Soil Aquifer Treatment System Performance: Israel's Shafdan Reclamation System as an Ultimate Case Study

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1 Introduction

Soil Aquifer Treatment (SAT) is a well-known method for treating water and polishing effluent for water reuse (Wilson et al. 1995; Peter 1998; Bouwer 2002; Drewes et al. 2003; Amy and Drewes 2006; Hernández et al. 2012; Lian et al. 2013).

Generally, the method is based on artificial recharge of effluent via infiltration ponds into the vadose (unsaturated) zone of the aquifer, where substantial contaminant removal takes place. The treated water is further stored in the saturated zone of the aquifer and later reclaimed for various reuse purposes.

Despite the simplicity of the SAT system, organizations such as the US Environmental Protection Agency (US Environmental Protection Agency 2012) and

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the World Health Organization (World Health Organisation 2006) recommend this method, along with other advanced technologies such as reverse osmosis, advance filtration and oxidation processes, as a proper solution for water reuse.

Beginning in 1970 and developing ever since, the Dan Region Wastewater Treatment system (Shafdan) collects, treats and reclaims municipal wastewater of the Dan metropolitan of Israel, now numbering about 2½ million residents. The system satisfies two main goals: 1. It minimizes environmental hazards and health risks using advanced sewage collection and disposal facilities and prevents discharge of raw sewage into the Mediterranean Sea. 2. It preserves Israel's water resources, enabling the use of recycled water for agricultural irrigation of all types of crops without limitation.

This present chapter describes the Shafdan SAT system structure, the actions and principles governing its management and the means and methods developed to ensure the chemical and biological quality of the reclaimed water.

2   The Shafdan Plant Main Components

The overall recycling process involves water purification by a central mechanical–biological wastewater treatment facility (Shafdan Waste Water Treatment Plant—WWTP) and a following SAT in the aquifer. The WWTP is a conventional activated sludge process of nutrient removal (general layout in Figs. 1 and 2) which produces secondary effluent of 10:10, i.e., 10 mg/L of total suspended solids and 10 mg/L of biochemical oxygen demand (Icekson-Tal 2014).
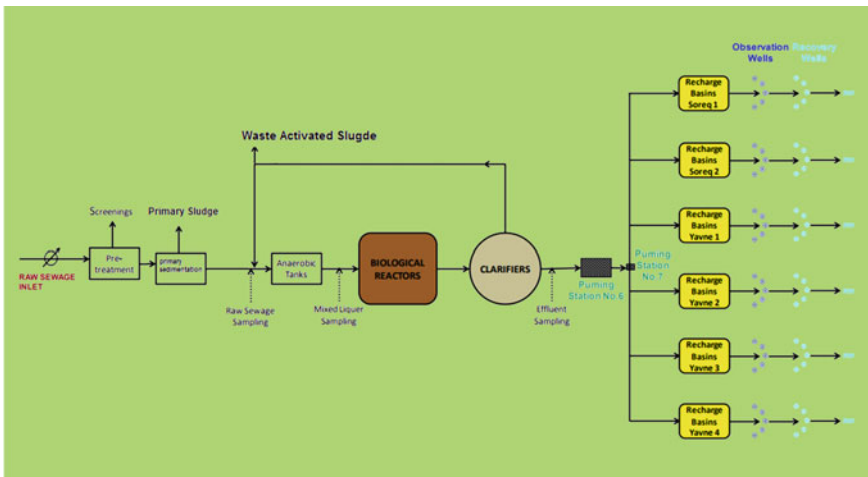

Fig. 1 Process flow diagram of the Shafdan WWTP and reclamation system. Modified after Icekson-Tal (2014)

Fig. 2 Shafdan WWTP (partial view). The raw sewage inlet pipe, the biological reactors and the clarifiers can be seen from back to front

Next, the secondary effluents are recharged via some 50 infiltration ponds into a hydrologically separated portion of the Israeli coastal aquifer (termed the Shafdan basin). During this activity, the effluents undergo a complementary, tertiary SAT treatment and enrich the underground reservoir for seasonal and annual storage. The water with complementing 20–30 Mm^3 of freshwater from the Coastal Plain aquifer is later recovered by a gallery of ~150 recovery wells, which provide annually 130–160 million cubic meters (MCM) of recycled water. The excellent quality water is delivered to the Negev region for unrestricted agriculture use, irrigating over 60% of its total crops. The SAT system layout is presented in Fig. 3.

The SAT of such a large scale demands comprehensive hydrological management and quality monitoring, in order to secure the aquifer storage, prevent effluent leakage to the fresh aquifer and maintain the Shafdan as a reliable, stable, sustainable and high-quality water provider.
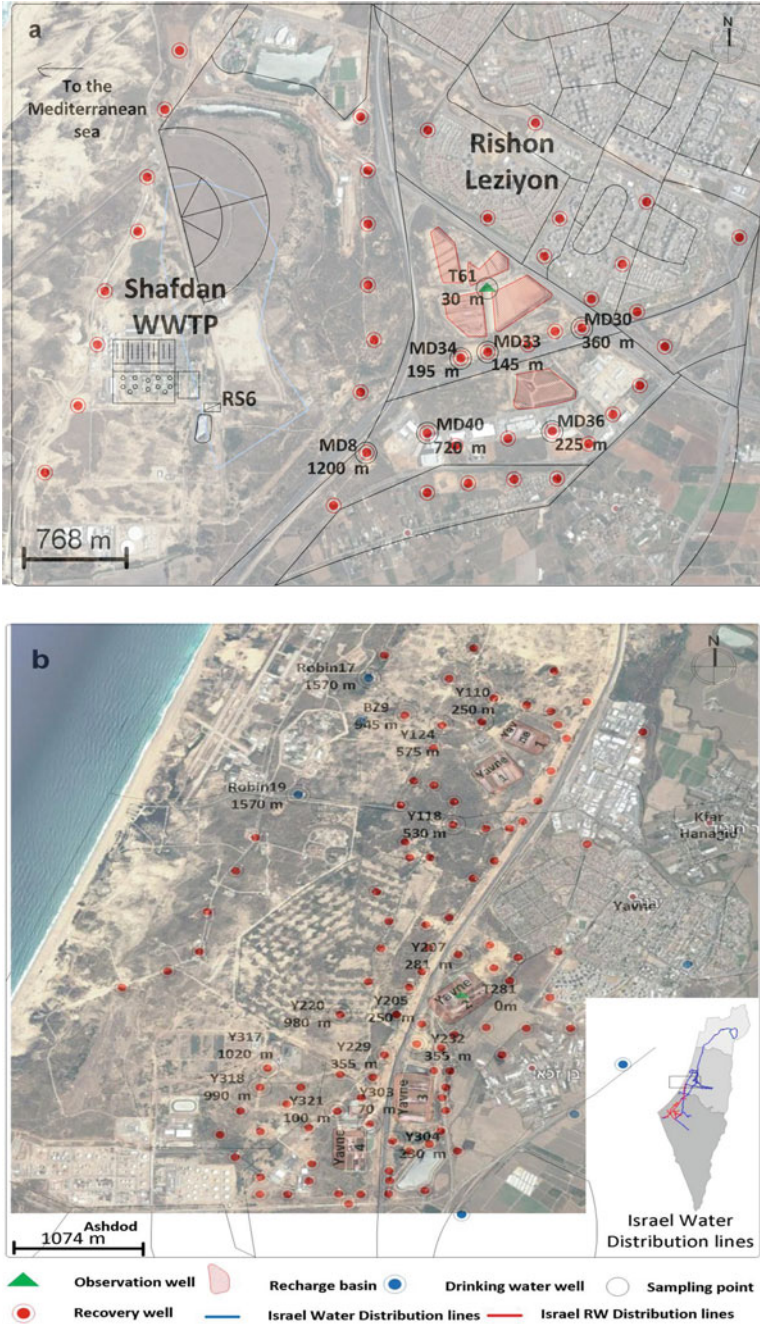
Fig. 3 a The northern part (Soreq) of the Shafdan SAT system and the location of Shafdan WWTP. **b** The southern part (Yavne) of the Shafdan SAT system. A location map including Israel's major water distribution system is shown at the bottom right corner. Modified after Elkayam et al. (2018)

3 Hydrogeological Setting and the Related SAT System Structure

The Israeli coastal aquifer, extending along the Mediterranean Sea on the Western part of the country, consists of Pleistocene-age coastal environment rocks dominated by calcareous sandstone (The Kurkar group). The aquifer was formed during a series of depositional cycles and is characterized by interbedding of sandstone layers with marine and continental clay, silt and shale lenses. These represent the varying sea level stages during the glacial and interglacial periods of the Pleistocene (Issar 1968; Bruce et al. 2001). The sandstone suite of the Kurkar Group is still accumulating today on the shallow continental shelf (Gvirtzman and Buchbinder 1978).

The coastal aquifer overlays the late Eocene to early Pleistocene Saqiye group, a thick, impermeable clayish unit which slopes westward. Consequently, the overlying aquifer reaches its maximum thickness (180–200 m) along the coastline and gradually wedges out eastward, until it vanishes some 10–15 km inland. The vadose zone below the infiltration ponds is approximately 30–40 m thick.

Three north–south trending, sub-parallel calcareous sandstone (kurkar) ridges, situated roughly 0.5–0.7, 1.3–2 and 3–3.5 km east of the coastline and separated by clayey elongated basins, dominate the aquifer morphology. The recharge ponds are constructed mostly on the Eastern Ridge. In some places, thicker marine clay layers divide the aquifer into sub-horizontal sections. This division is more dominant toward the coast and affects the western parts of the aquifer. Although the division is irregular, four main sub-aquifers situated one on top of the other can be identified and are named from top to bottom by the letters A–D (Fig. 4).

The Shafdan SAT system produces most of the water from sub-aquifer B—it is usually 60–80 m thick and is characterized mostly by sandstone and conglomerate of fairly high hydraulic conductivities. Typically, the conductivity is on the order of 4–10 m/s (Kloppmann et al. 2009). The RWs are arranged roughly in a double-ring structure around the percolation ponds; the inner ring pumps 100% treated effluent, whereas the outer ring pumps 70–85% of treated effluent and a complementary amount of natural, regional aquifer water. The number, locations, capacities, screen positions and other features of the wells were designed to create a closed SAT system, which is isolated from the surrounding freshwater aquifer and does not affect its chemical quality.

The first infiltration basins (Soreq) were set up west of Rishon Lezion in 1977 (Icekson-Tal 2014) and were designed to treat 50 Mm^3/year of effluent. The SAT system has expanded ever since to meet demand, and more facilities were constructed west of Yavne and north of Ashdod (Fig. 3). Presently, overall recharge of secondary effluent is approximately 130 Mm^3/year; whereas, reclaimed water totals approximately 145 m^3/year and is pumped by some 150 recovery wells.
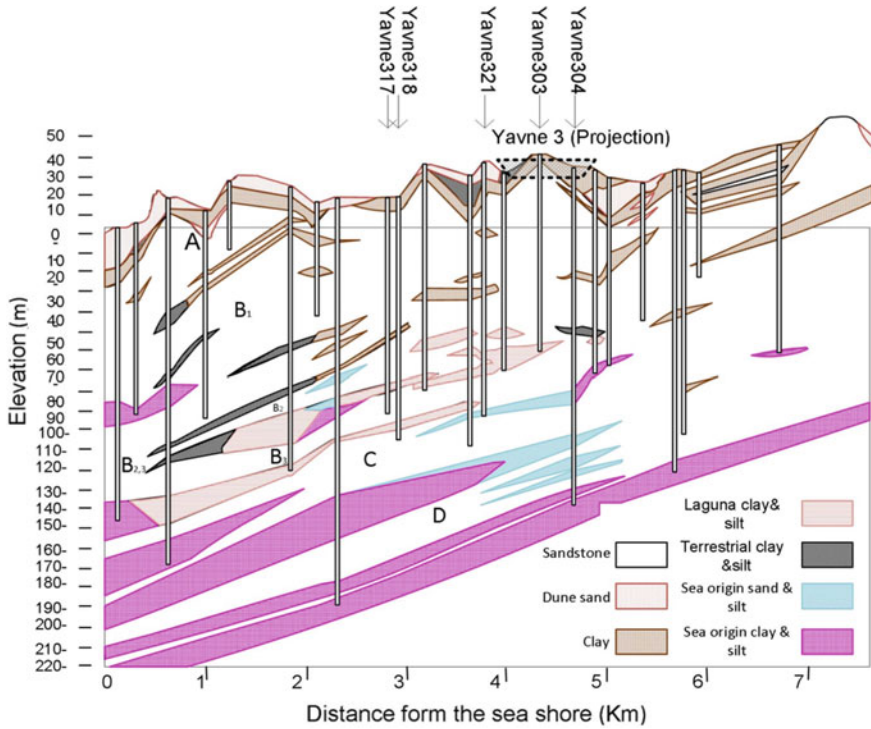
Fig. 4 Representative geological cross section of the Israeli coastal aquifer; recharge basin Yavne 3 and some of the surrounding wells are projected over the geological cross section; capital letters indicate sub-aquifers; the base of sub-aquifer D is the Saquie formation (Elkayam et al. 2018, based on TAHAL Atlas XX)

4 Hydrological Management of the SAT System

4.1 Goals and Constrains

The primary goal of the SAT management is to supervise the system's operation according to a balanced, sustainable plan, while securing the aquifer storage, preventing effluent leakage into the regional aquifer and avoiding salinization and any deterioration of the Shafdan water quality. Among further objectives are the improvement and adjustment of the recharge—recovery arrays to the current and predicted hydrological status, tracking and prediction of water quality shifts (especially spreading of the effluent and Mn dissolution trends in the aquifer).

Several factors, sometimes contradictory, affect the operational plan and production regime of the Shafdan basin. Three of the main factors may be defined as constrains:

1. The amount of effluent that is available and can be recharged: In the absence of alternative use for the secondary level effluents flowing from the biomechanical facility, the main challenge is to recharge the entire effluent amounts into the aquifer for complementary SAT . Higher effluents amounts, or alternatively poor utilization of the available recharge capacity, result in the dismiss of significant amounts of effluent to the sea.

2. Minimal recovery amounts: Recovery amounts can vary according to hydrological considerations and different operational constrains. However, a minimal recovery estimated to be ~120% of the recharge amount is required in order to prevent leakage of effluent to the surrounding, fresh aquifer. The 20% over-pumping is assumed to claim also the natural rain recharge over the pond areas and to stabilize the hydrological barrier between the Shafdan and the surrounding regional aquifer.

3. Water consumption demand: The amounts of recovered water which is supplied for irrigation are predetermined by the Water Authority, according to water quotas given to the farmers. Moreover, the agricultural water demand regime may vary significantly in time due to shifts in agronomical parameters such as climate, seeding seasons and plant types. For example, continuous and high precipitation during a rainy year can significantly limit the irrigation season to six months only (from April to October). As a result, the recovery amounts may dramatically drop due to the limitation of production capacity of the recovery wells and due to hydraulic restrictions of the third line.

In addition to these constraints, other factors and operational considerations may affect the production regime: the availability of recovery wells, hydraulic considerations, energy-saving issues and water quality regulations (especially relating high manganese concentrations and sand amounts).

Above all, there are the long-term hydrological considerations, intending to preserve the aquifer and its water quality over time. Therefore, a skillful hydrological management is a central tool for routine operation, necessary for settling various constraints and factors and for the future planning of the plant.

4.2 Means and Principles for the Shafdan Plant Hydrological Management

Hydrological management of the Shafdan plant is based on a detailed operational plan. The plan is set at the beginning of each (calendar) year and is based on the current hydrological conditions.

The hydrological condition analysis is based on up-to-date infiltration, production and rainfall data, as well as on groundwater levels recorded during the former fall season (usually during September–November). These data are used both for water balance calculations and for reliable, up-to-date evaluation of groundwater levels in the area.

Considering the abovementioned analysis, the annual infiltration prediction and the water budgets allocated by the Israel Water Authority, a detailed production plan for the coming year is prepared. The hydrological management principles are based on number of prime hydrological parameters and unique theoretical tools developed over the years.

Implementation of the production plan is complemented by close, monthly monitoring of the water balance major components, namely the infiltration in the ponds and the water amounts reclaimed by the production wells. Arrays of ~150 Shafdan recovery wells and 75 Shafdan inspection wells, as well as some 200 additional private and research, production and inspection wells, all provide further data on a monthly/yearly basis, regarding the aquifer water quality and water levels in the Shafdan vicinity. Occasional additional specific water level measurements are conducted at sensitive regions (especially at shoreline vicinity). All the gathered data are used to update the production plan and to prepare ahead for the coming year.

4.3   Water Balance and Groundwater Levels

The Shafdan water balance is based on the following principles:

1. A clear, although not sealing, boundary separates the Shafdan treatment volume from the fresh, regional aquifer, allowing to relate to the Shafdan aquifer volume separately.
2. The division of the Shafdan aquifer is into three sub-basins. Each basin contains a set of infiltration ponds, series of surrounding recovery wells and a series of coastal drain wells located to the west. The sub-basins are characterized by high groundwater level zones under the infiltration ponds and surrounding low-level areas created by pumping. Each sub-basin is hydrologically constrained by the sea toward west and by low head (water level) zones created by the outer recovery well rings, toward all other directions (Fig. 5).
3. A unique water balance is calculated for each sub-basin, based on its specific effluent infiltration, reclaim and estimated natural recharge.
4. The ponds evaporation component is small (<0.5%) and therefore is neglected.
5. Pumping rates by private wells adjacent to the Shafdan basins are small and are neglected as well.

The water balance components are evaluated as follows:

Effluent infiltration is based on monthly and annual sums of effluent volumes introduced into the infiltration ponds.

Natural recharge is evaluated from rainfall measurements (at the Shafdan meteorological station), assessment of the areas where effective infiltration takes place and estimation of the infiltration coefficient. The total recharge area for each sub-basin includes the ponds, the recovery wells area and some further 500–1000 m strip
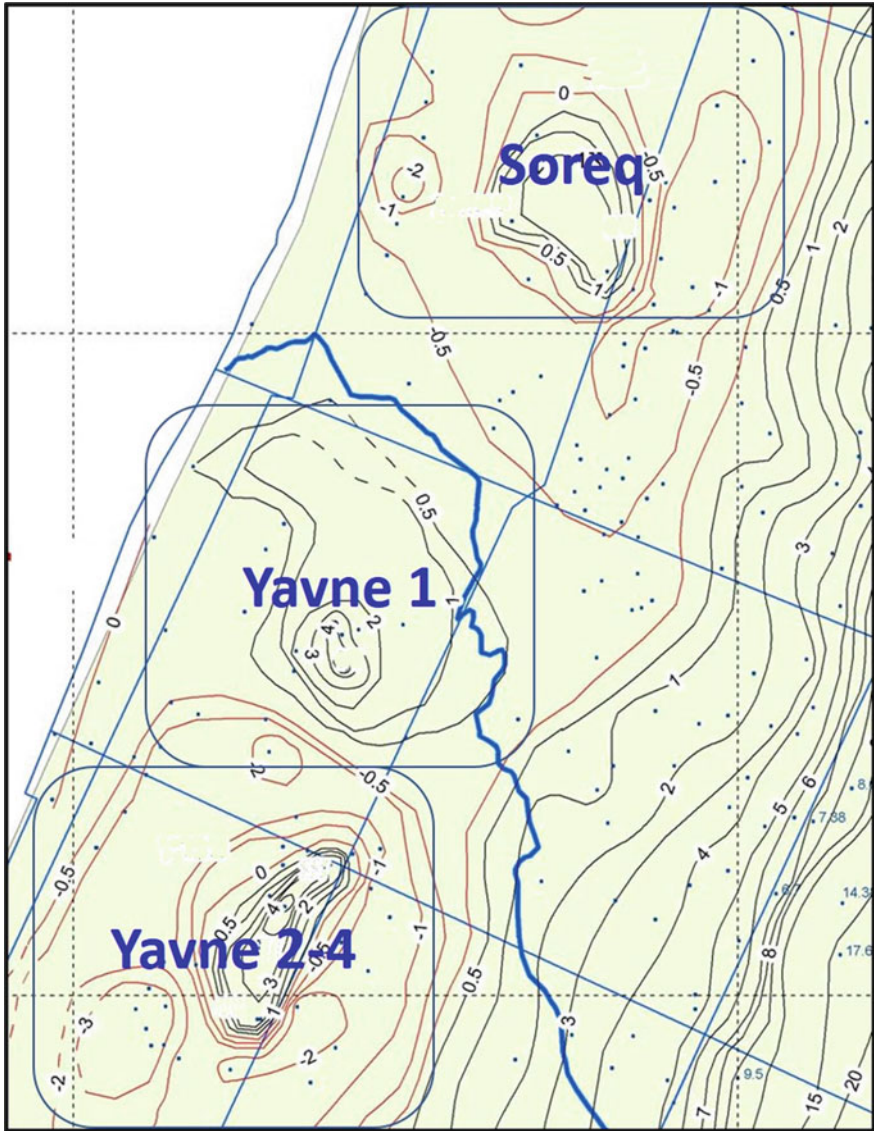
Fig. 5 Typical groundwater level map of the coastal aquifer—the Shafdan area

beyond the outer well ring. Toward west, the area is bounded some 750 m inland, roughly estimated as the fresh–salt water interface location.

The infiltration coefficient evaluation is based on the hydrological survey data, on elaborated analysis of soil characteristics and uses and on the spatial distribution of clay layers underlying a local perched aquifer. Furthermore, assumptions regarding the recharge contribution of single rain events were made: The infiltration coefficient

is multiplied by a contribution coefficient, ranging between 0 and 1, according to the amount and frequency of rain events. In this way, for example, during periods of frequent events (once a week at minimum) in winter, the contribution coefficient equals 1. During spring and fall seasons (or after a long rain cease in winter), the contribution coefficient may drop to 0.2 and alter the infiltration coefficient. During summer, the contribution coefficient is given 0, assuming that occasional summer rain events have negligible influence. It should be emphasized that the abovementioned attitude is conceptual and was not calibrated. However, it seems to better describe the local Shafdan climate and recharge conditions, which are characterized by relatively low precipitation and long periods of high temperature, dry conditions, even during winter.

Production amounts are derived from constant measure and monthly sum for every single recovery well of the Shafdan.

Lateral flow components, namely the exchange of groundwater between the Shafdan and the surrounding fresh aquifer, are evaluated by equations adapted for each sub-basin, as well as by numerical flow modeling. The net lateral flow is directed from the fresh aquifer into the Shafdan area, due to the excess pumping over infiltration policy.

Annual storage change in the Shafdan aquifer is evaluated via comparison of annual water level maps and water balance equations.

4.3.1   Groundwater Level

The hydrological management of the Shafdan aquifer includes preparation and analysis of water level maps, based on updated measurements during the former fall season. In addition, multi-year hydrographs are used for monitoring sensitive portions of the aquifer. These means are especially important as they directly associate the water balance calculations and the present aquifer state, thus enabling simultaneous update of the management plan. Water level measurements are done within ~400 recovery, production and inspection wells at the Shafdan aquifer and its surroundings. Much effort is dedicated to the collection and analysis of valuable data during a short period of time.

The water level maps are prepared via the Surfer software and cover the Shafdan influenced aquifer and the surrounding fresh aquifer, bounded from shoreline to 9 km inland. As a first step, the maps are used to locate sensitive areas where the target water levels were not reached, to track storage changes and flow directions. The maps are further compared to maps of previous years using grid volume calculations, allowing to assess the operational plan and to update it as necessary.

4.3.2 Groundwater Balance Equation and Its Implementation for the Sub-basins

The general groundwater balance equation is given by

$$R_C + R + \Delta f - P - \Delta V = 0 \tag{1}$$

where R_c is the effluent infiltration, R is the rain recharge, Δf is the net flow from the fresh to the Shafdan aquifer, P is the production of the recovery wells, and ΔV is the Shafdan aquifer storage change. All components represent water volumes.

Let B be the sum of the measurable components:

$$B = R_C + R - P \tag{2}$$

Next, the Shafdan aquifer storage delta may be evaluated using the specific yield (S_y), the aquifer area (A) and the change in hydraulic head (H):

$$\Delta V = A \cdot S_y \cdot \Delta H \tag{3}$$

After rearranging:

$$B = A \cdot S_y \cdot \Delta H - \Delta f \tag{4}$$

Assuming that the lateral flow is not dependent on infiltration, production or water levels in the aquifer, Eq. 4 suggests a linear relationship between B and ΔH. This allows to evaluate the effective porosity of the aquifer (the ratio between the curve inclination and the aquifer area) and to assess the flow of water into the Shafdan aquifer when no water level change occurs between one year to another (interception value when $\Delta H = 0$ in Fig. 6).

Figure 6 demonstrates the measured water balance B versus the average annual water level change ΔH, at the three sub-basins Sorek, Yavne 1 and Yavne 2–4. All component data were collected and analyzed during 2008–2017 according to the scheme described above. ΔH was calculated by water level map comparison of sequential years.

The summary of evaluated values of specific yields and net flow into each sub-basin is given in Table 1. Figure 6 suggests a good linear relationship between the measurable annual balance and ΔH, demonstrating a correlation coefficient of 0.7–0.8 for all sub-basins. This correlation further supports the assumption that given the average water levels variety measured during the recent years (−1.7 to +1.1 m MSL), the net flows are not dependent on water level state nor on the infiltration and production amounts. The effective porosity values evaluated for all sub-basins are 24–27% and are typical for the main rock types composing the coastal aquifer, namely calcareous sandstone, coarse- and medium-grained sand. In general, the relatively
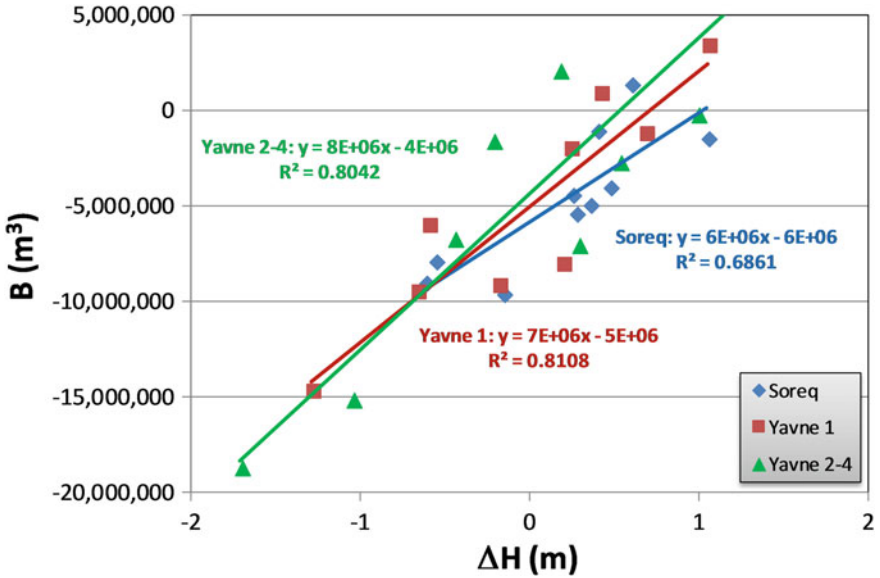
Fig. 6 Measured water balance (B = Recharge + Rain − Recovery) versus calculated water level differences (DH) for the Shafdan sub-basins

Table 1 Calculated specific yield and net fluxes to the Shafdan sub-basins

Sub-basin	Specific yield (%)	Yearly net flux to the basin (MCM)
Soreq	27	5.9
Yavne 1	24	5.1
Yavne 2–4	25	4.4

good correlation between the measured balance components and ΔH enables a short-term prediction (1–3 years) of water level states expected as a result of infiltration and production policies.

4.4 Regions of High Hydrological Sensitivity and Relating Production Priorities

The recovery wells are spatially dispersed and located in variable distances from the infiltration ponds, the watersheds and the shoreline. Therefore, the key for an appropriate hydrological management is a skillfull adjustment of the water production to the aquifers spatial conditions. In general, four indicative areas of different hydrological sensitivity are distinguished and are the basis for operation priorities:

1. The shoreline strip—includes the coastal drainage wells (Rishon and Rubin series) which produce water west of the infiltration ponds, some 1.5 km inland. Water production is taking place close to the fresh–saline interface, hence classifies this area as highly sensitive. Accordingly, the production in this area is limited and aims at balancing the local natural recharge, while maintaining water levels around (+)1 MSL.

2. The low water head areas—bounding the Shafdan aquifer toward north, east and south and separating it from the surrounding fresh aquifer. The production from this area is of the highest priority and aims at the delineation of the tertiary treatment activity while maintaining water levels of 0 to (−)1 MSL.

3. The infiltration ponds vicinities—characterized by the water mounding caused by the infiltration activity. Production in these areas is generally high, maintaining water levels at (+)2 to (+)7 MLS. Due to some limitations (as temporal lows in agriculture water demand) and pumping adjustment requirements, these areas are further subdivided into subsections (east, west and "manganese") for fine-tuning production.

4. High density wells areas—various reasons have led to an uneven well distribution in the Shafdan aquifer and to consequent low hydraulic head areas. A typical example is the "Yavne low," situated SW of Yavne 2–4 ponds and exhibits a relatively wide, low water level aquifer section.

The ongoing operation of the wells follows an annual operating plan and is coordinated with the Shafdan control room. The total group of 150 recovery wells is subdivided into 11 subgroups of variable operation priority, varying from high (group 1) to low (group 10). This allows to match the operation measures consumption needs to the spatial hydrological sensitivities.

Figure 7 shows the Sorek region water level map during fall 2011. For various reasons, the operational plan was not properly implemented during that year: Excess of production was only 4% ($B = +1.3$ MCM), over-pumping of 0.5 MCM took place within the coastal drainage wells, and priority-wise production was very limited. As a result, the low head hydrological boundaries had weakened and unwanted low head areas evolved near the shoreline.

On the contrary, Fig. 8 shows the water level map of Sorek region at the end of the year 2017, during which an operational plan was properly implemented, and resulting water levels and hydrological boundaries were reached and stabilized. A proper operational plan not only enables to reach the hydrological goals, but also positively affects the maintenance and rehabilitation of wells and the company's long-term planning in general.

4.5 Recharged Effluent Migration in the Aquifer

Reliable monitoring of the recharged effluent is essential for efficient management of the infiltration and recovery systems. Data regarding the location and expansion
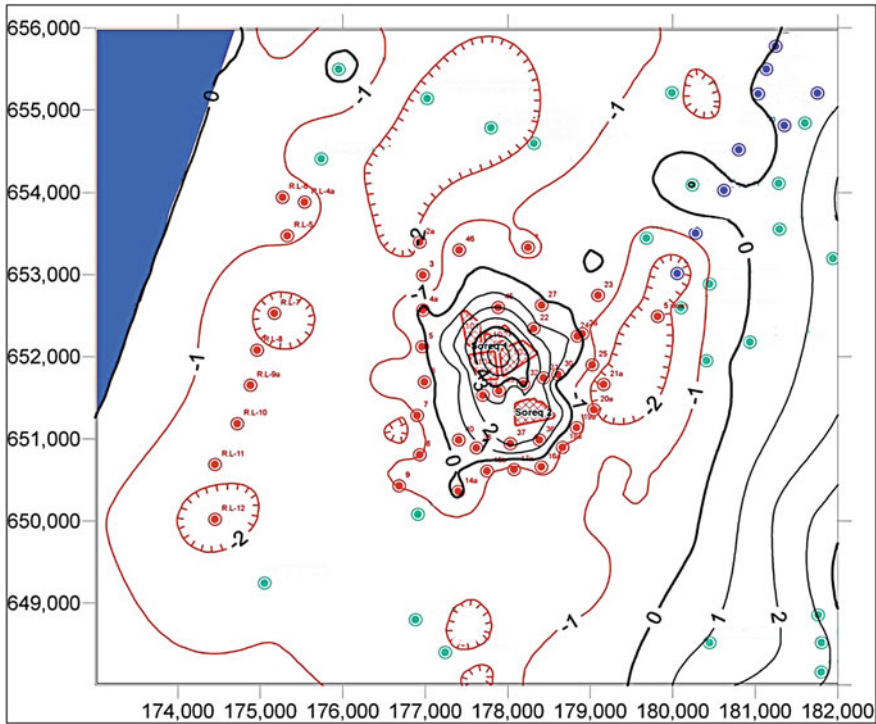
Fig. 7 Groundwater level map of the Soreq sub-basin at the end of the year 2011. The operation regime during 2011 did not match hydrological principals of water balances and production priorities according to hydrological sensitive areas

trends of the effluent frontiers are required to keep the Shafdan aquifer well defined and prevent effluent leakage to the surrounding fresh aquifer.

The effluent expansion rate is assessed by calculating the mixing ratios of effluent and freshwater in wells (inspection, recovery and production) of the Shafdan area and its vicinity. In general, calculations are based on the measured concentrations of a representative compound (marker) dissolved in the water, as follows:

$$\text{MR} = \frac{[X]_i - [X]_b}{[X]_{ef} - [X]_b} \tag{5}$$

where MR is the calculated effluent mixing ration at a specific location (well), and $[X]_i$, $[X]_b$ and $[X]_{ef}$ are the marker concentrations in the well, in the fresh regional aquifer and in the effluent, respectively. For years, the chloride ion (Cl^-) was used as a primary marker due to its inert nature, its measuring simplicity and the large difference between its concentrations in the effluent (200–300 mg/l) and in the regional aquifer (20–80 mg/l). However, considerable spatial diversity of background concentrations in the regional aquifer, additional local Cl ion sources and temporal changes in
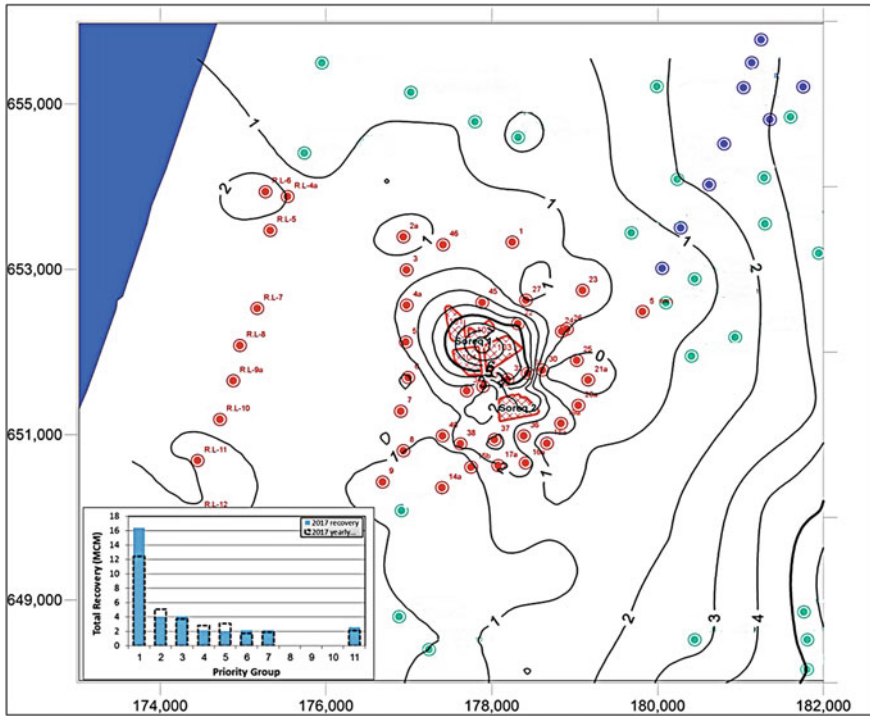
Fig. 8 Groundwater level map of the Soreq sub-basin at the end of the year 2017. The operation regime during 2017 followed the hydrological principals of water balances and production priorities according to hydrological sensitive areas (inset)

the effluent salinity (due to massive desalinated water consumption starting ~2010) led to uncertainties and statistical errors up to 40% in mixing ratio calculations (Gasser et al. 2011).

In recent years, two new markers identified in the Shafdan SAT system enable a quantum leap of the mixing equation sensitivity, and hence, gradually substitute the chloride as a tracking marker of the effluent distribution in the aquifer.

The first marker is carbamazepine (CBZ), an organic residue of an antiepileptic drug. CBZ is dissolved in the effluents; it does not decompose or undergo absorption or deposition during the various water treatments and is being influenced only by dilution. Unlike chloride, the spatial CBZ background concentration variance in the aquifer is small, and there is a considerable three order of magnitude difference between the CBZ background concentration and its concentration in the effluent. Technological advances in analytical analysis over the last decade allow measurement of concentrations of CBZ in the range of down to 0.1 ng/l, thus enabling the calculation of mixing ratios to the resolution of a few percent. However, the precision of the analysis of organic compounds at trace levels is low, and therefore, multiple measurements can reduce the intrinsic error considerably. In addition, the use of a

combination of acesulfam, a biorefractive and abundant sweetener and CBZ can also reduce the prediction error to a few percent only (Gasser et al. 2014).

Another new marker recently discovered is the isotope compositions of oxygen and hydrogen in water, δ^2H and $\delta^{18}O$ (Kloppmann et al. 2009; Negev et al. 2017). These became highly efficient markers for tracking effluent in the aquifer, due to massive entry of desalinated water into Israel's water system, beginning in 2010. The desalinated water component gradually led to significant isotopic enrichment of the effluents compared to the aquifer background composition. Using water isotopes as a marker has some advantages over the chloride marker (sensitivity) and the CBZ marker (environmental stability). Moreover, the significant differences in the isotope composition of the four main water sources of the National Water Carrier (namely the desalinated water, the Mountain Aquifer, the coastal aquifer and the Lake Kinneret) enable us to predict, by using simple dilution calculations, the isotopic composition of the effluent before recharge.

The computed mixing ratios within the Sorek sub-basin (2012) are given in Fig. 9. The ratios calculated for each well (recovery, production and observation) are based on the CBZ concentrations measured at the most distanced wells relatively to the infiltration ponds and chloride concentrations relatively to the infiltration ponds fields
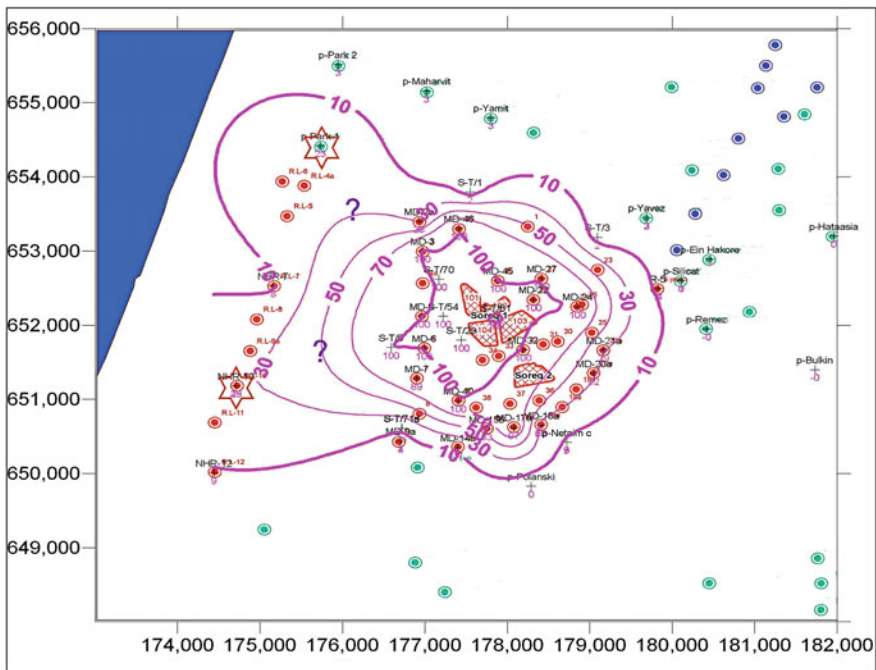

Fig. 9 Mixing ratio (MR) between the recharge effluents and the native water at the Soreq sub-basin, 2012. The MR map is based on CBZ measured concentrations at the distant wells (MR < 70%) and on Cl concentration at the wells near the recharge fields (MR > 70%)

and on the basis of chloride concentrations at the closest wells, in which calculated mixing ratio is greater than 70%. Analysis of the spatial trends of calculated mixing ratios was performed using Surfer 8.0 software and the Kriging method.

4.6 Numerical Modeling as a Management Tool

In order to test operational scenarios, to evaluate flow directions and velocities and to estimate retention times, a numerical flow and transport model was constructed for the saturated zone.

The model base was defined by the impermeable Saquie formation underlying the aquifer. Representing a phreatic aquifer, the model top was defined by the water level. Boundary conditions along the northern, eastern and southern model edges were set to be of transient head type, based on periodic water level measurements. The western edge was set to be a constant head type dictated by the sea. Initial conditions were based on static heads measured at dozens of wells included in the model (Fig. 10).

The geological data processed from well logs, geological and structural maps served as the basis for the conceptual model, constructed via the GMS software package. The variety of rock types was represented by four material categories, each characterized by a set of hydrological properties. Hundreds of well logs were analyzed using the T-PROGS (stochastic subsurface modeling system developed by
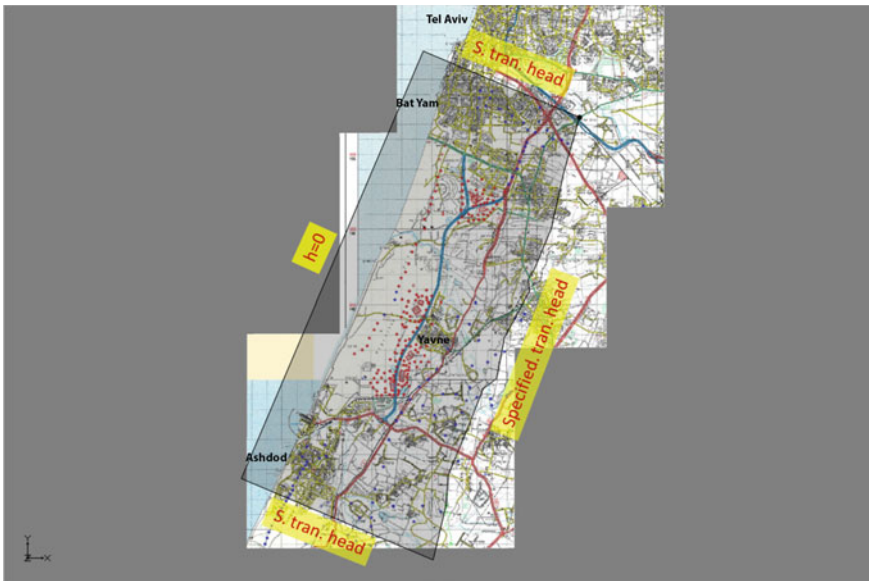
Fig. 10 Numerical model extent and boundary settings
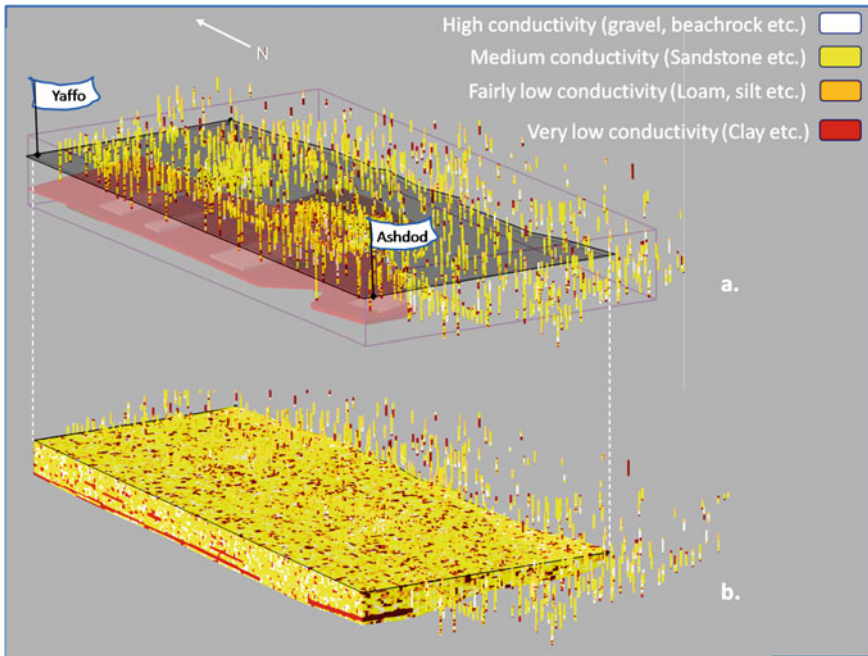
Fig. 11 Numerical model structure: Borehole logs and marine clay structural data (**a**) and the integrated geological configuration (**b**)

S. Carle, University of California, Davis) and provided the material spatial occurrence. This stochastically generated material array, conditioned to the borehole logs, was combined with structural map data of the major marine clay lenses present in the aquifer. The resulting model hence reflects the material proportions and transition trends, as well as the division into sub-aquifers by marine clay within the western part of the aquifer (Fig. 11).

Calibration of the model was done by matching the calculated heads and breakthrough curves to field data measured at various inspection wells. Using the model abilities, various factors as diverse geology and complicated flow regime conditions, which vastly affect the retention time and cannot be accounted for by simpler methods, were considered.

5 Water Quality Performance of the Shafdan SAT System

5.1 Overview

Since 1977, annual reports consistently prove that the Shafdan reclaimed water complies with all chemical drinking water quality parameters. Elkayam et al. (2015a, b) showed that most of the DOC and all of the ammonia are removed during filtration through the unsaturated zone. Recent research (Elkayam et al. 2015a, b; Sopliniak et al. 2017a, b) showed a large removal of DOC and a complete removal of ammonia, both taking place at the uppermost aquifer layers within a few hours. Moreover, Sopliniak et al. (2015) showed that appropriate operating conditions allow oxygen to penetrate a few meters into the unsaturated zone and enhance intermittent aerobic–anaerobic conditions, thus creating a unique effluent polishing reactor.

Routine water sampling conducted over decades has proven that the reclaimed water is clean from bacteriological pollution. A detailed examination and data summary done in 2015 (Fig. 12) showed that no fecal coliforms have reached the recovery wells in the Soreq area (Fig. 13) for over three decades. Moreover, the data imply that the entire bacteriologic contamination reduction occurs within the unsaturated zone.

The role of retention times of the water quality is well known, both, the vadose zone and the saturated aquifer influence the SAT efficiency and consequent water quality. Elkayam (2012) found that the retention time in the unsaturated zone is 15 ± 2 days for a 3 d cycle in the Yavne 2 basin. The retention times for various wells were evaluated by the numerical model and are given along with further data in Table 2.

Elkayam et al. (2018) analyzed the Shafdan water quality as a function of the distance from the basin and of retention time proved that most of the chemical and microbial removal takes place after the percolation through the unsaturated zone.

Figure 14 presents several measured water quality indicators as a function of retention time and flow distance. The water quality improvement with time and distance is noticeable but it is still much less significant than pollutant removal in the unsaturated zone, e.g., DOC removal from about 11 mg/L to about 1.5 mg/L, complete ammonia oxidation, 17% total nitrogen removal by denitrification and complete elimination of most Emerging Organic Contaminants, EOC (Elkayam et al. 2018).

Although conventional bacteriological tests have being done since the origin of the Shafdan SAT, a comprehensive survey to assess diverse pathogen removal during the process was conducted for the first time in 2018 (Elkayam et al. 2018). The survey aimed to provide a better insight regarding SAT pathogen removal efficiency and further unfold the effect of retention time and the distance from the recharge basin on reclaimed water quality, with a focus on microbial survival. Therefore, Elkayam et al. (2018) chose a combination of identification and enumeration methods of indicator and pathogenic bacteria and viruses, using growth techniques and qPCR techniques with state-of-the-art DNA probes. Elkayam et al. (2018) performed a
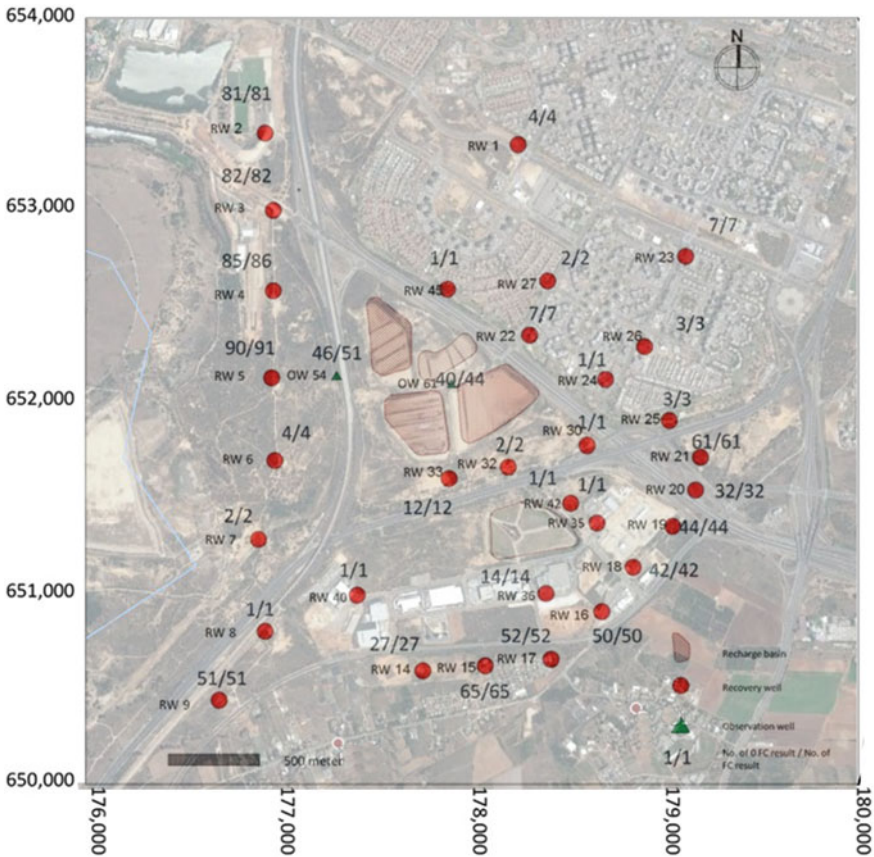
Fig. 12 Northern part (Soreq) of the Shafdan SAT system: location of the recharge basins and the surrounding water reclamation wells (RW) is shown. The number of fecal coliform analyses during 1980–2012 and the number of negative findings are denoted near each RW (Modified after Elkayam et al. 2015)

comprehensive survey in order to obtain a representative view of the SAT controlled closed system (CCS), by examining 25 sampling sites: 1. RS6 site represented the secondary effluent feed to the recharge basins; 2. Two observation wells (OWs) that sample the water beneath the recharge basins, just below the water table. The sampled water in the OWs represented the recharged water after percolation through the vadose zone, with little retention time in the saturated zone; 3. Twenty recovery wells (RWs) located at various distances from the recharge basins and 4. Two RW sites that represented reclaimed water from the regional aquifer, reclaiming less than 3% effluent origin water (EOW). We examined the water from these 25 sites, searching for four types of waterborne pathogenic viruses (adenovirus, enterovirus, norovirus, parechovirus), together with coliphage. The viruses are known to be of human origin and to have high severity of impact, long persistence in water and high

Fig. 13 Aerial view of several infiltration ponds of the Soreq 1 basin

relative infectivity (World Health Organisation 2006). In addition, Elkayam et al. (2018) performed microbial source tracking (MST) analysis, a molecular method that can determine the source of bacterial contamination (human, cattle, pig, etc.) (Ohad et al. 2015). The results are presented as the number of PCR cycles required to obtain identification (Cq), the fewer cycles it requires to identify the DNA, the higher is the level of the contamination. All results were transformed into ΔCq, which is the difference between the number of cycles required to obtain identification of DNA and the total cycles used, and thus, the higher the number, the higher the level of the contamination is. Since theoretically, in each PCR cycle, the amount of DNA is multiplied by 2, when comparing the results of different tests, and every additional PCR cycle indicates that the initial amount of DNA was higher by a factor of two. The difference in "X" units of ΔCq indicates exponential difference from the initial amount of the DNA sample (2^X). As mentioned above, the samples were tested in triplicate, and their average is presented even in cases where one or two of the triplicates tested negative (ΔCq < 5).

Elkayam et al. (2018) also incorporated into this study monitoring by means of quantitative PCR (qPCR) of two antibiotic resistance genes (16S rRNA was used as a proxy for overall bacterial abundance and blaTEM and *qnrS* which encode resistance to β-lactam and quinolone antibiotics, respectively). Antibiotic resistance genes are often targeted to assess levels of anthropogenic impact in the environment.

Table 2 Hydrological data regarding selected wells

Well tag	Near recharge basin	Minimal distance from basin* [m]	Calculated minimal retention time in the saturated zone [month]	Dilution ratio effluent/background [%]	Sub-aquifer	Top screen and water level height difference [m]	Bottom screen and water level height difference [m]
T 281	Yavne 2	0	0	100	AB	(+) 6	(−) 3
T 61	Soreq 1	30	0.3	100	AB	(−) 12	(−) 36
Y 303	Yavne 4	70	0.5	100	B	(−) 16	(−) 53
Y 321	Yavne 4	100	1.5	100	B	(−) 31	(−) 57
MD 33	Soreq 1	145	2	100	B (C)	(−) 45	(−) 72
MD 34	Soreq 1	195	3	100	B (C)	(−) 53	(−) 75
MD 36	Soreq 2	225	2	100	B (C)	(−) 33	(−) 55
Y 304	Yavne 4	230	1	100	B	(−) 24	(−) 47
Y 110	Yavne 1	250	2	100	B	(−) 49	(−) 67
Y 205	Yavne 2	250	2	100	B	(−) 26	(−) 45
Y 207	Yavne 2	281	2	100	B	(−) 28	(−) 60
Y 229	Yavne 3	335	4	90	B	(−) 27	(−) 59
Y 232	Yavne 3	355	3	100	B	(−) 23	(−) 54
MD 30	Soreq 1	360	4	100	B	(−) 35	(−) 61
Y 118	Yavne 1	530	6	100	B	(−) 31	(−) 65
Y 124	Yavne 1	575	5	100	B	(−) 37	(−) 77
MD 40	Soreq 2	720	14	100	C	(−) 59	(−) 80
BZ 9	Yavne 1	945	48	85	B	(−) 25	(−) 91
Y 220	Yavne 3	980	30	100	B	(−) 38	(−) 77
Y 318	Yavne 4	990	60	85	B	(−) 37	(−) 67
Y 317	Yavne 4	1020	60	100	B	(−) 33	(−) 77
MD 8	Soreq 1	1200	60	100	B	(−) 31	(−) 59
Robin 17	Yavne 1	1570	Out of range	0	AB	(−) 34	(−) 65
Robin 19	Yavne 1	1930	Out of range	3	AB	(−) 31	(−) 60

The table indicates the distance from the nearest recharge basin and the computed minimal retention time in the saturated aquifer (Elkayam et al. 2018). The water retention time in the vadose zone is estimated to be about two weeks for the different percolation basins (Elkayam et al. 2012)

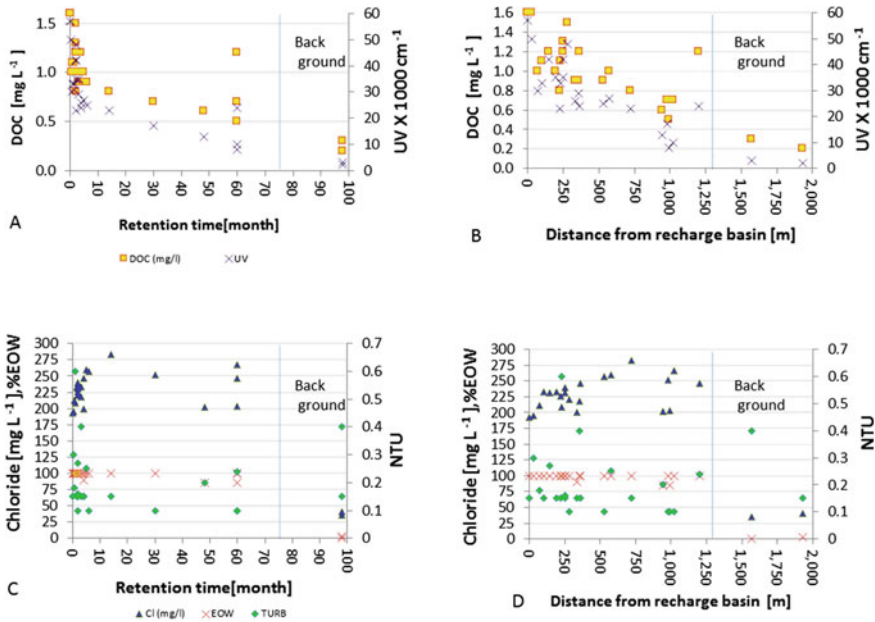*Distances are measured from the edge of the nearest basin

Fig. 14 Chemical measurements of samples from various sites. **a**, **b** DOC and UV in the sampled wells as a function of the distance from the basin and of retention time. **c**, **d** Chloride, turbidity and the effluent origin water (EOW) in the sampled wells as a function of the distance from the basin and of retention time (Modified after Elkayam et al. 2018)

Finally, Elkayam et al. (2018) included in the survey examination of classical indicator bacteria [total coliforms (Coli), fecal coliforms (fecal Coli), fecal streptococcus (STREP) and total bacteria counts (TOTB)]. Table 3 shows the bacteriological and MST results. The bacterial levels in the influent to the recharge basin were similar to the annual average (Icekson-Tal 2014); Coli, fecal Coli and STREP levels were 240,000 MPN/100 mL, 160,000 MPN/100 mL and 9400 MPN/100 mL, respectively. No fecal Coli or STREP was found in any other sites; however, a single Coli (1 CFU/100 mL) was found in one sample (Y110). Site Y110 is located 250 m from the edge of the nearest spreading basin and the minimal water retention time to reach this point is 2 months (Table 2). Large counts of total heterotrophic bacteria were found in RS6 and the two OWs (T61 and T281) with approximately 71,000, 5800 and 5700 CFU/mL, respectively. Sampling site MD8, approximately 1200 m from the nearest recharge basin, had approximately 220 CFU/mL. Other sampling sites had low levels of total heterotrophic bacteria plate counts.

Elkayam et al. (2018) showed the quantification of microbial gene indicators in the sampled wells. qnrS was detected in the effluent water before infiltration, but not in any of the infiltrated groundwater samples. Additionally, it was not detected in the background water adjacent to the sampled infiltrated groundwater wells. In addition, the antibiotic resistance gene blaTEM was above the detection limit (>2 log

Table 3 Bacteriological and MST results in all sampling sites (modified after Elkayam et al. 2018)

Location	Minimal distance form basin [m]	Minimal retention time in the saturated zone [month]	Classic bacteriological test				MST					
			Coli CFU/100 ml	Fecal coli CFU/100 ml	STREP CFU/100 ml	TOTB CFU/1 ml	GB1 ΔCq	HU4 ΔCq	HU5 ΔCq	HU6 ΔCq	EC10 ΔCq	CNT8 ΔCq
RS6*	–	–	240,000	160,000	9400	71,000	23.80	12.60	18.70	16.30	15.80	0
T 281	0	0	<1	<1	<1	5700	6.00	0	0	0	0	0
T 61	30	0.3	<1	<1	<1	5800	8.20	0	0	0	5	0
Y 303	70	0.5	<1	<1	<1	1	6.60	0	0	1.67	0	0
Y 321	100	1.5	<1	<1	<1	3	8.60	0	0	0	0	0
MD 33	145	2	<1	<1	<1	1	6.70	0	0	0	0	0
MD 34	195	3	<1	<1	<1	4	3.80	0	0	0	0	0
MD 36	225	2	<1	<1	<1	13	7.00	0	0	0	1.67	0
Y 304	230	1	<1	<1	<1	30	5.60	0	0	0	0	0
Y 110	250	2	1	<1	<1	4	4.23	0	0	0	0	0
Y 205	250	2	<1	<1	<1	30	5.70	0	0	0	0	0
Y 207	281	2	<1	<1	<1	9	5.50	0	0	0	0	0
Y 229	335	4	<1	<1	<1	0	6.60	0	0	1.67	0	0
Y 232	355	3	<1	<1	<1	20	8.80	0	1.67	0	0	0
MD 30	360	4	<1	<1	<1	8	3.33	0	0	0	0	0
Y 118	530	6	<1	<1	<1	0	3.93	0	0	0	0	0
Y 124	575	5	<1	<1	<1	0	5.50	0	1.67	0	0	0
MD 40	720	14	<1	<1	<1	18	1.67	0	0	0	1.67	0
BZ 9	945	48	<1	<1	<1	14	3.33	0	0	0	0	0

(continued)

Table 3 (continued)

Location	Minimal distance form basin [m]	Minimal retention time in the saturated zone [month]	Classic bacteriological test				MST						
			Coli	Fecal coli	STREP	TOTB	GB1	HU4	HU5	HU6	EC10	CNT8
			CFU/100 ml	CFU/100 ml	CFU/100 ml	CFU/1 ml	ΔCq	ΔCq	ΔCq	ΔCq	ΔCq	ΔCq
Y 220	980	30	<1	<1	<1	0	1.67	0	0	0	0	0
Y 318	990	60	<1	<1	<1	1	3.97	0	0	0	0	0
Y 317	1020	60	<1	<1	<1	1	4.07	0	0	0	1.67	0
MD 8	1200	60	<1	<1	<1	220	5.20	0	0	0	0	0
Robin 17	1570	–	<1	<1	<1	0	5.50	0	0	0	0	0
Robin 19	1930	–	<1	<1	<1	2	6.20	0	0	0	0	0

*Results of classic bacteriological test in MPN/100 ml units

copies/mL) in effluent water and was classified as DBNQ in infiltrated water (Y110 and Y118) and in the control groundwater (Robin 17 and Robin 19).

Elkayam et al. (2018) also showed the results of the tests for adenovirus, enterovirus, norovirus and parechovirus in the Shafdan SAT. These viruses were found in RS6 site at approximately $115,000 \pm 7000$, $65,000 \pm 78,000$, $13,000 \pm 18,000$ and $55,000 \pm 7000$ copies/1000 L, respectively.

Surprisingly, no pathogenic viruses were found in all sampling sites throughout the SAT system, and even more unexpected, no pathogenic viruses were found after the percolation through the unsaturated zone.

5.2   Retention Time, Regulation and Water Quality

For the Shafdan SAT, the regulator sets a guideline of 60 days retention time in the aquifer before supplying the reclaimed water for irrigation of crops eaten raw, and this regulation was set in order to assure all pathogenic hazards before unlimited irrigation. For decades, the notion was that the retention time in the aquifer at the Shafdan SAT varied from 6 months to more than a year, but a recent hydraulic model concluded that the retention time in the nearest recovery wells can be even shorter than one month and the longest retention time extends well beyond 3 years. Thus, some of the Shafdan SAT recovery wells may not fully comply with the guideline concerning minimal retention time. Nevertheless, as the recent study shows, the unsaturated zone plays a major role in the removal mechanism, and as shown the unsaturated zone alone is a barrier between the infiltration basins and the aquifer. It is important to note that the unsaturated thickness in the Shafdan area is between 30 and 40 m while according to Water Reuse EPA, 2012 for Indirect Potable Reuse, tertiary effluent (i.e., secondary after filtration and chlorination) should be infiltrated through a minimum of 2 m of the unsaturated zone only (and then must be "stored" 60 days in the aquifer before use). It might be more reasonable to grant a separate disinfection credit to deep unsaturated zone depending on its thickness, retention time, structure and proven microbial (and chemical) removal efficiency.

5.3   Suitability of the Shafdan Reclaimed Effluent
for Unlimited Irrigation

The current use of the Shafdan water is unrestricted irrigation of crops eaten raw. Nowadays, more than 150 MCM treated effluents are supplied to the Northern Negev by the Shafdan system. Although some of the recovery wells retention time may be shorter than 60 days, the water quality has been high and stable for decades. The demand for 60 days retention time before the supply for unrestricted irrigation should,

therefore, be carefully re-examined because it is pertinent to the use of the Shafdan effluent for unrestricted irrigation.

The U.S. Food and Drug Administration's Food Safety Modernization Act (FMSA), which was finalized in 2016 (US Food and Drug Administration 2016), specifies microbial quality criteria for crop irrigation. It does not specify the type of treatment required (to be applied to the water) but just the water quality requirements.

The American requirements (along with Israeli and other leading regulatory bodies) for unrestricted irrigation of crops eaten raw include pre-chlorination and post-chlorination (Table 4). However, as Elkayam (2019) concluded, the microbial "risk" of the use of the Shafdan effluent for irrigation, even without pre-disinfection is very low, and the Israeli demand for 60 days retention time in the aquifer before being supplied can be reduced—as the accumulated microbial observation in Elkayam et al. (2015a, b), Elkayam et al. (2018) prove that 30 days of retention in the aquifer (in addition to approximately 14 days in the unsaturated zone) are enough to achieve 0 *E. coli* consistently. In addition, pre-chlorination will generate (perhaps unnecessarily) disinfection by products and is likely to interfere with the microbial diversity in the unsaturated zone, where most of the removal of pollutants takes place.

Table 4 summarizes the leading regulatory bodies and their guidelines for bacteriological quality for unrestricted irrigation of crops eaten raw.

Table 4 List of regulatory bodies and water reuse guidelines for unrestricted irrigation of crops eaten raw (Elkayam 2019)

Country/regulatory body	Regulation/guidelines	Treatment processes	List of bacterial regulatory demands and disinfection	Source
USA	EPA water reuse	Secondary treatment Filtration Disinfection	No detectable fecal coliform/10 ml 1 mg/l Cl$_2$ residual (min.), contact time of at least 90 min	US Environmental Protection Agency (2012)
USA	California	Tertiary Filtration (media of membrane): **Media,** including coagulation—Turbidity ≤ 2 NTU **Membrane:** UF, MF, NF, RO—Turbidity ≤ 0.5 NTU Disinfection	Total coliform < most probable number (MPN) of 2.2 per 100 mL Disinfection: chlorine disinfection: CT <450 milligram-minutes per liter, modal contact time of at least 90 min Disinfection process that, when combined with the filtration process, has been demonstrated to inactivate and/or remove 99.999 percent of the plaque forming units of F-specific bacteriophage MS2, or poliovirus in the wastewater	California Department of Public Health (2014)
UN Food and Agriculture Organization (FAO)		Secondary treatment Filtration Disinfection	<1000 fecal coliform/100 mL <1 Intestinal nematodes eggs/l	Pescod, Engineering, Newcastle-upon-tyne, Nations and Division (1992)

Table 4 (continued)

Country/regulatory body	Regulation/guidelines	Treatment processes	List of bacterial regulatory demands and disinfection	Source
JRC SCIENC	EU	Secondary treatment Filtration Disinfection (advanced water treatments)	<10 fecal coliform/100 ml Legionella spp.: $\leq$ 1000 cfu/l helminth eggs: $\leq$ 1 egg/l Log removal in disinfection: *E. coli* $\geq$ 5 Total coliphages/F-specific coliphages/somatic coliphages $\geq$ 6 Clostridium perfringens spores/spore-forming sulfite-reducing bacteria $\geq$ 5 Alternatively, Campylobacter $\geq$ 5 Rotavirus: $\geq$ 6 Cryptosporidium: $\geq$ 5	Laura and Bernd (2017)
Australia	Victoria	Tertiary Pathogen reduction with sufficient log reductions to achieve: <10 *E. coli* org/100 mL <1 helminthes per liter <1 protozoa per 50 L <1 virus per 50 L	<10 *E. coli* org/100 mL Turbidity < 2 NTU4 1 mg/L Cl$_2$ residual after contact time of 30 min (or equivalent disinfection)	VEPA (2003)
Israel	Inbar committee	Secondary treatment Filtration Disinfection	10 fecal coliform/100 mL 1 mg/l Cl$_2$ residual (min)	Inbar (2007)

(continued)

Table 4 (continued)

Country/regulatory body	Regulation/guidelines	Treatment processes	List of bacterial regulatory demands and disinfection	Source
Israel	Halperin committee	Secondary treatment Filtration/high retention time in the reservoir Disinfection	10 fecal coliform/100 mL 1 mg/l Cl_2 residual (min) Contact time of at least 30 min	Halperin (2002)

References

Amy G, Drewes J (2006) Soil aquifer treatment (SAT) as a natural and sustainable wastewater reclamation/reuse technology: fate of wastewater effluent organic matter (EfOM) and trace organic compounds. Environ Monit Assess 129:19–26. https://doi.org/10.1007/s10661-006-9421-4

Bouwer H (2002) Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeol J 10:121–142. https://doi.org/10.1007/s10040-001-0182-4

Bruce D, Friedman GM, Kaufman A, Yechieli Y (2001) Spatial variations of radiocarbon in the coastal aquifer of Israel—indicators of open and closed systems. Radiocarbon 43:783–791. https://doi.org/10.1017/s003382220004145x

California Department of Public Health (2014) Regulations related to recycled water. http://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/lawbook/RWregulations_20140618.pdf

Drewes JE, Reinhard M, Fox P (2003) Comparing microfiltration-reverse osmosis and soil-aquifer treatment for indirect potable reuse of water. Water Res 37:3612–3621. https://doi.org/10.1016/s0043-1354(03)00230-6

Elkayam R (2012) Evaluation and identification of subsurface processes at the Shafdan SAT. M.Sc. thesis, The Hebrew University of Jerusalem (in Hebrew)

Elkayam R (2019) Shafdan soil aquifer treatment system; Process assessment & improvement. Ph.D. thesis, The Hebrew University of Jerusalem, Israel

Elkayam R, Michail M, Mienis O, Kraitzer T, Tal N, Lev O (2015a) Soil aquifer treatment as disinfection unit. J Environ Eng 141:05015001. https://doi.org/10.1061/(asce)ee.1943-7870.0000992

Elkayam R, Sopliniak A, Gasser G, Pankratov I, Lev O (2015b) Oxidizer demand in the unsaturated zone of a surface-spreading soil aquifer treatment system. Vadose Zo J 14. https://doi.org/10.2136/vzj2015.03.0047

Elkayam R, Aharoni A, Vaizel-Ohayon D, Sued O, Katz Y, Negev I, Marano RBM, Cytryn E, Shtrasler L, Lev O (2018) Viral and microbial pathogens, indicator microorganisms, microbial source tracking indicators, and antibiotic resistance genes in a confined managed effluent recharge system. J Environ Eng 144:05017011. https://doi.org/10.1061/(asce)ee.1943-7870.0001334

Gasser G, Rona M, Voloshenko A, Shelkov R, Lev O, Elhanany S, Lange F, Scheurer M, Pankratov I (2011) Evaluation of micropollutant tracers. II. Carbamazepine tracer for wastewater contamination from a nearby water recharge system and from non-specific sources. Desalination 273:398–404. https://doi.org/10.1016/j.desal.2011.01.058

Gasser G, Pankratov I, Elhanany S, Glazman H, Lev O (2014) Calculation of wastewater effluent leakage to pristine water sources by the weighted average of multiple tracer approach. Water Resour Res 50:4269–4282. https://doi.org/10.1002/2013wr014377

Gvirtzman G, Buchbinder B (1978) The late Tertiary of the coastal plain and continental shelf of Israel and its bearing on the history of the Eastern Mediterranean. In: Initial reports of the Deep Sea drilling project, vol 42. U.S. Government Printing Office, Washington, D.C., pp 1195–1222

Halperin R (2002) Halperin Committee Report, Principles for granting permits to irrigate effluents [WWW Document]. Minist. Heal. Isr. https://www.health.gov.il/hozer/bsv_Halperin.doc

Hernández M, Magarzo C, Lemaire B (2012) Degradation of emerging contaminants in reclaimed water through soil aquifer treatment (SAT). J Water Reuse Desalin 2:157–164. https://doi.org/10.2166/wrd.2012.016

Icekson-Tal N (2014) groundwater recharge with municipal effluent: recharge basins Soreq, Yavne 1, Yavne 2 and Yavne 3 : 2014. Mekorot Water Company Limited, Central District, Dan Region Unit

Inbar Y (2007) Inbar [WWW Document]. Minist. Environ. Prot. Isr. http://www.sviva.gov.il/InfoServices/ReservoirInfo/DocLib2/Publications/P0301-P0400/P0321.pdf

Issar A (1968) Geology of the central coastal plain of Israel. Isr J Earth Sci 17:16–29

Kloppmann W, Chikurel H, Picot G, Guttman J, Pettenati M, Aharoni A, Guerrot C, Millot R, Gaus I, Wintgens T (2009) B and Li isotopes as intrinsic tracers for injection tests in aquifer storage

and recovery systems. Appl Geochem 24:1214–1223. https://doi.org/10.1016/j.apgeochem.2009.03.006

Laura AS, Bernd G (2017) Minimum quality requirements for water reuse in agricultural irrigation and aquifer recharge. Publications Office of the European Union. https://doi.org/10.2760/887727

Lian J, Luo Z, Jin M (2013) Transport and fate of bacteria in SAT system recharged with recycling water. Int Biodeterior Biodegrad 76:98–101. https://doi.org/10.1016/j.ibiod.2012.06.012

Negev I, Guttman J, Kloppmann W (2017) The use of stable water isotopes as tracers in soil aquifer treatment (SAT) and in regional water systems. Water 9:73. https://doi.org/10.3390/w9020073

Ohad S, Vaizel-Ohayon D, Rom M, Guttman J, Berger D, Kravitz V, Pilo S, Huberman Z, Kashi Y, Rorman E (2015) Microbial source tracking in adjacent karst springs. Appl Environ Microbiol 81:5037–5047. https://doi.org/10.1128/aem.00855-15

Peter H (1998) Wastewater treatment and groundwater recharge for reuse in agriculture: Dan Region Reclamation Project, Shafdan. Artificial recharge of groundwater. A.A. Balkema, Rotterdam

Pescod T, Engineering EC, Newcastle-upon-tyne T, Nations U, Division P (1992) Wastewater treatment and use in agriculture - FAO irrigation and drainage paper 47. Food and agriculture organization of the united. Nat. Resour. Manag. Environ. Dep. vol 4.https://www.fao.org/docrep/T0551E/t0551e06.htm

Sopilniak A, Elkayam R, Lev O, Elad T (2015) Oxygen profiling of the unsaturated zone using direct push drilling. Environ Sci Process Impacts 17:1680–1688. https://doi.org/10.1039/c5em00270b

Sopliniak A, Elkayam R, Lev O (2017a) Nitrification in a soil-aquifer treatment system: comparison of potential nitrification and concentration profiles in the vadose zone. Environ Sci Process Impacts 19:1571–1582. https://doi.org/10.1039/c7em00402h

Sopliniak A, Elkayam R, Lev O (2017b) Quantification of dissolved organic matter in pore water of the vadose zone using a new ex-situ positive displacement extraction. Chem Geol 466:263–273. https://doi.org/10.1016/j.chemgeo.2017.06.017

U S Environmental Protection Agency (2012) 2012 guidelines for water reuse, development. EPA Environmental Protection Agency, Cincinnati, OH

US Food and Drug Administration (2016) Food safety modernization act (FSMA). Public Law

VEPA (2003) Guidelines for environmental management: use of reclaimed water. EPA Victoria, Southbank, Victoria, pp 1–101

Wilson LG, Amy GL, Gerba CP, Gordon H, Johnson B, Miller J (1995) Water quality changes during soil aquifer treatment of tertiary effluent. Water Environ Res 67:371–376. https://doi.org/10.2175/106143095x131600

World Health Organisation (2006) Guidelines for the safe use of seawater, excreta and graywater. Wastewater use in agriculture, vol 2