Environmental impact of irrigation with greywater treated by recirculating vertical flow constructed wetlands in two climatic regions

Amit Gross, Yuval Alfiya, Menachem Sklarz, Adi Maimon and Eran Friedler

ABSTRACT

Reuse of greywater (GW) has raised environmental and public health concerns. Specifically, these concerns relate to onsite treatment operated by non-professionals; systems must therefore be reliable, simple to use and also economically feasible if they are to be widely used. The aims of this study were to: (a) investigate GW treatment efficiency using 20 full-scale recirculating vertical flow constructed wetlands (RVFCWs) operated in households in arid and Mediterranean regions; and (b) study the long-term effects of irrigation with treated GW on soil properties. RVFCW systems were installed and monitored routinely over 3 years. Raw, treated and disinfected treated GW samples were analyzed for various physicochemical and microbial parameters. Native soil plots and nearby freshwater (FW) and treated GW irrigated soil plots were sampled twice a year – at the end of the winter and at the end of the summer. Soil samples were analyzed for various physicochemical and microbial parameters. Overall, the RVFCW proved to be a robust and reliable GW treatment system. The treated GW quality met strict Israeli regulations for urban irrigation. Results also suggest that irrigation with sufficiently treated GW has no adverse effects on soil properties. Yet, continued monitoring to follow longer term trends is recommended.

Key words | greywater, reuse, soil quality

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INTRODUCTION

Greywater (GW) reuse can significantly decrease domestic water consumption, while alleviating stress on existing water resources and contributing to more sustainable water use. However, inappropriate reuse of GW might negatively affect the environment and compromise human health as it often contains a range of pathogens (bacteria and viruses) as well as substances having the potential to induce undesired environmental consequences such as soil hydrophobicity, accumulation of salts and damage to plants. Therefore, appropriate treatment is needed for safe GW reuse (Alfiya *et al.* 2012; Negahban-Azar *et al.* 2012).

It is often argued that there is limited information on possible health and water quality problems resulting from poorly designed, operated or maintained systems. Similarly, knowledge of the extent of the long-term environmental impacts on soil, as well as on ground- and surface-water is limited (Negahban-Azar *et al.* 2012).

Onsite treatment of small volumes of GW originating from an individual household can be challenging due to significant fluctuations in GW quantity and quality, which are highly dependent on the lifestyles, habits and activities of household inhabitants. Significant variations in temperature of the incoming GW, and in the concentrations of various parameters such as organic matter, pH and surfactants are also to be expected. These oscillations can adversely affect the efficiency of biological processes that are commonly used in these onsite treatment systems. Alternatively, if properly managed, decentralized GW treatment systems can perform effectively, without harming human health and the environment. Such systems are acknowledged as a key component of wastewater infrastructure in the USA and many other countries (e.g. US EPA 2005). Unlike large, centralized treatment systems, maintenance of small onsite GW treatment and reuse

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systems (e.g. in a single-family home) is usually undertaken by the inhabitants themselves with limited (if any) professional intervention and/or support. Therefore, unless these onsite systems are reliable, environmental and public health might be compromised. Alfiya *et al.* (2013) demonstrated that the fault-tree approach, used to design the GW systems reported in this study, ensures high reliability as long as scheduled (relatively infrequent) maintenance is performed.

In recognition of these risks, regulations/guidelines for the reuse of GW have been proposed in recent years by different entities worldwide (e.g. WHO 2006; BSi 2010). Traditionally, these regulations/standards have been concerned primarily with public health considerations, such as exposure of residents to pathogens, rather than with the environmental impact on soil and groundwater of GW reuse. However, it is recognized that utilizing GW for irrigation could lead to the unwanted accumulation of various compounds in the soil. Some of these, such as nitrogen (N) and phosphorus (P), can be usefully taken up by plants, while others, such as boron (B) and salinity, may be directly phytotoxic (Nable *et al.* 1997), or may cause changes in soil chemistry that can adversely impact crop growth and/or soil structure (Stevens *et al.* 2011). Therefore, application of GW has to be carefully managed for effective use.

The aims of the current research were to: (a) investigate GW treatment efficiency in a large-scale field study, using 20 recirculating vertical flow constructed wetlands (RVFCWs) operated in single-family homes in two geographical regions; and (b) study possible long-term effects of irrigation with treated GW on soil properties.

MATERIALS AND METHODS

Twenty RVFCWs were installed in single-family homes and the treated GW effluent from the systems was used for landscape irrigation. As already mentioned, these were designed, constructed and operated following the fault-tree approach in order to minimize the associated risks (more details can be found in Alfiya *et al.* (2013)). Prior to installation, residents received information regarding the potential risks associated with GW reuse and 'behavioural means' to minimize them and reduce exposure to GW. The systems were installed in two different climatic regions in Israel as follows: nine units were installed in the northern and central parts of the country, where a Mediterranean climate prevails, with average annual precipitation of 500–600 mm (only during winter), and average winter and summer low and high temperatures of 10–21, and 20–29 °C, respectively. Eleven systems were installed in the Negev Desert and the Jordan Rift Valley, which are arid regions with average annual precipitation of less than 80 mm (also during the winter only), and average winter and summer low and high temperatures of 7.0–19, and 16–31 °C, respectively. The systems were installed in the summer of 2009 and have been operating since then. The volume of treated GW reused for irrigation was recorded and its quality was analysed at least every other month over 3 years. Treated GW was used for drip irrigation in household gardens. Each RVFCW system consists of two containers (1.0 m × 1.0 m × 0.5 m) placed one above the other (Figure 1). The upper container holds a planted three-layered bed, while the lower one functions as a reservoir. The bed consists of an upper layer of woodchips, followed by tuff gravel (25 mm average diameter) and a lower layer of limestone pebbles

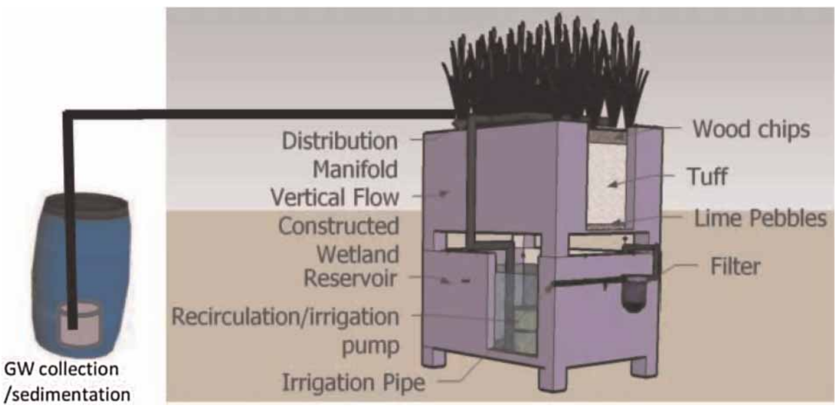

Figure 1 | Schematic of the on-site RVFCW GW treatment system (after Alfiya *et al.* 2013).

(25 mm average diameter). GW is pumped from a primary collection tank and applied to the top of the bed; from there, it drips through the bed and into the reservoir through the perforated bottom of the upper container. From the reservoir, GW is recirculated to the top of the bed at a rate of about 300 L/h. A detailed description of the system can be found in (Gross *et al.* 2008; Alfiya *et al.* 2013).

GW samples were analysed for pH, electrical conductivity (EC), Turbidity, total suspended solids (TSS), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), anionic surfactants (by the methylene blue active substances (MBAS) assay method), total N, total P and total boron. Analyses followed standard procedures (APHA *et al.* 2012). In addition, *Escherichia coli* was analyzed by spread plate method on tryptone Bile X-glucuronide (TBX) agar (Merck 2000).

Soil samples were taken from three plots in each garden: (1) drip irrigated with treated GW; (2) drip irrigated with freshwater (FW); and (3) native areas that were not irrigated at all. Samples were taken from the upper 5 cm layer near the dripper (where applicable) twice a year: at the end of the summer (long dry period of 6–7 months) and at the end of winter.

Overall, 108 native samples, 202 freshwater irrigated samples and 239 treated GW (TGW) irrigated samples, were collected. Soil was analysed for macro and micro elements by inductively coupled plasma atomic emission spectroscopy (Varian, model 720-ES ICP Inc., Australia) following extraction by the double acid method at a soil:acid ratio of 1:4. Then, pH and EC were measured after extraction with distilled water at a 1:1 solid:water ratio. Soil organic matter content was measured by incineration at 450 °C in a muffle furnace according to standard procedure (Benton 1999). Soil bacteria were evaluated by shaking 5–7 g of soil samples in 10 mL 0.005 M pyrophosphate buffer (pH 7) for 30 minutes. The extract was allowed to settle for 20 min and 100 μL of the supernatant (with and without dilution) was spread on TBX plates for detection of *E. coli*.

Principal component analysis (PCA) was used to identify differences between treatments and seasons and was conducted on the covariances using JMP® 10.0.0 software by SAS Institute.

RESULTS AND DISCUSSION

The quality of raw and treated GW was tested for compliance with strict Israeli regulations for unlimited reuse for irrigation (Inbar 2007). The impact of irrigation with treated GW on soil characteristics in comparison with FW irrigation was also evaluated.

Pathogens

The presence of pathogens in raw GW has been documented by various studies and might pose a public health risk (O'Toole *et al.* 2012). Similarly, indications for the presence of pathogens in raw GW was documented in the current study as evident by an average *E. coli* concentration in the order of 10^4 cfu/100 ml (Figure 2). Despite the reduction in the average *E. coli* concentration by two orders of magnitude (to the order of 10^2 cfu/100 ml) during the course of the GW treatment, it might not always be enough according to recent reviews on risk assessment and standards (e.g. Inbar 2007; Maimon *et al.* 2010). It is therefore recommended that treated GW should be disinfected and preferably used for inedible plants, in order to avoid the possible risk of infection. We found that disinfection of the treated GW by a simple low pressure 36 W UV lamp or chlorine tablets was almost always very efficient in removing pathogens (data not shown).

Humans are constantly in contact with soil, either directly or indirectly via food, water and air; thus, soil may act as a vector and source of human disease agents. Potential transmission of *E. coli* from water to plant or irrigated soil has been examined in a number of studies, with contradicting findings. One study (Johannessen *et al.* 2005) found that *E. coli* O157:H7 was not detected in the edible parts of lettuce grown on soil fertilized with manure inoculated with the same organism, and therefore concluded that transmission of *E. coli* O157:H7 from contaminated soil to lettuce did not occur. Alfiya *et al.* (2012) did not find any faecal coliforms in the drainage water of pots irrigated by either raw or treated GW, and reasoned their findings by the fact that the environment in the root zone is generally hostile to faecal coliforms. However, a different study (Ibenyassine *et al.* 2006) concluded that strains of enteropathogenic *E. coli* can persist in soil and in vegetables growing in fields treated with contaminated irrigation water for an extended period of time. In the current study, no differences were found between the *E. coli* concentrations of native, treated GW or FW irrigated soils (Table 1), suggesting no long-term effect from treated GW on soil pathogens. Similar and even more detailed findings were recently reported by Benami *et al.* (2013).

Inorganic constituents

The quality of major GW parameters are summarized (Figure 2) and discussed below, as they may affect irrigated

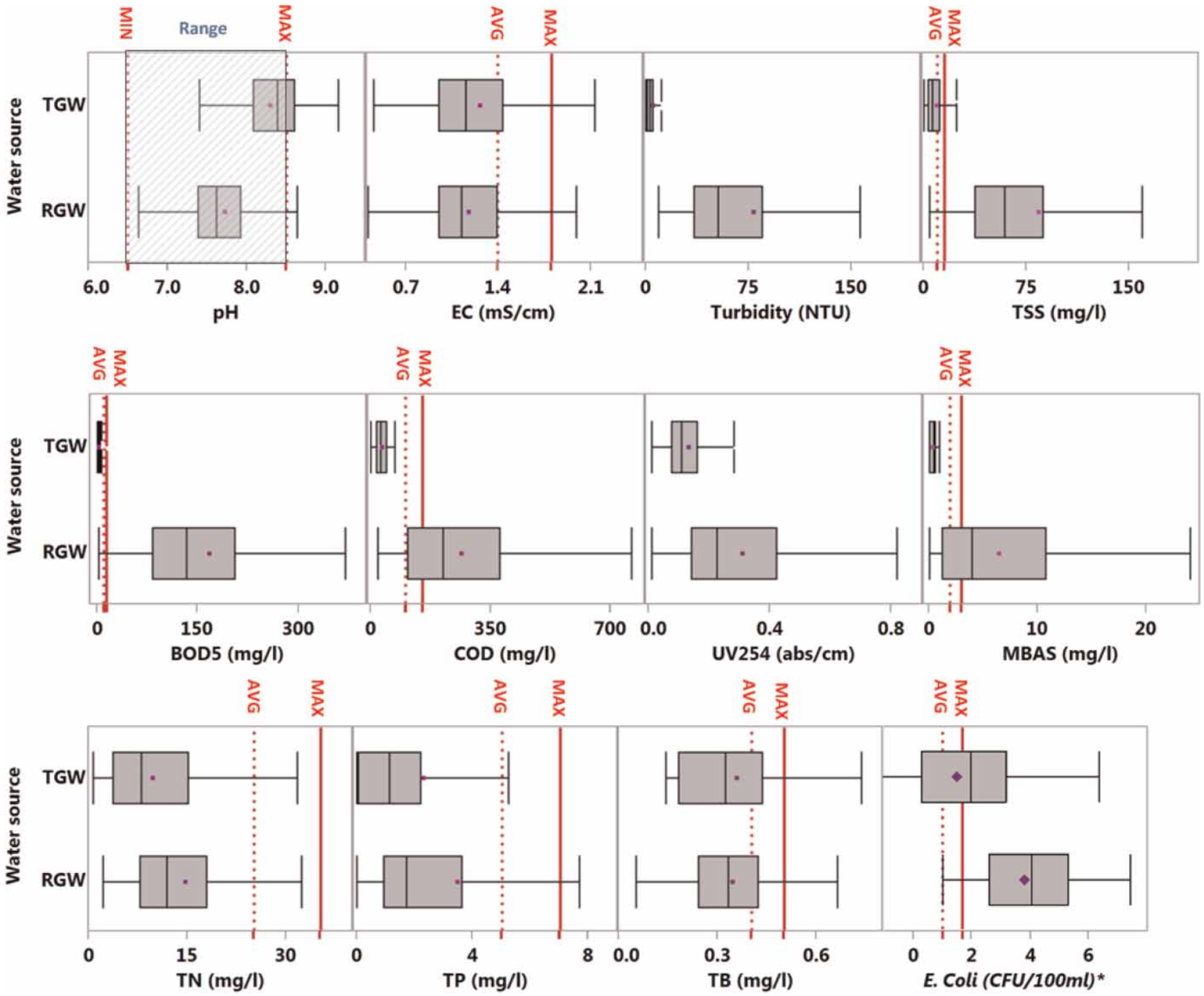

Figure 2 | Box plot summary of raw greywater (RGW) and the corresponding TGW quality from 20 houses that were sampled routinely for over 3 years. Treatment was performed by recirculating vertical flow constructed wetlands. EC = electrical conductivity; TSS = total suspended solids; BOD_5 5 d biochemical oxygen demand; COD = chemical oxygen demand; UV254 = absorbance at 254 nm; MBAS = methylene blue absorbing substances (represents anionic surfactants); TN = total nitrogen, TP = total phosphorus; TB = total boron; **E. coli* count is given in logarithmic scale. Diamonds represent the average concentration. Dotted and solid lines represent the average and maximum concentrations respectively allowed by the Israeli Inbar regulations for treated wastewater reuse for unlimited irrigation (Inbar 2007). For pH, the allowed range is presented.

Table 1 | Presence of *E. coli* in native soil, and in soil that was irrigated with either FW or TGW

Treatment	Native	FW	TGW
Number of samples (*n*)	101	193	227
Average (cfu/g soil)	17.4	46.5	14.8
Standard deviation	111	414	59.5
Geometrical mean	0.08	0.09	0.13
% samples below detection (<1 cfu/g)	92	82	61

soil properties. GW salinity is often higher than that of FW as it is enriched by various salts from detergents, among others. Moreover, since GW treatment in single-family homes is often performed in open systems (as in the current study), salinity might increase due to evaporation. Salinity (dissolved ions) might in turn affect soil properties and the growth of crops being irrigated (Stevens *et al.* 2011). For example, salinity in the form of sodium can directly affect soil properties through the phenomenon of swelling and dispersion (Halliwell *et al.* 2001), which subsequently impacts the soil's hydraulic conductivity. This in turn can affect the ability of water to infiltrate into the soil profile, and thus reduce water availability to the irrigated crops (Stevens *et al.* 2011). Alternatively, in free-draining soils, if the hydraulic conductivity is not reduced, there is the possibility of movement of salts through the soil profile into GW aquifers (Bond 1998).

Salinity of the raw GW and treated GW was similar, averaging 1.17 and 1.26 mS/cm respectively (Figure 2), somewhat higher than typical salinity (~0.7 mS/cm) of FW in the study area (data not shown). Nevertheless, these values are acceptable for unlimited irrigation and therefore no further measures to reduce salinity are needed. This may stem from the fact that washing machine powders, which are the major contributor of salts to GW, are required by Israeli standards to contain low salt concentrations (SII 1999). It should be noted that, despite evidence that salt phyto-remediation can ease the salinity burden in decentralized systems (Shelef *et al.* 2012), efficient salt removal is possible only by membrane technology. The average soil EC was 0.86, 0.85 and 1.03 mS/cm (with no statistically significant differences between treatments) for the native, irrigated with FW and treated GW, respectively (Figure 3); the average sodium adsorption ratio (SAR) was 1.88, 2.19 and 2.88 meq/kg, respectively. The difference in SAR between the native soils and those irrigated with treated GW was statistically significant ($p < 0.05$). Yet, no difference was found between freshwater irrigated soils and treated-GW-irrigated soils ($p > 0.10$).

Of specific interest is the B concentration in GW. Plant growth and yields are affected by B because it is an essential micronutrient. Yet, there is a narrow gap between desirable and toxic concentration (Weinthal *et al.* 2005). B is used extensively in the detergent industry as a bleaching agent, in the form of sodium per-borate. Consequently, B concentrations in GW are often high, particularly in industrialized countries. The highly recalcitrant B in water is difficult to remove even with reverse osmosis; therefore, the most obvious management solution is to reduce the amount of B in detergents. For example, in recent years, Israeli regulations have significantly reduced the use of B in laundry and dishwasher detergents, which resulted in a significant reduction of B in municipal wastewater (SII 1999, 2006). Our results indeed suggest that its concentrations in both raw and treated GW were only slightly higher than in freshwater, averaging 0.3 mg/L (Figure 2). Likewise, B concentration in the freshwater, RGW and TGW irrigated soils was similar, averaging 3.5, 2.7 and 3.0 mg/kg, respectively.

Heavy metals from wastewater are retained in the soil through adsorption and precipitation, so usually only very small amounts end up in crops (Page & Chang 1985). The amount of heavy metals mobilized in the soil environment is a function of pH, clay content, organic matter content, cation exchange capacity and other soil properties, making each soil unique in terms of pollution management (Mapanda *et al.* 2005). As expected, the treated GW did not contain significantly higher concentrations of metals than FW; hence no accumulation in the soil was observed (data not shown). However, longer-term effects should be studied.

Elevated nutrient concentration in GW poses an environmental hazard when the water is released into surface water bodies, as it can cause eutrophication. Since nutrients are required for plant growth, they are routinely added either *via* irrigation water in a practice known as 'fertigation' or directly to soil. The nutrients present in GW could reduce the need for fertilizers, which would make the use of GW more economically preferable (Qadir *et al.* 2007) as well as environmentally sustainable. The total nitrogen (TN) concentration in the treated GW was somewhat lower than in the raw GW, averaging 9.7 and 14.6 mg/L, respectively. This concentration is about 3–4 times lower than that commonly used for gardening via fertigation. We have previously shown that while most of the raw GW nitrogen is organic, it is converted to nitrate during treatment by the RVFCW, which is readily available for plants (Gross *et al.* 2008).

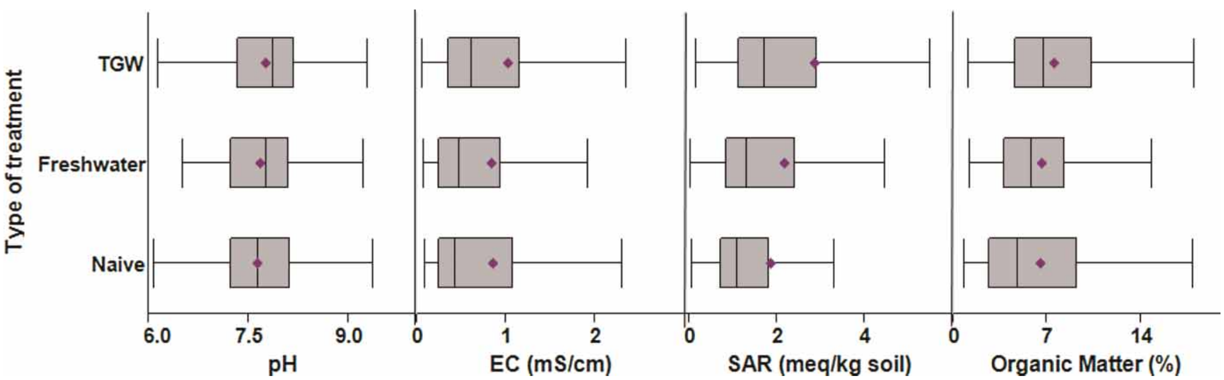

Figure 3 | Box plot representation of soil quality of nearby native garden plots (not irrigated), and plots that were irrigated either with freshwater or TGW over 3 years. Diamonds represent the average value. EC = electrical conductivity; SAR = sodium adsorption ratio.

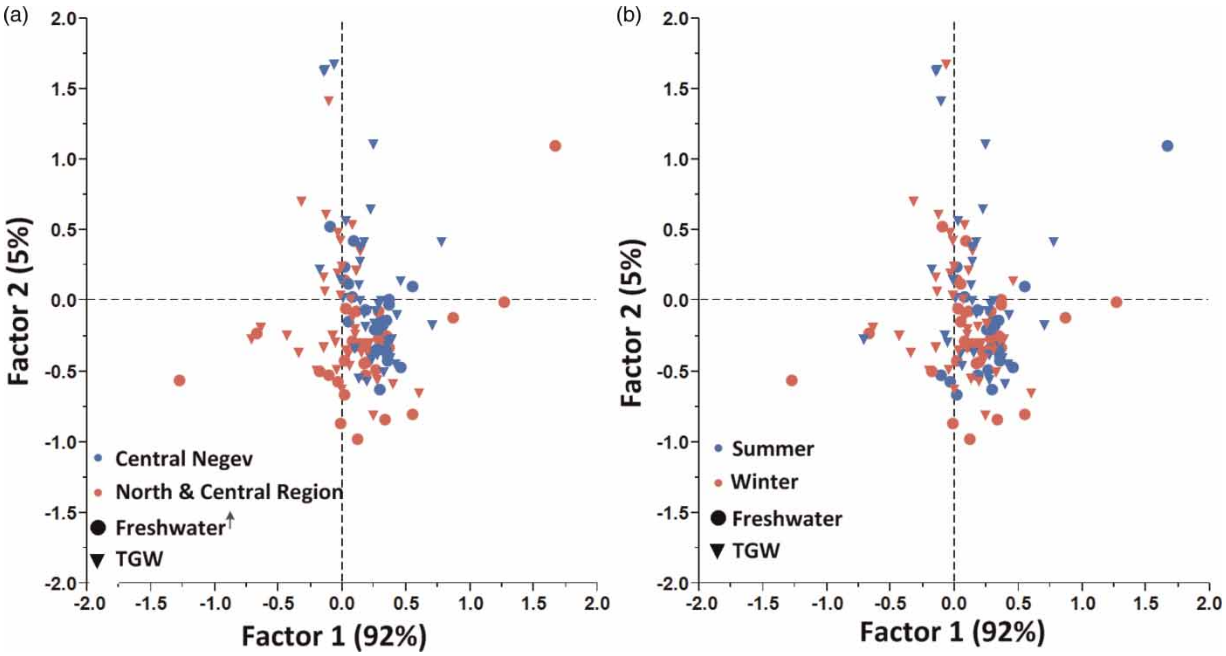

Figure 4 | Multivariate factor analysis of FW and treated GW irrigated soils (a) in the north (red) and the south (blue); (b) samples were taken after winter (red) and after summer (blue). The full colour version of this figure is available online at http://www.iwaponline.com/wst/toc.htm.

Organic matter

GW may contain many different types of organic compounds originating from human-related residues (e.g. skin particles), food remains (especially in GW originating from the kitchen), fabric fibres (laundry), and other organic compounds added through cleaning processes. GW is perceived as a major source of surfactants and personal care products, such as parabens and endocrine-disrupting compounds (Andersen *et al.* 2007).

Surfactants (mainly anionic) are a major organic component of detergents used in households and in personal care products. Recent studies demonstrated that surfactants might accumulate in GW irrigated soils and their presence can influence interfacial properties, and reduction of the water holding capacity of soils (Karagunduz *et al.* 2001; Wiel-Shafran *et al.* 2006). Other studies have demonstrated that accumulation of surfactants in soil can result in the formation of water repellent soil (Abu-Zreig *et al.* 2003) and significantly reduce capillary rise even at low surfactant concentrations of 20 mg/kg soil (Wiel-Shafran *et al.* 2006). The average anionic surfactant concentration in the raw GW was 6.4 mg/l and after the biological treatment, it was 0.3 mg/l. Consequently, no significant accumulation of organic matter was found ($p > 0.05$) in treated GW irrigated soils, which averaged at 74 mg/kg soil, as compared with FW irrigated soils that averaged 61 mg/kg soil.

A multivariate PCA was conducted, separating the results by treatment, location and season (Figure 4). The following soil data were used: macro and micro nutrients, SAR, EC, pH, organic matter, soil texture and *E. coli*. As expected, there is some difference between soil in the Negev and in the north (Figure 4(a)), most probably due to the inherent difference in soil characteristics (sandy loam in the north and Loess in the south). No differences (within each soil) were found between TGW and FW irrigated soils in both seasons and locations. Similar results were found when statistical analysis was performed for each parameter separately, as demonstrated in Figure 3. Furthermore, no differences were found between seasons (Figure 4(b)).

CONCLUSIONS

Overall, the RVFCW proved to be a robust and reliable on-site GW treatment system. The quality of the treated GW from all 20 full-scale sites met strict Israeli regulations for urban water reuse for irrigation. Average TSS was 10 mg/L, $BOD_5 < 10$ mg/L, and disinfected GW contained on average *E. coli* concentration <1 cfu/100 mL. These results coincide with previous findings for this system.

It is postulated that the efficient treatment of GW results from several properties inherent to the system, including a bed with high buffer capacity and recirculation, which minimizes bed clogging, enhances aeration and consequently promotes faster biodegradation. Moreover, the recirculation creates an almost completely mixed reactor so that the raw water is quickly diluted with the treated residual water (from the previous batch), thus improving its quality and easing the load on the bed. Results also suggest that irrigation with sufficiently treated GW did not affect soil properties during the 3 years of monitoring; yet, we intend to continue monitoring these plots in the next few years to follow possible longer-term trends.

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