The long-term performance of Soil Aquifer Treatment (SAT) for effluent reuse

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Abstract An innovative scheme of groundwater recharge for wastewater effluent reuse has been practiced on a large scale in the Dan Region Project in Israel since 1977. The system, referred to as SAT (for Soil Aquifer Treatment), provides advanced treatment prior to effluent reuse for unrestricted irrigation. A major study recently carried out consisted of a comprehensive analysis of the water quality data available in the recharged effluent (before SAT), as well as in observation wells and recovery wells (after SAT). The results obtained with respect to suspended solids, organics and nutrients (nitrogen compounds and phosphorus) are presented and discussed. The main processes occurring in the soil-aquifer system, which are responsible for the removal of the above contaminants are filtration through the upper soil layer, organic matter biodegradation and adsorption, ammonia adsorption and biological nitrification–denitrification, and chemical precipitation and adsorption of phosphorus. The findings of the study have provided valuable information on the above processes and their interaction, and have demonstrated that the SAT system should be considered an attractive method for effluent reuse in areas where hydrogeological conditions are suitable for groundwater recharge via spreading basins.

Keywords Advanced wastewater treatment; effluent reuse; groundwater recharge; soil aquifer treatment; water reclamation

Introduction
An innovative system of groundwater recharge for wastewater effluent reuse has been practiced continuously on a large scale in the Dan Region Project in Israel since 1977. The name given to this system more than 20 years ago by the senior author of this paper – SAT (for Soil Aquifer Treatment) – reflects its main feature: the use of the unsaturated zone above the aquifer and the aquifer itself for advanced effluent treatment, which removes a wide range of contaminants from the recharged effluent. The SAT system, in which “controlled” groundwater recharge is the means and effluent reuse is the final objective, differs considerably from the system used in California, in which effluent reuse is the means and groundwater recharge for aquifer replenishment is the final objective (Idelovitch and Michail, 1984).

About 120 Mm$^3$/yr of partially treated effluent from the wastewater treatment plant of the Dan Region (Tel Aviv Metropolitan Area) are being recharged to the groundwater aquifer via spreading basins in four recharge zones built in areas of predominantly sandy soils – a northern recharge zone (Soreq) and three southern recharge zones (Yavne 1, 2 and 3). The northern recharge zone (Soreq) has been in continuous operation since 1977, whereas the oldest southern recharge zone (Yavne 1) has been in operation since 1987 (Idelovitch, 1998). The other two southern recharge zones (Yavne 2 and Yavne 3) have been in operation since 1988 and 1995, respectively.

In the first stage of the project, between 1977 and 1987, only part of the Dan Region’s wastewater was conveyed to the plant and treatment prior to SAT consisted of oxidation ponds, high-lime treatment and ammonia stripping ponds. During that period, all the
effluent was recharged to the groundwater in the Soreq recharge zone. In the second stage of the project – since 1987, when the mechanical–biological treatment plant was operated – the wastewater from the whole Dan Region has been conveyed to the plant and the plant effluent has been recharged to the groundwater both in the Soreq recharge zone and in the Yavne recharge zones. Treatment prior to SAT presently consists of preliminary treatment (bar screens and aerated grit chambers) and biological treatment by a modified activated sludge process with nitrification–denitrification and biological phosphorus removal (without primary treatment). As a result of the changes in the wastewater sources feeding the plant and the treatment processes prior to recharge, the quality of the recharged effluent varied during time.

The following is a brief description of the Dan Region’s SAT system. Each recharge zone consists of several recharge basins which are divided into sub-basins. The operation of the recharge basins is intermittent, i.e., flooding periods alternate with drying periods to maintain high infiltration rates through the upper soil layer and to allow oxygen to penetrate into the soil, thus enhancing and diversifying the soil purification capacity. The recharged effluent gradually displaces the native groundwater and moves towards a ring of recovery wells surrounding the recharge basins. The recovery wells pump the high-quality reclaimed water obtained after SAT to a separate, non-potable conveyance system, which is used only for unrestricted irrigation of agricultural crops. The zone of the aquifer enclosed within the ring of recovery wells is hydrologically separated from the rest of the aquifer, which is not affected by the effluent recharge operation and continues to supply potable water. A small portion of the potable aquifer is thus “sacrificed” and dedicated to effluent purification by SAT, as well as to seasonal storage that is required anyhow as the reclaimed water for irrigation is needed mostly in the summer season. A large number of observation wells, which are located between the recharge basins and the recovery wells, provide the means for monitoring the SAT system.

Objectives of the study
A major study of the Dan Region’s SAT system was carried out during 1999–2001 (Idelovitch, 2001). It consisted of a comprehensive analysis of the large amount of water quality data accumulated over a period of 25 years. The main objectives of the study were to: (a) evaluate the recharge effluent quality prior to SAT, (b) evaluate the reclaimed water quality after SAT, (c) estimate the purification capacity of the soil aquifer system and its efficiency, and (d) analyze the performance of the physical, biological and chemical processes occurring during SAT, and try to predict their long term behavior.

Monitoring of SAT system
An extensive monitoring program has accompanied the recharge-recovery operation since its inception in 1977, thus providing an unusual wealth of large-scale, reliable data on the effluent quality before and after SAT. The monitoring program has two major objectives: (a) to follow the movement of the recharged effluent in the aquifer (hydrological aspects), and (b) to detect the changes in the physical, chemical and bacteriological characteristics of the groundwater in the recharge zone and its vicinity (water quality aspects). The monitoring program includes two sampling points for the recharge effluent (before SAT), as well as some 50 observation wells and 100 recovery wells (after SAT). In the recharge effluent (RE), some 60 physico-chemical and biological parameters are analyzed with a frequency varying from once per week for common physico-chemical parameters to twice per year for bacteriological indicators and some trace elements. In the observation wells (OW) and the recovery wells (RW), a “routine analysis” consisting of some 20 parameters is performed with a frequency varying from once to four times per year. In addition, a “comprehensive...
Data taken into account
The study took into account the water quality data available before and after SAT. The effluent quality before SAT was based on the analyses carried out on samples taken from Pumping Stations No. 5 and No. 6, which pump the recharge effluent (RE) to the northern and southern recharge zones, respectively.

The effluent quality after SAT was based on selected observation wells (OW) and selected recovery wells (RW) that are located at various distances from the recharge basins in two recharge zones (Soreq and Yavne 1). The wells considered in each zone were selected as follows: an observation well located close to the recharge basins (50 to 100 m from the edge of the nearest basin), an observation well located further from the recharge basins (250 to 300 m) and a recovery well located at 450 to 500 m from the recharge basins. The following wells were selected for the detailed and comprehensive analyses carried out in this study: OW 61 (near), OW 54 (far) and RW Dan 5 in the Soreq zone; and OW 9 (near), OW 17 (far) and RW 122 in the Yavne 1 zone. The above wells have been pumping 100% recharge effluent for a long time: the Soreq observation wells since 1978–1980, the Soreq recovery well since 1985; the Yavne 1 observation wells since 1989–1990 and the Yavne 1 recovery well since 1995.

The data taken into account in this study cover a period of about 25 years for the Soreq recharge zone and about 15 years for the Yavne 1 recharge zone. The data utilized are the seasonal averages provided by the detailed yearly project reports available (Idelovitch et al., 1977–1984; Michail et al., 1985–1990; Kanarek et al., 1991–1994; Soffer et al., 1995–1996; Icekson Tal et al., 1997–2000).

Results and discussion
In order to analyse, present and interpret the large amount of data accumulated during the years, the parameters included in the monitoring program were divided into seven groups as follows:
(a) chlorides, the main parameter that indicates the arrival of the recharged effluent at a certain well and permits estimating the percentage of effluent in the well water;
(b) parameters characterizing wastewater type and strength such as total and volatile suspended solids (SS and VSS) and total and filtered biochemical oxygen demand (BOD and BODf);
(c) parameters measuring organic substances such as: total and filtered chemical oxygen demand (COD and CODf), total and dissolved organic carbon (TOC and DOC), ultraviolet absorbance (UV absorbance) and detergents;
(d) main nutrients: ammonia (NH3/NH4), Kjeldahl nitrogen (TKN), nitrite (NO2), nitrate (NO3), and phosphorus (P);
(e) parameters measuring the salinity of the effluent and its ionic composition;
(f) heavy metals and trace elements;
(g) microbiological parameters.

In this paper, the following parameters belonging to the first four aforementioned groups, are presented and discussed: (a) chlorides, (b) SS and BOD, (c) CODf and UV absorbance, and (d) nitrogen compounds and phosphorus.

Chlorides
The selection of the chloride ion as a reliable indicator was based on the following criteria: (a) the chloride ion concentration, which is a measure of the effluent salinity, does not
change during SAT and (b) there is a difference of one order of magnitude between its concentration in the recharged effluent (200 to 400 mg/L) and in the native groundwater (20 to 40 mg/L). The chloride concentration in observation and recovery wells followed the concentration in the recharged effluent, with a time lag depending on the distance of the well from the recharge basin. The behavior of the chloride ion in wells located at various distances from the recharge basins confirmed that it is a reliable indicator (Figure 1).

SS and BOD
The concentration of suspended solids before SAT varied between 10 and 80 mg/L and that of BOD between 5 and 40 mg/L. Most of the SS are of organic nature (VSS) and most of the BOD is particulate (values of \( \text{BOD}_f \) were generally very low). The concentration of suspended solids in observation and recovery wells (after SAT) was nil and the BOD concentration was negligible (less than 0.5 mg/L). The SAT removal efficiency was thus very high for SS and BOD, as a result of two main processes: filtration through the upper soil layer and biodegradation in the soil.

Dissolved organics
Of the various parameters included in the monitoring program for measuring total dissolved organics, filtered COD (\( \text{COD}_f \)) and UV absorbance at a wavelength of 254 nm were found to be the most suitable. The COD concentration in the recharged effluent varied between 40 and 160 mg/L and that of \( \text{COD}_f \) between 40 and 80 mg/L. The COD and \( \text{COD}_f \) concentrations after SAT dropped to values between 10 and 20 mg/L. Because of the absence of suspended solids in the well water there is virtually no difference between total and filtered COD (Figure 2).

UV absorbance values varied between 150 and 400 before SAT and between 30 and 100 in the reclaimed well water (after SAT). The UV absorbance values for native groundwater were 10 or below. The unit of expression for UV absorbance values is “per cm” (cm\(^{-1}\)), and the values obtained were multiplied by 1,000 for convenience purposes.

The important reduction in the dissolved organics concentration by SAT indicates that significant biological and biochemical processes take place in the SAT system. Two processes are essentially responsible for the removal of dissolved organics: biodegradation and adsorption. These two processes complement one another, i.e., part of the organic matter adsorbed onto soil particles undergoes biological degradation during time. The long detention time in the aquifer – months or even years – allows for the biodegradation of organic substances usually considered “refractory”, which require a long period of time for the development and acclimatization of the microbial population capable of degrading them.
The relative removal efficiency (RRE) of the different organic parameters was calculated based on their values before and after SAT, for two separate periods: the first recharge period (1977–1995) and the last recharge period of about 5 years (since 1996) when the overall quality of the recharged effluent was higher (as a result of the expansion of the treatment plant installations) and the water quality of the observation wells was lower in terms of some parameters. High removal efficiency of organic parameters was obtained, which confirmed that the SAT process performs as a biological treatment process. However, a reduction in the removal efficiency was observed in the last few years at the Soreq site only, mostly in terms of two parameters: UV absorbance and detergents, and in a lesser measure in terms of three additional organic parameters: DOC, COD and phenols.

**Nutrients**

Several processes occurring in the soil-aquifer system affect the concentration of the main nutrients in the effluent: nitrogen (N) on its various components and phosphorus (P). The N concentration in the recharged effluent varied between 5 and 30 mg/L and consisted mostly of soluble Kjeldahl nitrogen, which reflects the unoxidized nitrogen compounds (ammonia and organic N). The ammonia concentration in the recharged effluent varied between 2 and 18 mg/L. The concentration of oxidized nitrogen compounds (NO₂ and NO₃) was negligible in the recharged effluent. Nitrogen concentration after SAT varied between 5 and 10 mg/L, the bulk of which was in the form of nitrates.

The nitrogen concentration in the reclaimed water is lower than in the recharged effluent as a result of the following three main processes occurring in the soil-aquifer system: (a) removal of particulate Kjeldahl nitrogen by filtration through the upper soil layer, (b) removal of ammonia by nitrification and denitrification occurring in the soil and the aquifer, and (c) removal of dissolved Kjeldahl nitrogen (mostly ammonia) by adsorption onto soil particles.

The above processes are also complementing one another: part of the nitrogen adsorbed onto soil particles undergoes biological nitrification and denitrification processes during time. As a result of the short recharge cycle adopted (one day flooding and two to three days drying), the prevailing conditions in the soil–aquifer system are aerobic; thus, nitrification – an aerobic process – is efficient and reliable. Denitrification, on the other hand, which is an anoxic process, occurs only in limited anaerobic pockets found within the predominantly aerobic zone and is thus partial and sporadic. Consequently, the ammonia and Kjeldahl nitrogen concentrations were reduced considerably in the soil–aquifer system – usually to less than 1 mg/L – whereas nitrate concentrations fluctuated within a wide range.
Monitoring of ammonia and nitrate concentrations in observation wells at the Soreq recharge site indicated that in the last few years (since 1996), nitrate concentrations dropped to negligible levels whereas ammonia concentrations went up. This occurred in parallel with the rise in the concentration of organic matter expressed by means of UV absorbance.

Phosphorus concentration in the recharged effluent varied between 1 and 4 mg/L during the period 1977–1989 when the effluent was subjected to chemical treatment prior to recharge, and between 3 and 10 mg/L since 1990 when effluent treatment prior to recharge has included only biological treatment by the modified activated sludge process with nitrification–denitrification and biological phosphorus removal. Phosphorus concentration after SAT was below 0.1 mg/L (Figure 3). The above indicates the very high efficiency of phosphorus removal by SAT, which has not dropped during time. The main processes responsible for phosphorus removal are chemical precipitation and adsorption.

The relative removal efficiency (RRE) of the main nutrients was calculated based on their values before and after SAT, for two periods: the first recharge period (1977–1995) and the last recharge period of about 5 years (since 1996), when the N and P concentrations in the recharged effluent were lower (as a result of the expansion of the treatment plant installations) and the ammonia and Kjeldahl concentrations in observation wells in the Soreq area went up considerably.

In the first recharge period, the ammonia and Kjeldahl nitrogen were removed very well by SAT, but in the last few years a considerable reduction in the removal efficiency of these parameters was noted at the Soreq recharge zone. This is due to the formation of anaerobic conditions in the soil–aquifer system, which prevents the occurrence of the aerobic nitrification process (conversion of ammonia to nitrate). Phosphorus removal efficiency, on the other hand, was excellent and remained stable over time. The concentrations of different parameters (organics and nutrients) before and after SAT, together with the average relative removal efficiency (RRE) are summarized in Table 1.

Long-term forecast

The long term forecast with respect to the purification processes occurring during SAT depends on the type of process. The physical process, filtration through the upper soil layer, which is responsible for the removal of suspended solids, will last forever if the maintenance and cleaning of the recharge basins are done appropriately. The biological processes – bacterial degradation and nitrification–denitrification, which are responsible for the
removal of dissolved organic matter and nitrogen, respectively, will also last forever, if the conditions required for bacterial activity and the delicate balance between aerobic and anaerobic conditions are preserved.

As for the chemical processes (chemical precipitation and adsorption), which are responsible for the removal of phosphorus as well as of heavy metals and trace elements (which are not included in this paper), the long-term forecast is that they will last only a limited amount of time, until the precipitation and/or adsorption capacity are exhausted. However, this is only a theoretical forecast. In reality, the above processes can last for a long time – tens or even hundreds of years – as confirmed by the excellent and stable removal of phosphorus and trace elements obtained during 25 years of operation of the SAT in the Dan Region Project. This is due to the large soil volume participating in the process, as well as to the combined action of chemical and biological processes. Some of the contaminants adsorbed or precipitated onto soil particles by chemical processes undergo in time biological processes, and thus liberate the soil sites for adsorption or precipitation of new contaminants.

It is not possible to separate between the organic matter removed by biodegradation and that removed by adsorption. The biodegradation process can last indefinitely, whereas the adsorption process should last only during a limited period of time (until the soil adsorption capacity is exhausted). Similarly, it is not possible to separate between the ammonia removed by adsorption and that removed by nitrification–denitrification. The former process would last only a limited period of time, whereas the latter (nitrification–denitrification which is a biological process) can last indefinitely.

The increase in the concentration of dissolved organics and ammonia that occurred in the last few years at the Soreq recharge zone is presumably due to the formation of predominantly anaerobic conditions in parts of the soil-aquifer system (normally aerobic conditions prevail in the soil-aquifer system, with anaerobic conditions found only in small pocket zones which are not exposed to oxygen penetration during recharge). As a result, the aerobic microbial population capable of converting ammonia to nitrate and degrading certain organic substances could not develop. The anaerobic conditions that developed at the Soreq site were a result of the gradual reduction of the infiltration capacity of the upper soil layer, the insufficient maintenance and cleaning of the spreading basins, followed by the need to extend the flooding periods and shorten the drying periods, thus allowing less oxygen to penetrate into the soil. The reduction of iron and manganese which was observed at the Soreq site, together with the fact that at the Yavne site (where aerobic conditions prevail) no increase in the ammonia or UV absorbance occurred, strengthen the hypothesis presented above.

In the last year since the completion of this study, the quality of the recharged effluent
and the condition of the Soreq recharge basins have improved. Consequently, the infiltration capacity of the basins has increased and the ratio between the length of drying and flooding period has increased, too. Thus, aerobic conditions prevail again in a larger portion of the soil-aquifer system. As a result, the concentrations of ammonia and UV absorbance in the observation wells have been going down. It is hoped that this tendency will continue in the future.

Conclusions
The SAT process has an excellent capacity for removing a wide range of contaminants. The parameters presented and analyzed in this paper are: COD$_f$, and UV absorbance, which measure the concentration of dissolved organic substances, and the main nutrients – nitrogen compounds and phosphorus. Organics are efficiently removed during SAT by a combination of filtration through the upper soil layer, biodegradation and adsorption. Nitrogen is efficiently removed by a combination of ammonia adsorption and biological nitrification–denitrification. Phosphorus is excellently removed by chemical precipitation and adsorption.

References