are no South African guidelines for Ca^{2+} concentrations in irrigation water (Department of Water Affairs & Forestry, 1996). The Ca^{2+} levels are important since appreciable amounts of Ca^{2+} may help to reduce the SAR and PAR and as a result, mitigate the impacts of Na^+ and K^+ on soil structural stability. There are also no guidelines available for Mg^{2+} levels in irrigation water (Department of Water Affairs & Forestry, 1996). Similar to Ca^{2+}, Mg^{2+} can also play a positive role in decreasing the SAR. However, crops that are irrigated with Mg-rich water may be affected by Mg-induced Ca^{2+} deficiencies, but due to insufficient data, the Ca:Mg ratio is not regularly used for evaluation (Ayers & Westcot, 1985). Nevertheless, the Mg^{2+} levels in the TMW were relatively low and ranged from 6.1 mg/ℓ to 11.6 mg/ℓ (Table 5).

Potassium: The mean level of K^+ in the irrigation water was 20.3 mg/ℓ (Table 5). This was below ranges of 23 mg/ℓ to 25 mg/ℓ observed in Australia (Laurenson *et al*., 2012) and 22 mg/ℓ to 37.4 mg/ℓ in Greece (Paranychianakis *et al*., 2006). Since K^+ concentrations in municipal wastewater are often relatively low compared to other constituents, it is generally not reported (Stevens, 2009). Subsequently, the South African Water Quality Guidelines (Department of Water Affairs & Forestry, 1996) omitted a legal limit for K^+ concentrations in irrigation water. Previous studies have shown that increased K^+ concentrations in soils may lead to a reduction in soil hydraulic conductivity and water infiltration rate (Quirk & Schofield, 1955; Levy & Van der Watt, 1990). Potassium can have a broad spectrum of possible effects on water infiltration, ranging from being similar to Na^+ (negative effect) to being similar to Ca^{2+} (positive effect) (Arienzo *et al*., 2009). It was also shown that K^+ had an intermediate effect relative to Na^+ and Ca^{2+} on soil hydraulic properties (Levy & Van der Watt, 1990). Given the relatively low K^+ concentration of the TMW used in this study, it is not expected that K^+ supplied *via* irrigation would have a negative impact on the soil hydraulic properties.

TABLE 4
Total nitrogen (N), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N) and phosphorous (P) levels in the TMW used for vineyard irrigation near Philadelphia from 2006/07 until 2017/18.

Element	Minimum	Maximum	Mean
Total N (mg/ℓ)	1.0	16.0	4.3±1.5
NH_4-N (mg/ℓ)	0.1	12.7	2.1±1.0
NO_3-N (mg/ℓ)	0.0	5.6	2.4±1.6
P (mg/ℓ)	0.1	9.5	3.2±1.1

TABLE 5
Calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+) levels in the TMW used for vineyard irrigation near Philadelphia from 2006/07 until 2017/18.

Element	Minimum	Maximum	Mean
Ca^{2+} (mg/ℓ)	33.4	67.3	46.4±8.8
Mg^{2+} (mg/ℓ)	6.1	11.6	8.5±1.5
K^+ (mg/ℓ)	14.8	32.6	20.3±6.2
Na^+ (mg/ℓ)	100.7	173.6	120.9±18.1

 DOI: https://doi.org/10.21548/43-2-5466

Sodium: The variation of Na^+ levels in the TMW was between 100.7 mg/ℓ and 173.6 mg/ℓ (Table 5). This was lower than the range of 208 mg/ℓ to 264 mg/ℓ in municipal wastewater that have undergone secondary treatment *via* the activated sludge method (Paranychianakis *et al*., 2006). In contrast, the Na^+ levels were considerably higher than the range of 40 mg/ℓ to 70 mg/ℓ in reclaimed water (Chen *et al*., 2013). The mean Na^+ concentration of 120.9 mg/ℓ exceeded the critical value of 100 mg/ℓ which is the legal limit for irrigating grapevines in South Africa (Howell & Myburgh, 2013 and references therein). Grapevines are considered to be moderately sensitive to foliar injury by excessive Na^+ (Howell, 2016 and references therein). A concentration of 115 mg/ℓ Na^+ in the irrigation water is considered the upper threshold for overhead irrigation for all crops (Department of Water Affairs & Forestry, 1996). As the experiment grapevines were irrigated by means of drippers below the canopy, the leaves were not wetted with irrigation water. However, increasing Na^+ levels in the soil due to wastewater irrigation may have adverse effects on soil structure (Rengasamy & Olsson, 1991). It must be noted that soil structural damage caused by Na^+ is usually irreversible.

Sodium and potassium adsorption ratio: The mean SAR of the TMW (Table 6) also met the criteria stipulated by the General Authorisations for irrigating up to 500 m^3 per day (Table 3). The SAR only exceeded the threshold of 5 $(mmol/ℓ)^{0.5}$ during the 2017/18 season (data not shown). According to the SAR values of 0 to 10 $(mmol/ℓ)^{0.5}$ proposed by Van Zyl (1981), the TMW had a low sodium hazard. Furthermore, the SAR was below the threshold value of 20 $(mmol/ℓ)^{0.5}$ at which Na^+ toxicities are expected in grapevines (Ayers & Westcot, 1985 and references therein). However, the combination of the relatively low EC_w (mean 0.9 dS/m) and low SAR (mean 4.3 $(mmol/ℓ)^{0.5}$) may potentially result in problems with water infiltration (Ayers & Westcot, 1985). The PAR variation of 0.3 $(mmol/ℓ)^{0.5}$ to 0.6 $(mmol/ℓ)^{0.5}$ (Table 6) was similar to values of 0.4 $(mmol/ℓ)^{0.5}$ to 0.6 $(mmol/ℓ)^{0.5}$ reported by Laurenson *et al*. (2012). The PAR has been less widely adopted for wastewater quality evaluation due to the typically low K^+ concentrations present in most wastewaters (Laurenson *et al*., 2012). However, the PAR can be an important measurement to estimate soil dispersion risks where agro-industrial wastewaters are used for irrigation (Smiles & Smith, 2004).

Chloride, bicarbonate and sulphate: The mean Cl^- concentration of the TMW was 160.2 mg/ℓ, but ranged between 111.2 mg/ℓ and 281.2 mg/ℓ throughout the 11-year study period (Table 7). The Cl^- levels present in the irrigation water were well below the threshold value of 700 mg/ℓ at which toxicity problems in grapevines might occur (Van Zyl, 1981). The levels of HCO_3^- in the irrigation water ranged between 142.1 mg/ℓ and 242.0 mg/ℓ (Table 7), which is higher than the values of 50 mg/ℓ to 100 mg/ℓ reported by Chen *et al*. (2013). However, the mean HCO_3^- concentration measured throughout the study period was similar to secondary treated municipal effluents in Botswana (Emongor & Ramolemana, 2004). It should be noted that high levels of HCO_3^- in irrigation water may have negative impacts on crops, soils and irrigation equipment (Howell, 2016 and references therein). The addition of water rich in HCO_3^- and carbonate (CO_3^{2-}) may increase HCO_3^- in the soil solution and result in the precipitation of insoluble Ca^{2+} and Mg^{2+} carbonates when the soil dries out (Van Zyl, 1981). The SO_4^{2-} levels in the irrigation water varied between 54 mg/ℓ and 276 mg/ℓ (Table 7) and were similar to values of 66 mg/ℓ and 192 mg/ℓ previously reported for municipal wastewater treated *via* the activated sludge method in California (Pescod, 1992 and references therein). There are currently no guidelines available for the permissible levels of SO_4^{2-} in irrigation water (Department of Water Affairs & Forestry, 1996). However, it is important to measure SO_4^{2-} levels in irrigation water, since waters containing high levels of both Ca^{2+} and SO_4^{2-} may result in the precipitation of gypsum ($CaSO_4$) in irrigation equipment and subsequent clogging

TABLE 6
Sodium adsorption ratio (SAR) and potassium adsorption ratio (PAR) in the TMW used for vineyard irrigation near Philadelphia from 2006/07 until 2017/18.

Parameter	Minimum	Maximum	Mean
SAR $(mmol/ℓ)^{0.5}$	3.0	5.5	4.3±0.7
PAR $(mmol/ℓ)^{0.5}$	0.3	0.6	0.4±0.1

TABLE 7
Chloride (Cl^-), bicarbonate (HCO_3^-) and sulphate (SO_4^{2-}) levels in the TMW used for vineyard irrigation near Philadelphia from 2006/07 until 2017/18.

Element	Minimum	Maximum	Mean
Cl^- (mg/ℓ)	111.2	281.2	160.2±39.8
HCO_3^- (mg/ℓ)	142.1	242.0	203.0±33.5
SO_4^{2-} (mg/ℓ)	54.0	276.0	84.4±11.3

of equipment (Du Plessis *et al*., 2017). High amounts of SO_4^{2-} in wastewater may also cause corrosion of equipment (Venkatesan & Swaminathan, 2009).

Trace elements: Levels of B^{3+} in the irrigation water ranged between 0.18 mg/ℓ and 0.50 mg/ℓ with a mean value of 0.27 mg/ℓ over the course of the study (Table 8). Although B^{3+} is considered an essential plant nutrient, it can be toxic at reasonably low concentrations. Grapevines have been classified as sensitive (Ayers & Wetscot, 1985; Department of Water Affairs & Forestry, 1996) to highly sensitive (Van Zyl, 1981) to B^{3+} toxicities. A maximum B^{3+} concentration of between 0.5 mg/ℓ and 0.75 mg/ℓ has been suggested by Ayers and Westcot (1985) for water used for irrigating grapevines. With regard to these thresholds, the TMW used for the present study did not hold any risks in terms of B^{3+} toxicity. Concentrations of Cu^{2+} in the TMW varied from being completely absent to a maximum concentration of 0.06 mg/ℓ (Table 8). According to Ayers and Westcot (1985), Cu^{2+} can be toxic to some plants at levels between 0.1 mg/ℓ and 1.0 mg/ℓ, which are higher than the values obtained in this study. Therefore, no Cu^{2+} toxicities were expected. The Fe^{2+} levels ranged between zero and 0.34 mg/ℓ with a mean value of 0.10 mg/ℓ throughout the 11-year study period (Table 8). The Fe^{2+} concentration in the wastewater never exceeded the critical value of 5 mg/ℓ that is the recommended maximum concentration of Fe^{2+} in irrigation water used for irrigation of grapevines (Van Zyl, 1981). In addition, the measured Fe^{2+} levels were below the value of 1.5 mg/ℓ at which Fe precipitation and the clogging of drip irrigation systems might occur (Department of Water Affairs & Forestry, 1996). Levels of Mn^{2+} in the irrigation water varied from being absent to a maximum concentration of 0.08 mg/ℓ (Table 8). A maximum level of 0.2 mg/ℓ is the recommended norm (Ayers & Westcot, 1985). However, according to South African guidelines levels of Mn^{2+} should not exceed 1.5 mg/ℓ, since Mn^{2+} may cause clogging of irrigation pipelines, *i.e.* similar to Fe^{2+} (Department of Water Affairs & Forestry, 1996). The maximum concentration of Zn^{2+} measured in the TMW was 0.21 mg/ℓ, whereas the mean was 0.05 mg/ℓ (Table 8). A maximum level of 2 mg/ℓ is the norm for grapevines under continuous irrigation on all soil types (Van Zyl, 1981).

Heavy metals: No As^{3+} and Hg^{2+} were detected in the TMW. Chromium was present in every season up to 2012/13, with concentrations ranging between 0.001 mg/ℓ and 0.023 mg/ℓ. Concentrations of Cd^{2+} and Pb^{2+} in the TMW were less than 0.003 mg/ℓ and 0.004 mg/ℓ, respectively. Due to the low concentrations measured and cost implications, analyses of heavy metals were terminated in 2013/14.

Amount of elements applied

Nitrogen: The amounts of NH_4-N and NO_3-N applied to the grapevines were comparable, irrespective of the landscape position (Table 9). The annual amount of total-N applied to grapevines in all the plots was equivalent to 4.3 kg per 100 mm irrigation (data not shown). This was appreciably less than the estimated 22.6 kg/ha applied *via* 100 mm of municipal wastewater irrigation (Laurenson *et al*., 2012). Grapevines require *ca*. 50 kg/ha N annually to produce 10 tonnes of grapes per hectare (Saayman, 1981). Although the DLD grapevines received double the amount of total-N applied *via* TMW irrigation, it was still inadequate to supply in the annual N requirement.

Phosphorus: The mean amounts of P applied annually *via* TMW to grapevines at the three sites were comparable (Table 9). Grapevines in all plots received the equivalent of 3.2 kg/ha P per 100 mm irrigation annually (data not shown). This amount is appreciably lower than the estimated 8.2 kg/ha P applied *via* 100 mm of municipal wastewater irrigation (Laurenson *et al*., 2012). Grapevines require *ca*. 0.7 kg P per tonne of grapes produced (Saayman, 1981). According to this norm, grapevines in the SLD plots received insufficient P *via* the TMW irrigation to sustain a grape yield of 10 t/ha. Where more irrigation was applied at the DLD plots, P slightly exceeded the grapevine requirements. Previous studies have shown that levels of P in grapevines improved upon irrigation with TMW (Neilsen *et al*., 1989; Paranychianakis *et al*., 2006). Higher element mobility within the soil profile (Laurenson *et al*., 2012), as well as more efficient plant utilisation (Sakadevan *et al*., 2000) was observed where P was applied *via* municipal wastewater irrigation. In contrast, irrigation with sewage effluent reduced petiole-P of Shiraz grapevines compared to fresh water (McCarthy, 1981). This could be due to a decrease in plant available P as the pH change upon wastewater irrigation in some soils (Mulidzi *et al*., 2016). Consequently, TMW irrigation might not always be beneficial in terms of P nutrition.

Potassium: The ratio between the amounts of K^+, Na^+, Ca^{2+} and Mg^{2+} applied to the grapevines was approximately

TABLE 8
Boron (B^{3+}), copper (Cu^{2+}), iron (Fe^{2+}), manganese (Mn^{2+}) and zinc (Zn^{2+}) levels in the TMW used for vineyard irrigation near Philadelphia from 2007/08 until 2017/18.

Element	Minimum	Maximum	Mean
B^{3+} (mg/ℓ)	0.2	0.50	0.27±0.09
Cu^{2+} (mg/ℓ)	0.0	0.06	0.02±0.02
Fe^{2+} (mg/ℓ)	0.0	0.34	0.10±0.08
Mn^{2+} (mg/ℓ)	0.0	0.08	0.04±0.03
Zn^{2+} (mg/ℓ)	0.0	0.21	0.05±0.02

2.5:15: 6: 1 (Table 10). Grapevines in all plots received the equivalent of 20.3 kg/ha K^+ per 100 mm irrigation annually. This was less than the estimated 29.4 kg/ha K^+ applied *via* 100 mm of municipal wastewater irrigation (Laurenson *et al*., 2012). Grapevines have an annual requirement of *ca.* 3 kg K^+ per tonne of grapes produced (Saayman, 1981). Therefore, the amount of K^+ applied to grapevines in the SLD plots would be adequate to sustain a yield of 10 t/ha. Based on this norm, however, excessive K^+ was applied *via* the TMW irrigation to grapevines in the DLD plots. An over-supply of K^+ to grapevines can have numerous implications for wine production. Since grapevine berries are considered to be a strong sink for K^+ (Mpelasoka *et al.*, 2003), excessive application may lead to an accumulation of K^+ in the berries. This, in turn, may have negative impacts on wine quality. A high concentration of K^+ in grape juice may lead to a reduction in the concentration of tartaric acid in the juice and result in increased juice, must and wine pH (Saayman, 1981; Mpelasoka *et al*., 2003; Kodur, 2011). Consequently, the increased pH may lead to the development of unstable musts and wines, as well as a reduction in colour quality of red wines (Somers, 1975; McCarthy & Downton, 1981; Mpelasoka *et al*., 2003). The application of excessive amounts of K^+ may also reduce the juice N content (Saayman, 1981), and subsequently increase the risk of stuck fermentation during winemaking (Bell & Henschke, 2005; Malherbe *et al*., 2007). Excessive K^+ in the soil can also reduce the uptake of Ca^{2+} and Mg^{2+} by grapevines due to an antagonistic interaction between K^+ and these cations (Morris & Cawthon, 1982). Furthermore, it must be noted that the supplied K^+ will only be beneficial for grapevine nutrition for a short period after harvest as K^+ absorption decreases during the post-harvest period (Conradie, 1981b).

Sodium: Since Na^+ is not considered an essential element for grapevine growth (Winkler *et al*., 1974), no threshold value with regard to the amount of Na^+ applied to vineyards exists (Howell, 2016). However, the high amounts of Na^+ applied *via* the TMW in relation to the other cations, particularly Ca^{2+} (Table 10), suggests that sodic soil conditions may develop over time. This could reduce soil hydraulic conductivity and water infiltration rate of the soils (Halliwell *et al*., 2001). Furthermore, excessive Na^+ application may reduce vegetative growth and yield, as well as suppress Ca^{2+} uptake by plants (Myburgh & Howell, 2014a and references therein). Excessive Na^+ may also have a direct toxic effect on grapevines (Saayman, 1981). It must be noted that the sodicity problem will be aggravated in an arid climate and/or

TABLE 9
Mean annual, as well as total ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total nitrogen (Total-N) and phosphorous (P) applied *via* TMW used for vineyard irrigation from 2006/07 until 2017/18 near Philadelphia.

		NH_4-N		NO_3-N		Total-N		P	
Landscape position	Dripper lines	Annual (kg/ha)	Total (kg/ha)	Annual (kg/ha)	Total (kg/ha)	Annual (kg/ha)	Total (kg/ha)	Annual (kg/ha)	Total (kg/ha)
Shoulder	Single	3.4	37	3.8	42	6.9	76	5.1	56
	Double	6.7	74	7.7	84	13.8	151	10.2	112
Backslope	Single	3.5	39	4.0	44	7.2	79	5.4	59
	Double	7.1	78	8.1	89	14.4	159	10.8	118
Footslope	Single	3.6	40	4.1	45	7.4	81	5.5	61
	Double	7.2	79	8.3	91	14.8	163	11.0	121

TABLE 10
Mean annual, as well as total potassium (K^+), sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}) applied *via* TMW used for vineyard irrigation from 2006/07 until 2017/18 near Philadelphia.

		K^+		Na^+		Ca^{2+}		Mg^{2+}	
Landscape position	Dripper lines	Annual (kg/ha)	Total (t/ha)	Annual (kg/ha)	Total (t/ha)	Annual (kg/ha)	Total (t/ha)	Annual (kg/ha)	Total (t/ha)
Shoulder	Single	32	0.36	193	2.13	74	0.82	14	0.15
	Double	65	0.71	387	4.26	148	1.63	27	0.30
Backslope	Single	33	0.38	203	2.23	78	0.86	14	0.16
	Double	68	0.75	406	4.47	156	1.72	28	0.31
Footslope	Single	35	0.38	208	2.29	80	0.88	15	0.16
	Double	70	0.77	416	4.57	160	1.76	29	0.32

in soils with poor internal drainage, *e.g.* clayey soils. Under such conditions, irrigation with TMW is unlikely to sustain economically viable grape production.

Calcium and magnesium: The amount of Ca^{2+} applied *via* the municipal wastewater irrigation to the grapevines was higher compared to K^+ and Mg^{2+}, but substantially less than the amount of Na^+ applied (Table 10). According to Saayman (1981), grapevines annually require *ca*. 2 kg Ca^{2+} per tonne of grapes produced. Based on this recommendation, the TMW supplied adequate amounts of Ca^{2+} to sustain yields in excess of 10 t/ha in all the experiment plots. Furthermore, the application of excess Ca^{2+} may also be beneficial in mitigating the possible negative effects of Na^+ applied *via* wastewater irrigation due to its role in decreasing the SAR. The amount of Mg^{2+} applied *via* the TMW was appreciably less than the K^+, Na^+ and Ca^{2+} (Table 10). Grapevines annually require 0.6 kg Mg^{2+} per tonne of grapes produced (Conradie, 1981a). Consequently, the TMW supplied more than adequate amounts of Mg^{2+} to the grapevines.

Chloride, bicarbonate and sulphate: The ratio between the amounts of Cl^-, HCO_3^- and SO_4^{2-} applied was approximately 2 : 2.5 : 1 (Table 11). The application of excessive amounts of Cl^- to soils can impact negatively on grapevine water relations, since grapevines have to take up water at high osmotic potential. The large amounts of HCO_3^- applied through the irrigation water is alarming, as it may lead to the precipitation of insoluble Ca- and Mg-carbonates when the soils dry out, resulting in the removal of Ca^{2+} and Mg^{2+} from the soil solution (Van Zyl, 1981). This, in turn, will increase relative Na^+ levels and subsequently lead to higher SAR levels which may have an impact on soil physical properties (Van Zyl, 1981). High concentrations of SO_4^{2-} in TMW may increase levels of SO_4^{2-} in soil. Elevated levels of SO_4^{2-} can reduce K^+ and Mg^{2+} uptake by grapevines (Myburgh & Howell, 2014b). This is most likely due to sulphate salinisation (Marschner, 1995).

Trace elements and heavy metals: Since the trace elements in the TMW were undetectable, or present in low concentrations (Table 8), the amounts applied annually *via* the TMW irrigation were extremely low under the prevailing conditions (Table 12). Due to the low level of application, the trace elements were unlikely to have impacted negatively on the soil and/or grapevines. Likewise, the absence, or low concentrations of the heavy metals in the TMW as discussed above, and the subsequent extremely low amounts applied, suggested that no negative effects on the soil and/or grapevines were to be expected.

CONCLUSIONS

In addition to using artificial "wastewater", most of the previous studies were carried out in laboratories. Therefore, this study was unique in the sense that actual TMW was used for vineyard irrigation under field conditions. It was evident that the chemical load in the TMW varied substantially. This caused inevitable fluctuations in the amounts of elements applied to the grapevines. Since the volumes of TMW applied differed between the vineyards, it also contributed to variation in the amounts of elements applied to the different vineyards. Due to the variability, it was crucial to continue the study over a period of 11 years to establish trends, and draw reliable conclusions. In terms of pH, EC_w and SAR, the quality of the TMW used for vineyard irrigation in the study met the minimum criteria stipulated by the General Authorisations that allow up to 500 m^3 irrigation per day. The P concentration in the TMW consistently exceeded the long-term critical value of 0.05 mg/ℓ which demarcates a risk for algal blooms in water storage facilities, as well as bio-fouling of irrigation equipment. The mean Na^+ concentration of 120.9 mg/ℓ in the TMW exceeded the critical value of 100 mg/ℓ for irrigating grapevines in South Africa. Chloride levels in the TMW were well below the threshold value of 700 mg/ℓ at which toxicity in grapevines might occur. Consequently, regular analyses of TMW is essential when using TMW as an alternative source of water for vineyard irrigation. This will ensure that the chemical load conforms to recommended thresholds and norms. In doing so, irreversible damage to irrigation equipment, soils and grapevines can be avoided.

The low N content in the wastewater was not sufficient to supply the annual N requirement of grapevines. The low

TABLE 11
Mean annual, as well as total chloride (Cl^-), bicarbonate (HCO_3^-), and sulphate (SO_4^{2-}) applied *via* TMW used for vineyard irrigation from 2006/07 until 2017/18 near Philadelphia.

		Cl^-		HCO_3^-		SO_4^{2-}	
Landscape position	Dripper lines	Annual (kg/ha)	Total (t/ha)	Annual (kg/ha)	Total (t/ha)	Annual (kg/ha)	Total (t/ha)
Shoulder	Single	255	2.80	323	3.55	134	1.48
	Double	509	5.60	646	7.10	268	2.95
Backslope	Single	276	3.03	349	3.84	145	1.60
	Double	551	6.06	698	7.68	290	3.19
Footslope	Single	269	2.96	341	3.75	142	1.56
	Double	538	5.92	682	7.50	284	3.12

TABLE 12
Mean annual, as well as total boron (B^{3+}), copper (Cu^{2+}), iron (Fe^{3+}) manganese (Mn^{2+}) and zinc (Zn^{2+}) applied *via* TMW used for vineyard irrigation from 2006/07 until 2017/18 near Philadelphia.

Landscape position	Dripper lines	B^{3+} Annual (g/ha)	B^{3+} Total (kg/ha)	Cu^{2+} Annual (g/ha)	Cu^{2+} Total (kg/ha)	Fe^{3+} Annual (g/ha)	Fe^{3+} Total (kg/ha)	Mn^{2+} Annual (g/ha)	Mn^{2+} Total (kg/ha)	Zn^{2+} Annual (g/ha)	Zn^{2+} Total (kg/ha)
Shoulder	Single	429	4.72	32	0.35	159	1.75	64	0.70	80	0.87
	Double	859	9.44	64	0.70	318	3.50	127	1.40	159	1.75
Backslope	Single	464	5.11	34	0.38	172	1.89	69	0.76	86	0.95
	Double	929	10.22	69	0.76	344	3.78	138	1.51	172	1.89
Footslope	Single	454	4.99	33	0.37	168	1.85	67	0.74	84	0.92
	Double	907	9.98	67	0.74	336	3.70	134	1.48	168	1.85

level of N was also unlikely to cause pollution of natural water sources. Where double the normal irrigation volume was applied, TMW supplied adequate amounts of P to meet annual grapevine requirements. The amounts of K^+ applied *via* TMW irrigation were in excess of grapevine requirements, and could have negative effects on wine quality. In general, using TMW irrigation can supply grapevine nutrients in a plant-available form, but some nutrient amounts may be insufficient, whereas others may be excessive. Consequently, growers are recommended to use an integrated fertiliser program by adjusting fertiliser amounts according to the amount of nutrients applied *via* the wastewater. Growers could also consider diluting the wastewater with raw water to reduce oversupply of certain elements, if indicated by analysis.

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