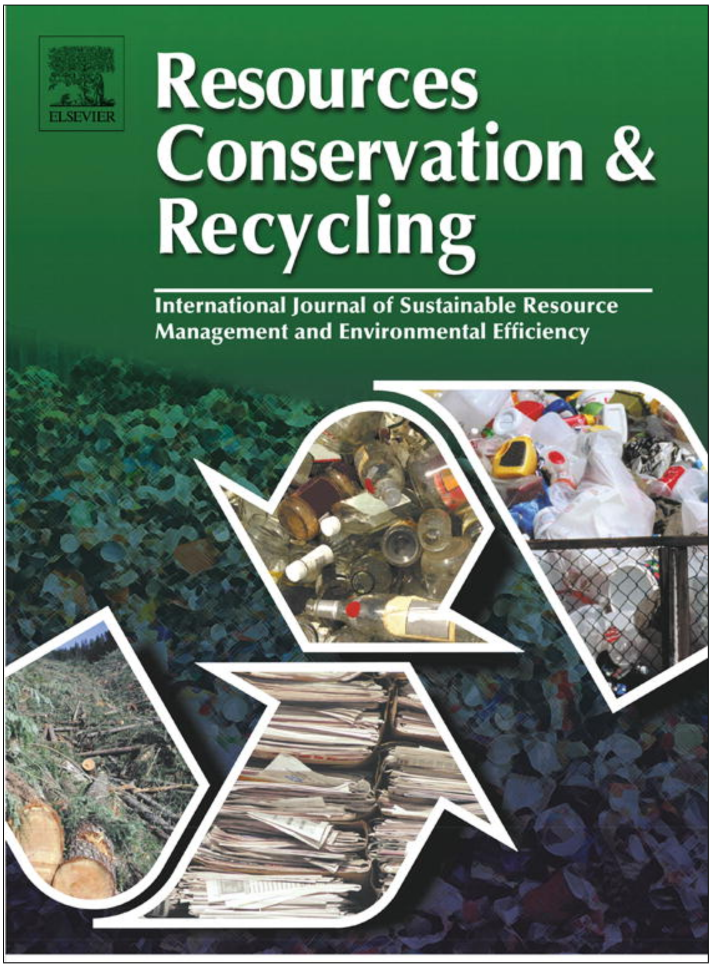
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The effect of reservoir operational features on recycled wastewater quality

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ABSTRACT

Israel's wastewater recycling program is unprecedented internationally, with close to 80% of sewage treated and reused in agriculture. This article presents findings from a national survey of Israel's wastewater reservoir network. Israel's extensive reuse of wastewater is possible due to a national network of reservoirs that has been established in recent years. Sixty effluent reservoirs presently operating in all parts of Israel, were reviewed and evaluated for static data and sampled for water quality analysis during the intensive irrigation season of 2008. The measurement of 16 chemical, physical and biological parameters, along with 21 major and trace elements was carried out, revealing a wide range of concentrations that reflect reservoir physical and operational characteristics. Results indicate that 65% and 78% of the supplied wastewater volume met the old 20 mg/L BOD and 30 mg/L TSS regulations for unlimited irrigation. With reference to Israel's updated, more stringent, regulations, only 22% and 28% of the supplied wastewater volume met the new TSS and E.C. regulations for unlimited irrigation, respectively, and only 48%, 58%, 58% and 62% met the new BOD, fecal coliforms, chloride and sodium regulations for unlimited new irrigation, respectively. All measured major and trace elements were well under existing standards, although there were considerable regional variation. Both principal component analysis and redundancy analysis were used to examine how the wastewater quality relates to multiple static construction features and operational parameters of the studied reservoirs. Sewage treatment plant technology, along with the reservoir operational regime, were found to have the greatest influence on the organic, nutrient and suspended solids loads of the wastewater supplied. The geographic location of the reservoirs along with their designed area to volume ratio, were found to have the largest influence over salinity components loads. Careful consideration should be given to the aforementioned features in future the reservoir planning process.

1. Introduction

Some 97% of Israel's lands are defined as drylands (CLEMDES, 2004). For several decades, total water consumption has exceeded the safe yield of its limited water resources (Gvirzman, 2002; CBS, 2007; Israel Water Authority, 2008). The chronic over pumping of water led to depletion in water reserves and deterioration in water quality. At the same time, continuous growth in sewage production constituted significant sources of pollution to streams and aquifers. This situation is hardly unique. Worldwide demographic growth and economic development are putting unprecedented pressure on renewable, but finite, water resources, particularly in arid regions (FAO, 2007). Moreover, the major sources of intensive water pollution are contaminated municipal and industrial effluents (Shiklomanov, 2000). Wastewater reclamation, recycling and reuse address these challenges by reducing pollution levels while creating new sources of water supplies (Wade Miller, 2006).

Today, the primary use of wastewater in Israel is for agricultural irrigation. In order to reach maximum utilization of available wastewater; seasonal storage must be provided. To that end, there are more than 200 wastewater storage and treatment reservoirs (WSTRs) operating in Israel, regulating treated wastewater inflow, which occurs throughout the year and withdrawal for irrigation, which occurs particularly during the dry summer (Swarzt, 1996; Shevah, 2000; Arlosoroff, 2007).

In addition to supplying continuous, reliable wastewater flows for agricultural irrigation and lowering the pressure on fresh water demand, wastewater storage in WSTRs also serve as a solution for wastewater disposal via irrigation, while allowing further polishing of the wastewater quality during the storage period (e.g. Dor and Raber, 1990; Juanico and Shelef, 1991, 1994; Barbagallo et al., 2003; Cirelli et al., 2008).

Wastewater irrigation, however, may be hazardous to the environment since treated effluents typically still contain several pollutants that threaten the environment, soil, aquifers and

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Table 1
Major wastewater pollutants and their environmental impacts.

	Pollutants	Environmental impact
Physical	Suspended solids	May cause anaerobic conditions (sludge deposition) and malodorous
Chemical–inorganic	Nutrients (N,P) Trace metals Dissolved solids (minerals)	May cause eutrophication resulting in an excessive algae growth and may lead to groundwater pollution Mostly toxic in nature and disrupts the ecological balance Increase water hardness and restricts wastewater irrigation
Chemical–organic	Refractory organics Biodegradable organics	Resistant to biodegradation. Cause taste and odor nuisances, and may be toxic or cancerous Lead to biological degradation and the concomitant dissolved oxygen depletion, resulting in septic conditions
Biological	Pathogenic bacteria	Transmit infectious diseases and may lead to epidemics

Source: Tomar (1999).

crops (Table 1) (Bond, 1998; Haruvy, 1998; Tarchitzky et al., 1999; Bouwer, 2000; Ben-Hur, 2002; Agassi et al., 2003; Kümmerer, 2003; Wallach et al., 2005; Koyuncu et al., 2008; Avisar et al., 2009). These contaminants include suspended and dissolved solids, nutrients, trace metals, refractory and biodegradable organic materials, pathogenic bacteria and also trace organic contaminants such as hormones, pharmaceutics and antibiotics.

WSTRs in various forms are still have become increasingly ubiquitous around the world. Given that WSTRs are the last "station", prior to land application of wastewater their function plays a key environmental role. This highlights the significance of a systematic examination of WSTR performance in real world conditions and the monitoring of the supplied wastewater quality.

This article presents findings from a national survey of Israel's WSTR network. It characterizes the wastewater qualities provided by WSTRs in Israel during the intensive irrigation season, their dependence on design parameters, environmental conditions and sensitivity to different operational regimens. To fill the existing information gap, new empirical data regarding wastewater qualities and WSTRs static design and operational features, were collected as part of a comprehensive monitoring program of stored wastewater. The findings shed light on the environmental impacts of Israel's WSTRs system based on the wastewater qualities found. They also provide policy makers with possible strategies for improving wastewater reuse practices as well as the long-term construction features and operational parameters in future WSTRs. Recommendations emphasize the importance and feasibility of upgrading currently operating WSTRs, with the concomitant benefits of reduced environmental hazards and improvement in crop yields and quality.

2. Israel's reservoir program

In light of a chronic water scarcity and the anticipated increase in sewage production the master plan for water development in Israel considers and includes wastewater as a key water resource (Rebhun, 1985), making Israel a pioneer in perceiving treated wastewater as a valuable water resource, and focus on total wastewater treatment and reuse as a national objective (Arlosoroff, 2007).

Given that agriculture constitutes Israel's main water consuming sector (≈60%), reclaimed wastewater emerged as the most immediately available additional source of water for agricultural irrigation, making way for the launching of a large scale initiative to augment agricultural water supply by creating seasonal storage of wastewater in reservoirs (Tal, 2006). Currently, over 500 mcm/year of sewage are produced in Israel. Of this amount, 72%, ≈360 mcm/year is stored in some 200 reservoirs and reused for agricultural irrigation (Cohen et al., 2008). This portion is expected to continue to increase during the coming years.

Deep wastewater reservoirs were conceived in Israel in the early 1970s, merely for seasonal storage of wastewater. Soon thereafter, additional improvements they provide to the stored wastewater as a result of concurrent physical, chemical and biological processes became evident (e.g. Dor and Raber, 1990; Liran et al., 1994; Asano and Levine, 1998; Eitan, 1999; Eren, 1999; Mancini et al., 2007).

Several factors significantly influence the wastewater quality stored in and provided by the reservoir: the influent source and quality, type of sewage treatment plant (STP) treating the influent prior to its entrance to the reservoir, multiple designed construction features and operational parameters of the reservoir, as well as the geographical location and weather conditions.

The source of influents entering STPs, and later reservoirs, can be roughly classified as domestic, industrial and dairy. In most cases a mix of different types of influents reach STPs and subsequently WSTRs.

2.1. Sewage treatment processes

The purpose of sewage treatment in Israel's water management system is to reclaim the water while removing the waste materials that have been added to it through different uses. The specific processes selected are dictated by the characteristics of the raw sewage (especially the organic and nutrient content), the designated use and quality requirements, and other engineering and economic considerations (Brenner et al., 2000). Most of the wastewater stored in the 60 WSTRs studied had gone through secondary treatment, and undergone three main processes: activated sludge (23), aerated lagoons (18), and oxidation ponds (19).

2.2. WSTR design and operational parameters

Different design parameters affect the WSTRs water quality such as the physical dimensions of WSTRs which determine links between the depth, volume of water (V), area of the water surface (A), and area of the wetted perimeter. These in turn influence the extent of mixing in the water column, hypolimnion (lower anaerobic layer) depth, solar radiation penetration to lower water layers, and other parameters affecting the stored (and supplied) wastewater quality (Friedler, 1999; Friedler et al., 2003).

Evaporation losses in WSTRs are a function of evaporation rate and water surface area. In a 6–8 m deep WSTR, located in central/northern Israel and operating under a continuous flow regime, water loss through evaporation may account for as much as 15% of the entering influents during a given year.[1] Besides the water loss, evaporation increases salinity (especially in the lower water layers, where heavier wastewater accumulates) in the remaining wastewater. While constructing deeper reservoirs offers a partial solution, it may lead to other problems (Juanico, 1999).

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[1] The evaporation rate changes throughout the year, requiring a daily/monthly calculation.

Organic matter removal has a significant correlation with reservoir design parameters. Dissolved oxygen derives from photosynthetic activity of algae and from diffusion of atmospheric oxygen. High water levels and the concomitant low A/V ratio leads to a poor dissolved oxygen balance and has a negative effect on pathogen removal efficiency (Juanico and Shelef, 1991). WSTRs with a low A/V ratio tend to develop a strong and permanent thermal stratification, preventing the mixture of the water column, while a high A/V ratio reflects better aeration (main oxygen source in winter) and a larger photosynthetic layer (serving as a primary oxygen source in summer).

In the common, continuous flow WSTR, maximum distance must be maintained between inlet and outlet. In addition, inlet location at the bottom of the WSTR helps to improve the oxygen balance and avoid hydraulic short-circuiting between inlet and outlet. Half the WSTRs examined in this study (30/60) have their inlet point at the reservoir bottom.

The soil/sealing layer characteristics also affect the system since it has an influence on seepage rate and suspended matter accumulation (Friedler, 1999; Friedler et al., 2003). The majority of WSTRs examined in this study (45/60) use a plastic sealing layer for a liner; the rest are sealed with heavy clay.

Not only the WSTR physical design affects water quality. The locations from where the water is pumped is also influential. For example: Romen (1999) recommended that water be pumped from the WSTR upper layers releasing better quality wastewater, while avoiding the drag off of sediments from the bottom. Usually, the outlet is made of a pipe hanging from a flout which maintains the opening ≈1 m below the water surface at all water levels. Indeed, the majority of the WSTRs examined in this study (50/60) draw water from reservoir upper layers.

2.3. WSTRs operational regime

Most of the WSTRs constructed in Israel (especially during the 1970s and 1980s) were designed to operate under a continuous flow regime (Juanico, 1999). The design and operation criteria for 49 out of the 60 studied WSTRs are based on seasonal storage-single WSTR concept, while 11 were based on a multi-seasonal, multiple WSTRs concept, relying on two WSTRs working in tandem.

2.3.1. Continuous flow WSTR

The concept of this regime is to maintain constant inflow to the WSTR while there is no outflow in the fall–winter season, and outflow higher than inflow in the summer. Among the primary advantanges of continuous flow WSTRs' are their ability to supply large amounts of wastewater in relation to their relatively small size, making their operation being simple and elastic. Nonetheless, this regime produces an annual, "empty–full–empty" cycle, making WSTRs a nonsteady-state treatment system subject to seasonal changes in the hydraulic loading.

The hydraulic operation of WSTRs has been found to be the main factor affecting WSTRs performance and wastewater quality. The percentage of fresh effluents (PFE) was found to be the parameter best representing the hydraulic operation (Juanico and Shelef, 1994; Juanico, 1999). High rate reactions, such as fecal coliform (FC) removal, correlate better with PFE_{1-5} (i.e. PFE that were introduced into WSTRs during the last 1–5 days), while low rate reactions (organic matter degradation, i.e. BOD removal) correlate better with PFE_{10-30} (Juanico, 1999). Since the PFE relies only on the fraction of fresh influents, its influence increases once WSTR volume decreases (i.e. during the irrigation season and especially toward its end).

The increment of fresh influents reduces WSTR pollutant removal efficiencies, with low water level creating "dead areas" due to poor mixing conditions (Juanico and Shelef, 1991, 1994; Juanico, 1999; Liran et al., 1994; Barbagallo et al., 2003).

Table 2
Quality standards for unlimited irrigation (selected parameters) (Inbar, 2007).

Parameter	Units	Standard	Parameter	Units	Standard
BOD	mg/L	10	TN	mg/L	25
COD	mg/L	100	TAN	mg/L	20
TSS	mg/L	10	TP	mg/L	5
FC	cfu/100 mL	10	B	mg/L	0.4
E.C.	dS/m	1.4	SAR	$\text{mmol/L}^{0.5}$	5
Chloride	mg/L	250	Na	mg/L	150

2.3.2. Continuous flow WSTRs

WSTRs operating as continuous flow in a series can provide a longer storage period, higher treatment capacity, and relatively easy operation. It also allows for periodic cleaning of the WSTR bottom whenever required. The two basins in the WSTR may or may not be of equal size. The normal operation method is for the influents to enter one basin, then flow (by gravitation) to the second basin, and from there discharge into the irrigation system. Each basin typically has its own inlet while the outlet can be operated separately (Eren, 1999).

Previous research suggests that performance of two WSTRs working in tandem under continuous flow is equal to the sum performances of each WSTR working separately (Juanico and Milstein, 2004). Organic matter degradation in the first basin is much higher than in the second. This is due to the initially lower and less degradable organic load entering the second basin, and the difficulty in maintaining low levels of organic matter due to sporadic growth of algae. The FC can drop a full order of magnitude in each basin and can ultimately reach zero (Juanico and Milstein, 2004).

2.4. Israel's wastewater quality standards

Due to the wide-ranging potential for wastewater reuse, setting a monolithic quality standard for all types of reuses is a challenging task. Two main sets of international regulations were designed to control wastewater reuse for unrestricted agricultural irrigation:

(1) The stringent California—Title 22 requirements, which basically require tertiary treatment (coagulation, filtration, and chlorination).
(2) The World Health Organization (WHO) guidelines that require an FC count of less than 1000 per 100 mL and not more than one helminth egg per liter (Asano and Levine, 1998; WHO, 1989).

In 1992 basic regulations defining wastewater quality requirements from treatment plants in Israel were promulgated. These are known as the "20/30 regulation set". According to these regulations, every settlement with over 10,000 inhabitants is obligated to treat its effluents to a quality level of 20 mg/L BOD and 30 mg/L TSS. But this level of treatment was soon deemed inadequate.

In 2005 a draft set of new waste water reuse requirements was published containing 38 updated quality parameters. These are known locally as the "Inbar" standards after the committee chairman who oversaw the standard review (Table 2), and were adopted by the Israel Ministry of Environmental Protection (Lawhon and Schwartz, 2006; Inbar, 2007). Future treatment plants are designed to produce waste water at a quality that allows for "unlimited irrigation" while existing treatment plants must be upgraded to that level (Ministry of National Infrastructures, 2006).

Hormones, pharmaceutics and antibiotics are not included in the "Inbar" regulations. Nonetheless, regulating trace organic contaminants constitutes the next step in the evolution of Israel's wastewater quality regulations.

This study was designed to examine and inform the construction parameters and local policy for future WSTRs, with an eye toward assessing the feasibility of upgrading currently operating WSTRs with low wastewater quality levels. Specific research objectives were to establish a profile of wastewater qualities provided by WSTRs and identify factors associated with either high or low wastewater qualities.

3. Study design and methodology

Sixty WSTRs presently operating in different geographic regions in Israel were reviewed and evaluated for static data associated with technical aspects, management and operation, and sampled for water quality analysis. WSTRs spatial distribution, sorted by storage volume, is presented in Fig. 1.

At the outset of the study, static data regarding the studied WSTRs were gathered from existing data bases, processed and computed. These data were later verified by visiting the WSTRs, interviewing their operators and sampling the water quality of discharged effluents.

Sampling of the 60 WSTRs took place during the intensive irrigation season of 2008. Grab samples of the irrigation water coming out from WSTRs' (e.g. after passing through the pumps and filters) were collected. To ensure collection of fresh and representative sample, pipes allowed some rinsing time prior to collection. In cases where it was not possible to collect the samples from the outflow point (pumps are off, etc.), samples were taken from the WSTR pumping area, ≈1 m below the water surface, by using a weighted bottle sampler (Boyd and Tucker, 1998). All samples were stored in two 500 mL plastic bottles + one 50 mL sterilized tube (for the FC analysis) previously labeled. Samples were placed in an ice-box, covered with crushed ice and kept cold and in the dark, while being transported to an analytical laboratory within 10 h of sampling. The samples hydro-chemical-biological analysis included the measurement of 16 chemical, physical and biological parameters and 22 major and trace elements. Aforementioned analyses have followed standard methods (APHA, 2005) unless stated differently.

TSS was analyzed by the gravimetric method. Turbidity was determined by the nephelometric method. pH measurement was performed by the "Cyberscan pH 11" electronic pH meter (±0.01

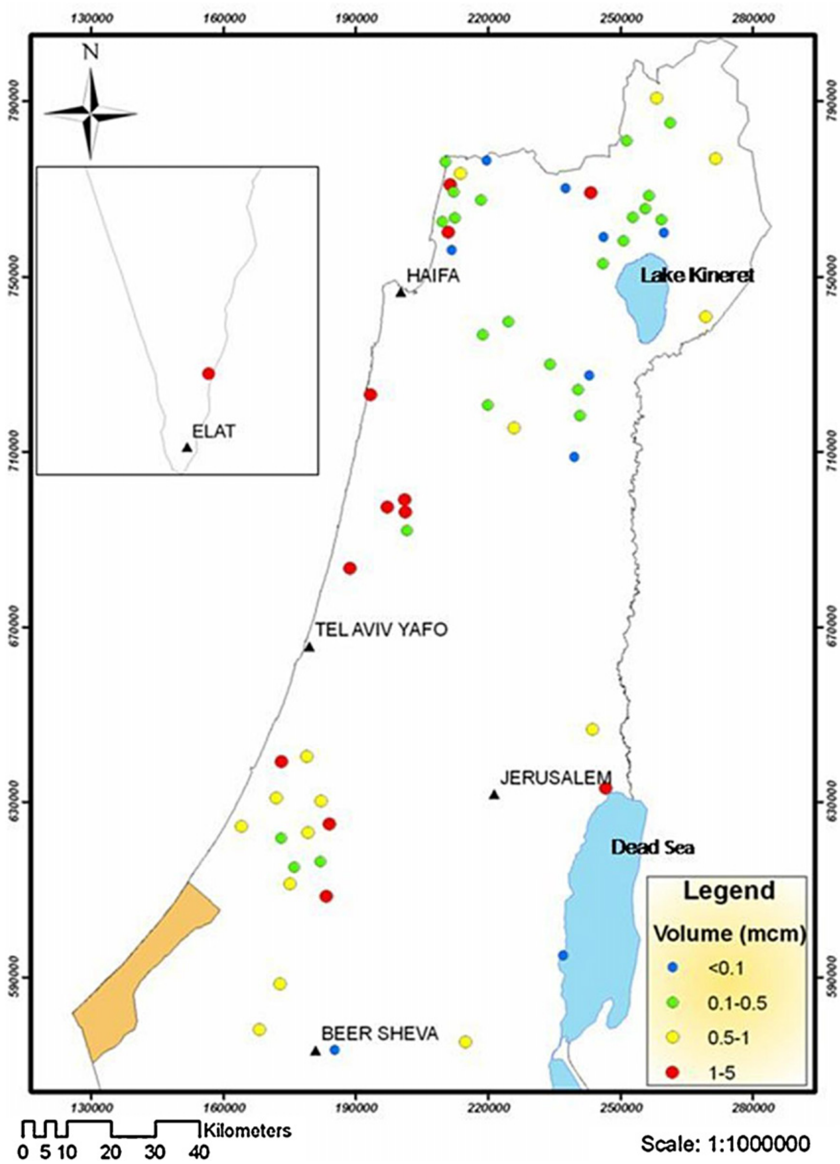

Fig. 1. WSTRs spatial distribution map sorted by volume.

accuracy). Alkalinity was analyzed by the titration method. E.C. measurement was performed by the "Cyberscan CON 11" electronic conductivity meter (±0.2 μS accuracy). Chloride was analyzed by the argentometric method. SO_4^{2-} was analyzed by the turbidometric method. SAR value was calculated using the mequiv./L values of Na versus [Ca + Mg] ratio. Major and trace elements (Ca, Si, B, K, P, Li, Al, Mn, Mg, Ag, P, Fe, Co, Ba, Sr, Ni, Cd, Cr, Cu, Pb, Zn, S) concentrations were analyzed by *plasma emission spectroscopy* using inductively coupled plasma (ICP) (Varian, XX). TN was analyzed using the persulfate digestion method, followed by UV analysis for nitrate (Gross and Boyd, 1998). TAN was analyzed by the nesslerization method (APHA, 1989). Nitrate was analyzed by the second-derivative ultraviolet spectrophotometric method (Ferree and Shannon, 2001). Nitrite was analyzed by the colorimetric method (Diazo color). BOD was analyzed using the 5-day BOD test. COD was analyzed by the dichromate closed reflux titrimetric method. FC was analyzed using the membrane filtration technique and FC were grown on TBX selective agar. Chlorophyll *a* (Chl *a*) concentration was analyzed by the acetone–methanol extraction method, followed by a spectrophotometric determination technique (Pechar, 1987).

4. Statistical analysis

Due to the large amount of data accumulated for each sample and to the multiple static factors contributing to the complexity of the data, multivariate analysis techniques were used to characterize water quality. Two types of analyses were performed using the "*CANOCO*" (version 4.5) computer software: (1) principal component analysis (PCA), to identify multiple quality parameters simultaneously and, (2) redundancy analysis (RDA) which projected multiple static factors for characterizing patterns and relationships within the complex data set.

Prior to multivariate analysis, *detrended correspondence analysis* (DCA) was performed to confirm that the data produce a linear response (Ter Braak and Smilauer, 2002). Square root and log transformations did not increase the total explained variance by the first principal components (PCs), so the untransformed data set was retained. Furthermore, a correlations matrix (rather than a covariances matrix) was used, by dividing the quality parameters values by their standard deviation (SD). This action counteracts the distortion caused by large variance parameters and allows all the parameters to be more comparable (Ter Braak and Smilauer, 2002). Finally, all values were scaled to zero mean and unit SD, to avoid the issue of different scales used for different parameters (McGarigal et al., 2000; Ter Braak and Smilauer, 2002).

5. Results and discussion

5.1. Wastewater quality

Out of the total monitored WSTRs (60), 54 (90%) were actively operating during the intensive irrigation season of 2008, supplying ≈76 mcm of wastewater for agricultural irrigation. Of the 6 WSTRs not supplying wastewater for irrigation, two released their water into nearby streams, two were unauthorized to release their wastewater by the Israeli Ministry of Health, one served as an operational reservoir and one was not yet connected to electricity for pumping to take place.

Table 3 compares the quality parameter concentrations found in all 60 WSTRs along with the new, updated parameter under the "Inbar" regulations.

When monitoring results are compared with the old "20/30 regulations", 65% and 78% of the supplied wastewater complied with BOD and TSS standards, respectively.

5.2. Physicochemical parameters

Only 10 of 59 WSTRs and 22% of the total supplied wastewater volume met the new 10 mg/L TSS standard for unlimited irrigation. Of the 39 WSTRs not meeting regulations, 2 WSTRs were found supplying wastewater unfit for irrigation with >90 mg/L TSS. Only 17/60 WSTRs and 28% of the supplied wastewater volume met the 1.4 dS/m E.C. new standard for unlimited irrigation.

Altogether 36/59 WSTRs and 52% of the supplied wastewater volume met the 6.5–8.5 pH range standard for unlimited irrigation. Most important is the fact that all WSTRs exceeding regulations were found to have a pH level > 8.5. This appears to be the result of photosynthetic processes taking place during periods of algal growth which can decline once photosynthetic activity is reduced, with no direct relation to the wastewater quality.

5.3. Inorganic constituents

Altogether 28 of the 54 WSTRs releasing effluents for irrigation and 58% of the supplied wastewater volume met the 250 mg/L Cl standard for unlimited irrigation. Of the WSTRs not meeting regulations, 4 WSTRs supplying 13% of the total wastewater volume, were found having wastewater unfit for irrigation containing >400 mg/L Cl.

The absolute majority of WSTRs (54/58) and supplied wastewater volume (94%) met the 0.4 mg/L boron standard for unlimited irrigation. In 1999 Israeli regulations limited the boron content in

Table 3
Cross monitoring results summary with comparison to the "Inbar" regulations.

Parameter	Units	Regulation for unlimited irrigation	No. of WSTRs meeting regulation[a]	Volume of wastewater meeting regulation (%)[b]
BOD	mg/L	10	24/54	49
TSS	mg/L	10	10/59	22
COD	mg/L	100	45/58	90
E.C.	dS/m	1.4	17/60	28
pH		6.5–8.5	36/59	52
FC	cfu/100 mL	10	32/59	58
Cl	mg/L	250	28/54	58
Na	mg/L	150	33/58	62
SAR		5	42/56	82
Boron	mg/L	0.4	54/58	94
TP	mg/L	5	42/58	74
TN	mg/L	25	37/54	74
TAN	mg/L	20	41/58	76

[a] Figures not out of 60 illustrate missing values for some parameters in a few WSTRs.

[b] Figures refer to 76 mcm wastewater supplied by 54 WSTRs actively operating at 2008.

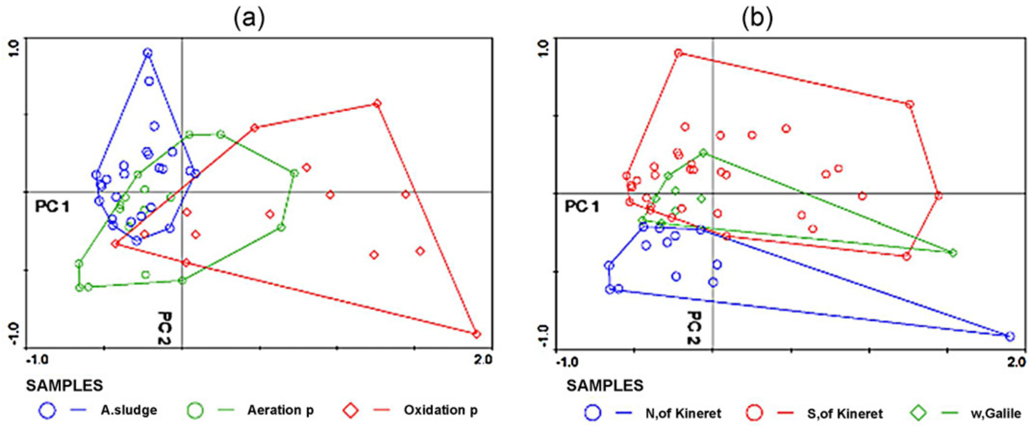

Fig. 2. WSTRs scores on the plane defined by PC$_1$ and PC$_2$, color coded by pre-treatment (activated sludge, aeration pond and oxidation pond (a) and by location north (N), south (S) and west (W) of Lake Kineret (b)).

washing detergents (the major contributor of boron to effluents) reducing its concentration to ≈0.2 mg/L. This is reflected in the results and the relatively low boron concentrations measured in wastewater.

Ca, Si, B, K, Li, Al, Mg, Ag, Fe, Co, Ba, Sr, Ni, Cd, Cr, Cu, Pb, Zn and S, were all well under the new "Inbar" standards, with a single exception where a concentration of 0.38 mg/L Mn (standard stands at 0.2 mg/L) was measured.

5.4. *Nutrients and organic constituents*

Altogether 37/54 WSTRs and 74% of the supplied wastewater volume met the 25 mg/L TN standard for unlimited irrigation. Nonetheless, 11 WSTRs and 10% of the supplied wastewater volume were found to have >40 mg/L TN concentrations. As expected, the distribution of total ammonia nitrogen (TAN) concentration among WSTRs is similar to that of TN,

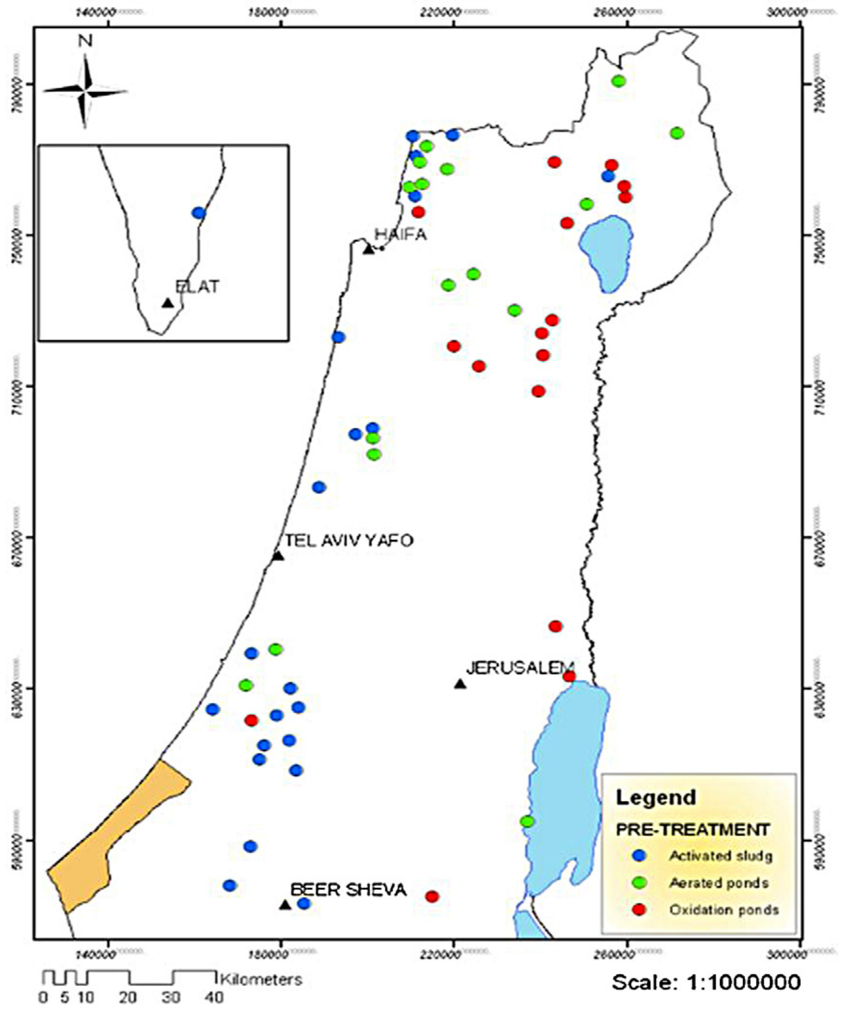

Fig. 3. WSTRs spatial distribution map sorted by effluent pre-treatment processes.

with 41/58 WSTRs and 76% of wastewater volume meeting the standard.

Altogether 42/58 WSTRs and 74% of the total supplied wastewater volume met the 5 mg/L total phosphorus (TP) standard for unlimited irrigation.

Most WSTRs (36/54) and wastewater volume supplied for irrigation (65%) met the old 20 mg/L standard for BOD concentration. Further, 24/54 WSTRs and 49% of the total supplied wastewater volume met the new 10 mg/L standard for BOD concentration recommended by the "Inbar" committee for unlimited irrigation.

BOD values do not represent current pollution but rather an integrative measure of pollution, and are dependent on the diurnal and seasonal biological cycle, i.e. high diurnal variability is expected to be found in measured BOD values, giving rise to erroneous interpretation of data (Nishri and Sukenik, 2008). Therefore, excessively strict limitations driven by BOD concentration may unnecessarily rule out the use of large quantities of reasonable wastewater volumes stored in WSTRs, highlighting the importance of seeking alternatives to BOD measurements. The majority of WSTRs (45/58) and supplied wastewater volume (90%) met the 100 mg/L COD standard, recommended by the "Inbar" committee for unlimited irrigation.

Table 4
Quality parameter loadings on PC_1 and PC_2.

Parameter	PC_1	PC_2	Parameter	PC_1	PC_2
BOD	**0.71**	−0.25	SAR	0.38	**0.82**
TSS	**0.84**	−0.28	Chl a	**0.63**	−0.22
FC (log)	**0.6**	−0.1	TP	0.58	−0.07
COD	**0.82**	−0.2	TN	**0.62**	0.15
pH	−0.27	−0.01	TAN	**0.77**	0.05
E.C.	0.5	**0.76**	NO_3	−0.25	0.03
Turbidity	**0.62**	−0.2	SO_4	−0.08	**0.8**
Chloride	0.28	**0.85**	K	**0.67**	−0.08

5.5. Microbiological parameters

Most WSTRs (32/59) and wastewater volume supplied for irrigation (58%) met the 10 (cfu/100 mL) FC standard for unlimited irrigation. In the majority of cases a correlation between WSTRs

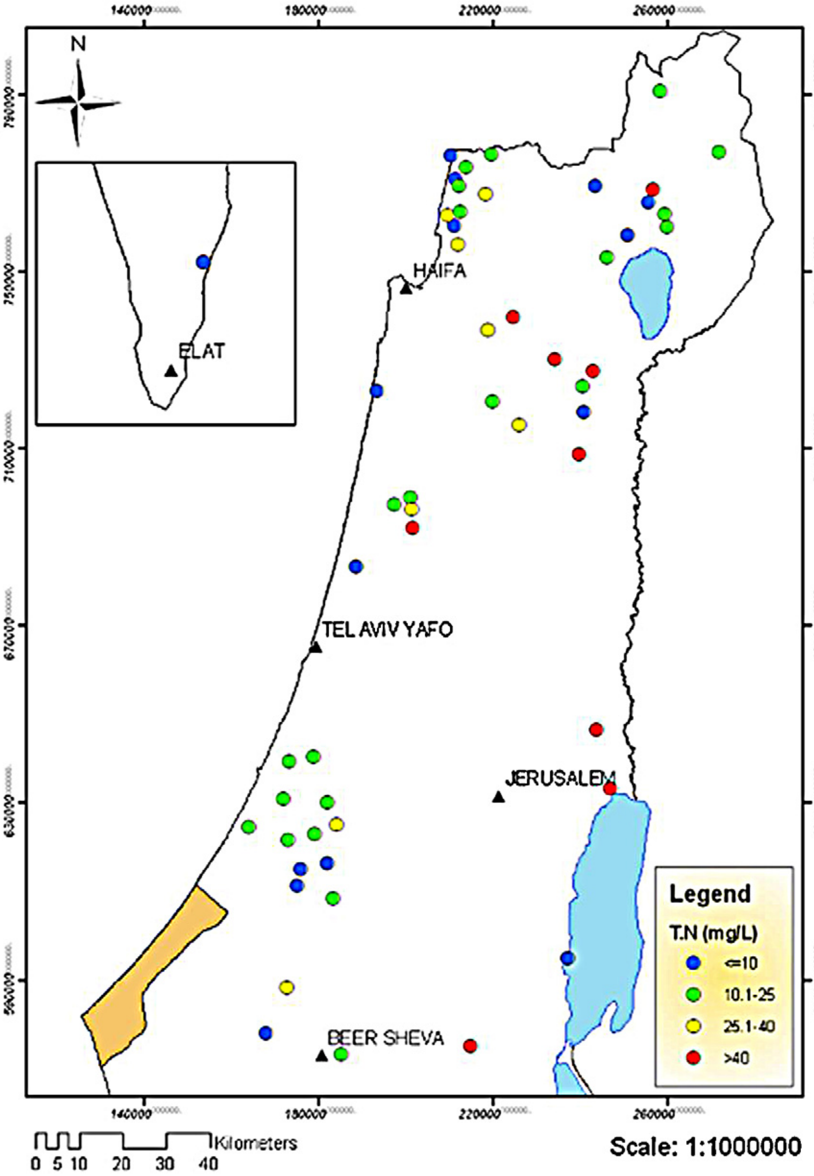

Fig. 4. WSTRs spatial distribution map sorted by TN concentration.

with <10 cfu/100 mL FC concentration and the presence of chlorination facilities was detected.

5.5.1. Factors related to high/low wastewater qualities

PCA was conducted on data obtained from 60 WSTRs samples to assess the correlations between the 16 quality parameters measured. Initially, 14 PCs were computed, with the first two PCs representing up to 53% of the total variance (PC_1 34%; PC_2 19%) of the observations.

Examination of the quality parameter loadings on the first two PCs (Table 4) suggests that PC_1, with high loadings (>0.6) of: BOD, TSS, FC, COD, turbidity, Chl *a*, TN, TAN and K, can be associated with organic and nutrients loads, while PC_2, with high loadings (>0.7) of: E.C., Cl, SAR and SO_4, can be associated with salinity.

Several classification attempts by different static factors were conducted, seeking to identify trends within the weighted WSTRs scores matrix, consistent with wastewater quality levels. Fig. 2a and b presents the weighted WSTRs scores classified by STP type and location, respectively. The relationship between WSTRs can be displayed by their relative position on the matrix (McGarigal et al., 2000) and the study sampled is thus presented in Fig. 2. The distance between symbols (WSTRs) approximates the dissimilarity of their wastewater quality.

Results by STP type classification (Fig. 2a) demonstrate that there is a distinct difference between the water quality in WSTRs whose water originates in activated sludge treatment compared to oxidation pond treatment, where the water of the WSTRs originates from aeration pond effluent. The STP type classification best relates to PC_1 (characteristic of organic and nutrients loads). WSTRs receiving water after activated sludge treatment are distinct in the negative PC1 region, due to lower organic and nutrient loads. WSTRs receiving water after oxidation ponds treatment only are mostly situated in the positive PC1 region and WSTRs receiving water after aeration ponds treatment are found equally in both negative and positive PC1 regions.

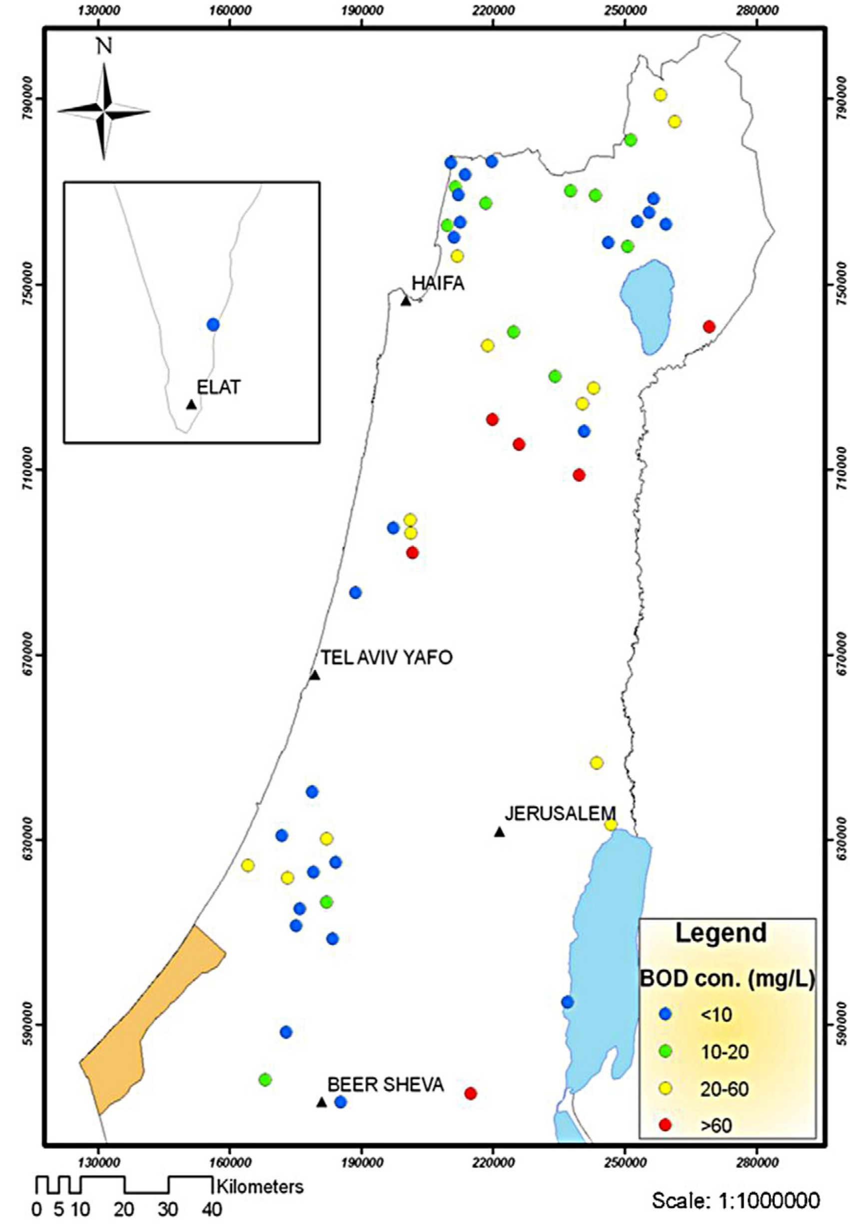

Fig. 5. WSTRs spatial distribution map sorted by BOD concentration.

Results by location classification (Fig. 2b) demonstrate that there is a distinct difference between the water quality in WSTRs whose water originates from different geographical regions. The location classification (Fig. 2b) best relates to PC_2 (characteristic of salt content). All WSTRs in the far north of Israel, in the Jordan River watershed, are distinct as comprising a "negative PC2 region", characterized by low E.C., Cl, SAR, and SO_4 concentrations. The majority of WSTRs south of the Kineret Lake are situated in a positive PC2 region. WSTRs located at the western Galilee were found equally in both negative and positive PC2 regions.

The aforementioned associations also become apparent by using a visual spatial presentation of the data at the national scale. Fig. 3 presents an overview of STPs spatial distribution. Figs. 4–6 provide an overview of selected wastewater quality parameter concentrations ranges, determined according to wastewater irrigation regulations and agricultural considerations.

The studied WSTRs are more or less equally divided into three groups according to the STP technology supplying the WSTRs: activated sludge, aeration ponds and oxidation ponds. Further, most activated sludge facilities are located in the central Coastal plain, Inner plain, Negev and West Galilee areas, while WSTRs receiving effluents that were treated in oxidation ponds are located mainly in more peripheral regions such as the Jezreel valley, Galilee, Golan Heights, and Judea areas.

Figs. 4 and 5 demonstrate that in the areas situated with advanced STPs, better quality wastewater was found as measured in nutrient and organic loadings. WSTRs receiving effluents treated in oxidation ponds (located mainly in the Jezreel valley, Golan, and Judea areas) were found to have lower wastewater qualities in terms of nutrient and organic concentrations.

Fig. 6a and b demonstrates the effect of the geographic location on salinity associated parameters; chloride and E.C., respectively. WSTRs located in the far north of Israel inside the Jordan River watershed are distinct as having low chloride concentrations (<150 mg/L) and E.C. concentrations <1.4 dS/m. This can be explained by the salinity differences in the background water. The watershed above Israel's Lake Kineret is known for having low salinity water which comes from local springs. The other regions of the country mainly use water originating from Lake Kineret, water that has always been characterized with higher salinity levels. These differences are later reflected in the wastewater quality. It is important to mention that the average chemical composition of the Kineret Lake (in terms of salinity associated parameters) is very similar to the values defined by "Inbar" regulations. Because salinity can only increases due to other anthropogenic releases as well as evaporative processes during the storage period in the WSTRs, desalination will need to be considered in order to meet standards.

Figs. 4–6 identify the Jezreel valley as an area subjected to higher nutrient and organic loads and also salinity associated parameters (relative to other areas). High nutrient and organic loads can be attributed primarily to the low tech STPs that treat sewage in the Jezreel valley area; i.e. oxidation ponds operating in 6/9 WSTRs, as well as the high component of dairy effluents contributing waste to 5/9 WSTRs. High concentrations of salinity associated parameters can be attributed to the fact that the subsurface hydrology in the Jezreel valley was modified after being intensively cultivated, irrigated and covered with reservoirs. All of these factors contributed to increased salinity throughout the valley (Adar et al., 1989, 1992; Sorek et al., 1992; Weekes, 1997; Gafni and Zohar, 2007). Moreover, the introduction of agricultural drainage water back into the WSTRs is also reflected in increased salinity.

Further PCA was conducted on the individual pre-treatment and location groups. The goal of this analysis was to distinguish other factors that create group formations. In the case of WSTRs

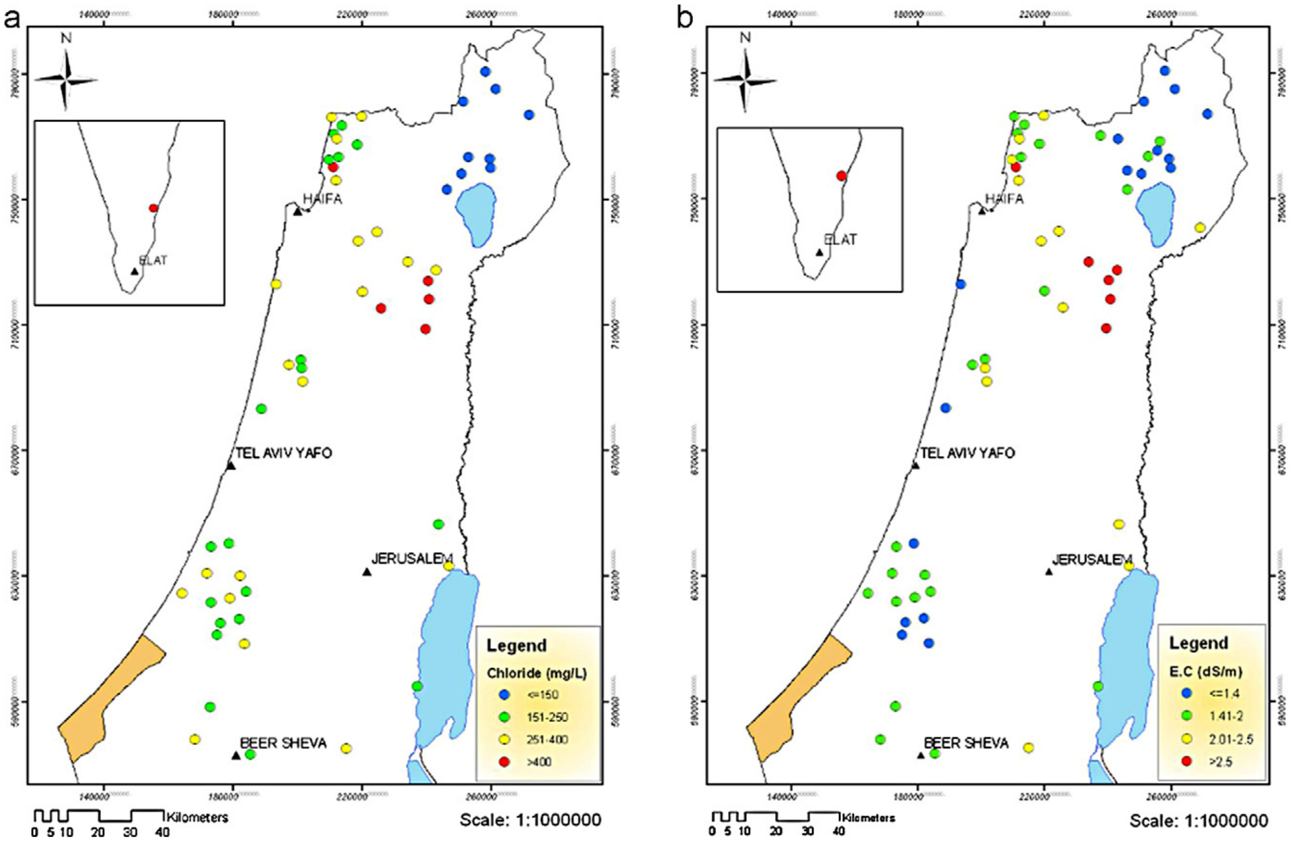

Fig. 6. (a) WSTRs spatial distribution map according to chloride concentration. (b) WSTRs spatial distribution map according to E.C. concentration.

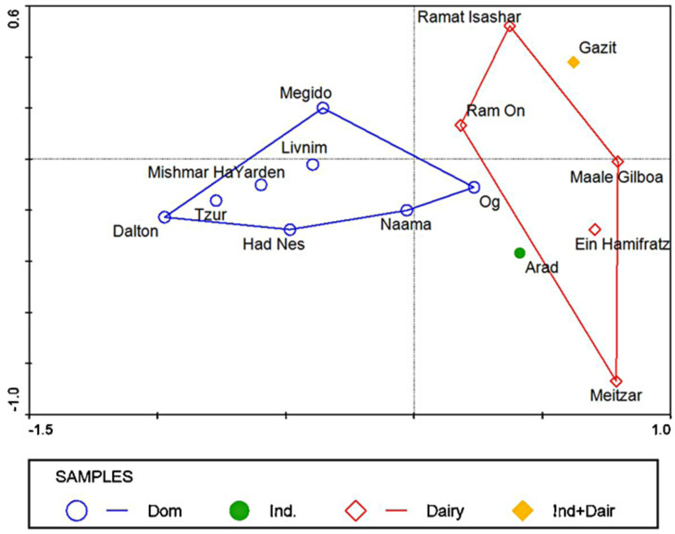

Fig. 7. Oxidation pond WSTRs scores on the plane defined by PC_1 and PC_2, color coded by effluent source: domestic (Dom), industrial (Ind), dairy and industrial + dairy (Ind + Dair).

that relied on oxidation ponds, it was found that classification by effluent source (Fig. 7) produces a separation between domestic effluents and dairy (and to a lesser degree, industrial) effluents.

The groups are separated by PC_1, which explains 31% of the total variance of the observations, with high (>0.6) loadings of: COD, BOD, K, TN and TSS (Fig. 7). Dairy effluents are distinct in the positive PC1 region due to the higher organic and nutrient loads that they produce. Domestic effluents are distinct in the negative PC1 region (except Og WSTR) due to their lower organic and nutrient loads. The most noticeable effect identified involved WSTRs whose effluents had been treated earlier by oxidation ponds, reflecting their low performance levels when faced with heavily loaded effluents, such as dairy effluents.

RDA was used to examine how wastewater quality relates to multiple static factors, and involved 16 quality parameters and 21 static factors. This was done by ranking static factors, using a manual forward selection, along with the Monte Carlo Permutation test for statistical significance set at 0.05 (Ter Braak and Smilauer, 2002). Tested static factors explained 49% of the total variance, though only those statistically significant static factors (6); explaining 35%, were selected. Fig. 8 presents a bi-plot of the quality parameters and the static factors.

The black arrows, representing the quality parameters, and the red arrows, representing the static factors, all point in the direction of the steepest increase of values. The angles between arrows indicate the types of correlation between them, i.e. positive correlation when the angle is sharp and vice versa. The length of the arrow is a measure of its fit.

The most statistically significant association between static factors and quality parameters to emerge involves the STP technology. This is reflected in organic, nutrient, physical and biological quality parameters. A strong positive correlation exists between high concentrations of these parameters and oxidation ponds (and, to a lesser degree dairy sources) along with a negative correlation between high concentrations of the later parameters and activated sludge. In addition, activated sludge is also positively correlated with NO_3.

The next association to emerge confirms that WSTRs location influences salinity and inorganic constituents. A strong positive correlation occurs between high concentrations of E.C., Cl, SAR, and SO_4, and WSTRs located south of the Kineret Lake, along with a strong negative correlation between high concentrations of the latter parameters and WSTRs located to the north of it. In addition, a high A/V ratio is also correlated with high concentrations of E.C., Cl, SAR, and SO_4.

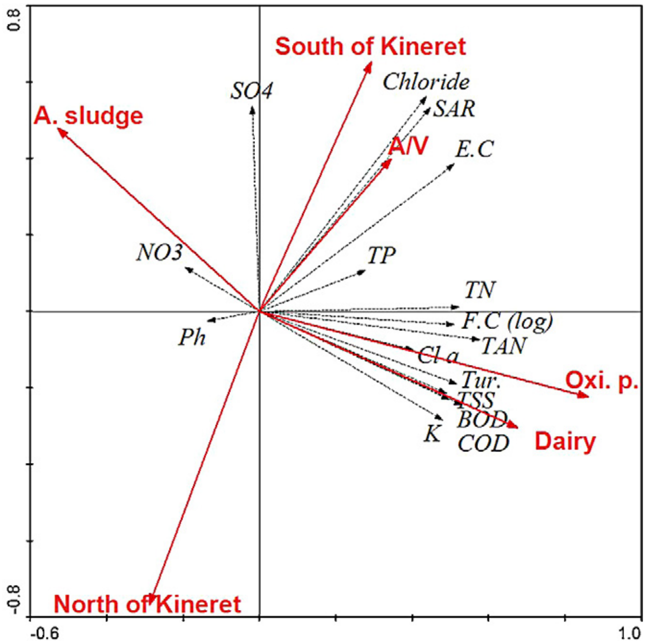

Fig. 8. Cross sampling RDA ordination diagram [PC1 × PC2], with quality parameters and static factors.

6. Conclusions

The WSTRs studied augment Israel's agricultural irrigation water supply by ≈76 mcm in 2008, representing over 1/5 of the total waste water recycled in Israel. Cross sampling results indicate that most WSTRs met the BOD and TSS requirements for unlimited irrigation (65% and 80%, respectively) according to the standards in place at the time of the study. Yet, as these old standards are not sufficient in light of the new, more stringent "Inbar" regulations; here the study shows that, most WSTRs fail to meet several of the new quality parameters requirements such as E.C., TSS and BOD and, to a lesser extent, FC, chloride and sodium.

Multivariate statistical performance analysis shows that the STP technology, prior to discharge to the WSTRs, has the greatest influence over the organic, nutrient, suspended solids and fecal coliform loads in the wastewater released from reservoirs. Upgrading the associated facilities requires serious consideration during the WSTR planning process, with a clear preference toward STPs adopting proven advanced treatment technologies.

The study also confirms the significance of addressing water quality problems associated with Israel's dairy and beef industry. The results show that even when relatively small portions of dairy effluents (treated in oxidation ponds) are integrated into WSTRs, higher organic and nutrient loads are produced. Therefore it is advisable to separate dairy effluents and treat them in advanced centralized STPs.

RDA results indicate that both the geographic location and the WSTR A/V ratios are linked to salinity increase, making it necessary to carefully consider the background water salinity along with expected evaporation rates at specific locations to reach an optimal A/V ratio. One way or another, in order for most WSTRs to meet Israeli E.C., Cl and Na concentrations as defined by the "Inbar" regulations (1.4 dS/m, 250 and 150 mg/L, respectively) desalination may need to be applied prior to the discharge of wastewater into the WSTRs or desalinating the better quality water of the WSTRs (this will reduce desalination costs and further salinization due to evaporation in the WSTRs themselves). National scale findings emphasize the necessity of creating alternative wastewater reuse programs for the Jezreel valley, including improved STPs, desalination, constructed wetlands, etc., in order to improve wastewater quality.

Even though substances found in low concentrations such as hormones and antibiotics are not yet addressed by current regulations, further examination of these substance concentrations in wastewater is needed, and their removal efficiencies in WSTRs, STPs should be better understood. The relative effectiveness of desalination processes and constructed wetlands may also be required. This issue has become more urgent in recent years considering the increase in the consumption of pharmaceuticals and anecdotal data suggesting contamination by antibiotics and endocrine disruptors in Israel. Finally, the potential for WSTR leakage, along with high resistance to subsurface biodegradation of the such micro-contaminants, highlights the importance of sealing technology using plastic liners.

Wastewater reuse will continue to be a central pillar of water management strategy for dryland countries around the world. Reservoir storage constitutes a central component of this approach, particularly in regions where rainfall is seasonal. But if investment is not made in appropriate infrastructure, water quality will not be sufficient to irrigate responsibly. Attention also needs to focus on wastewater regulation treatment, monitoring and engineering specifications during the planning process.

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