018530 - SWITCH

Sustainable Water Management in the City of the Future

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D 3.2.1.f - i Guidelines for Design and Operation and Maintenance of SAT (and Hybrid SAT) system

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Sustainable Water Management in the City of the Future

Guidelines for design, operation and maintenance of SAT (and hybrid SAT) systems

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ABSTRACT

This "Guidelines for design, operation and maintenance of SAT (and hybrid SAT) systems" developed under EU SWITCH project[1] is one of the key deliverables of Natural Treatment Systems Research theme and will assist the design engineers and planners in feasibility assessment, planning, design and operation and maintenance of different types of Soil Aquifer Treatment (SAT) systems depending on water quality and hydrogeological conditions. These guidelines can also be useful for the city strategic planner for the selection of wastewater treatment and reuse system for the city.

This "Guidelines" have been prepared as a combined key deliverable to fulfill the requirements of the following Deliverables of EU SWITCH project WP 3.2 Safe Water Reuse:

a. D 3.2.1f: Demonstration study of SAT

b. D 3.3.1g: Conceptual model and framework for facilitating technology transfer of SAT to other potential sites

c. D 3.2.1h: Definition of time/distance relationship required for contaminant elimination in a SAT system

d. D 3.2.1 i: Development of hybrid SAT-membrane system

a. D 3.2.1f: Demonstration study of SAT

Chapters 5, 6, 9 and 11.1 relate to the Demonstration Study that was conducted in Shafdan Israel in the context of the EU SWITCH project[1] and was based on the improvement of the actual long – term SAT by using a short SAT system as pretreatment for a Nanofiltration polishing step.

b. D 3.3.1g: Conceptual model and framework for facilitating technology transfer of SAT to other potential sites

In order to facilitate the technology transfer Chapters 1-7, 10 and 11 methodically guides the reader to how to choose the proper infiltration system, to select the site, plan and design the SAT system, operate and maintain the system. Also capital and O & M costs examples (Chapter 10) and existing worldwide big SAT systems (Chapter 11) have been given to guide the engineer during the planning, design and operation stages.

c. D 3.2.1h: Definition of time/distance relationship required for contaminant elimination in a SAT system

Chapters 2.3 and 4 mainly relate to the results of the bench scale studies performed in UNESCO-IHE and the conclusions that were derived.

The removals of contaminants, generally, increase with residence/travel time and travel distance. Travel time has more influence on DOC and other contaminants removal than travel distance.

For a given vadose zone depth and wastewater quality, lower infiltration rates enable more retention time for bio-treatment. Conversely, the high rate application of different grades of treated wastewater enable to have longer rest periods (1-2 days flooding, 2-7 days rest) allowing more oxygen to penetrate the vadose zone and help enhance the biological activity removing more biodegradable organic matter and also reduce the anaerobic conditions in the aquifer and prevent manganese dissolution.

Correlation analysis showed that for all the water quality parameters among others, **residence/travel time** in the soil layer was the main parameter governing the effluent quality from SAT for all primary, secondary and tertiary effluents. It is evident that longer travel times will allow breakdown of slowly biodegradable organics.

Chapters 8, 9 and 11.1 show the time/distance relationship obtained in the actual Shafdan Project SAT and in the new developments like the UF-short SAT system (EU RECLAIM project[2]) or the short –SAT –NF system (EU SWITCH project[1]).

d. D 3.2.1 i: Development of hybrid SAT-membrane system

Chapter 3.2 explains the limitations of the conventional (soil spreading) SAT and Chapters 8 and 9 relate to different pre or post treatment methods to improve the conventional SAT systems.

Mekorot developed, by means of the short SAT – NF pilot in the context of EU SWITCH project[1], a short system which can be almost an isolated core of soil (by wells over pumping around the chosen 15-20 m. radius area) that can be used as a natural bioreactor (and still conform the non-pollution of the natural water courses that the EU requires). This bioreactor comes before NF polishing, to remove organic matter, ammonia and phosphates, particulate matter and microorganisms better than UF pre-treatment applied in RO systems for effluent reuse in indirect drinking water purposes.

In order to disseminate these outputs to wider audiences, it is advisable to integrate them into the SWITCH Global Training Package. Also it can be disseminated to wider professional audience by producing a publication through networks like IWA, the EU publications or UNESCO-IHP. In parallel the effort to disseminate the knowledge by presentations in major training workshops or conferences around the world will continue.

1. INTRODUCTION

1.1 Managed aquifer recharge concept and particular use as Soil Aquifer Treatment (SAT)

Increasing demand for water caused by population growth and industrial development on one hand and deterioration of fresh water sources and climate change on the other hand is causing water stress around the world. To cope with this situation the effective management of water resources is required. In this context, in recent years effective methods for Aquifer Recharge management are being developed and implemented in different countries in the world.

Managed Aquifer Recharge (MAR) comprises a wide variety of systems in which water is intentionally introduced into an aquifer. The objectives are:

i) To store excess water during the rainy season to be used in dry periods (mainly in arid and semi-arid regions)

ii) To introduce an (additional) barrier for treatment of water for a specific use

iii) To reduce the risk of intrusion of impaired water (e.g. in coastal aquifers).

Different types of MAR systems used for groundwater recharge are:

1. Dune filtration	2. Infiltration ponds	3. Bank filtration
4. Percolation tank	5. Soil Aquifer Treatment (SAT)	6.Underground Dam
7. Sand Dam	8. Recharge release	

Those methods are more efficient for unconsolidated rocks (e.g., sandstone, gravel)

The different processes that use direct injection into aquifer are:

- Aquifer Storage Recovery (ASR)
- Aquifer Storage Treatment and Recovery (ASTR)
- Rain water harvesting

Those methods can be efficient either for unconsolidated and consolidated rocks (limestone, dolomite).

Groundwater recharge can be performed in two ways: Through soil and subsoil passage or by direct entrance (injection) into the aquifer. Reclaimed water reused by direct aquifer recharge can be allowed for potable reuse, only after advanced tertiary treatment (membrane processes, reverse osmosis, advanced oxidation process) and other barriers such as percolation through the soil which acts as a barrier retaining contaminants. A classical system which uses the favourable characteristics of soil, subsoil and aquifer for further treatment of the infiltrated water to potable quality is the SAT (Soil Aquifer Treatment) developed by

Bouwer (1978). One of the big scale applications of the SAT principle is the Dan Region project in Israel (130 M m^3/yr).

Soil Aquifer Treatment (SAT) is a MAR technology, which alone or in combination with other wastewater treatment technologies can produce effluent suitable for indirect potable reuse. It is a relatively low cost and robust process that can be an alternative to fresh water sources (for agricultural irrigation, sea water intrusion, municipal uses, and park irrigation). SAT has been applied in wastewater reuse in arid regions (USA, Israel, and in a smaller scale in Australia) where there is significant lack of water resources (Idelovitch and Michail, 1984: Peters et al, 1998).

Contrary to slow sand filtration (SSF) or Intermittent Sand Filter (ISF) which are slow rate (annual hydraulic loading rate 5-50 m/yr) land treatment systems for effluent irrigation, the conventional SAT systems are relatively high loading rate systems (average annual hydraulic loading 50-720 m/yr).

1.2 Description of the SAT process

Soil aquifer treatment (SAT) provides wastewater treatment during flow through unsaturated soils and the aquifer and the treated water is recovered by means of recovery wells (see Fig. 1). SAT is an advanced (beyond secondary) wastewater treatment process.

The treatment is done in three steps: Surface infiltration, percolation through the unsaturated zone (vadose zone) and slow transport through the aquifer (Fig. 3 and Table 1).

In the SAT method, dissolved organic matter is removed by combined biological, chemical, and physical processes mainly in the vadose zone (the unsaturated zone). The vadose zone and aquifer act as natural, slow filters that effectively reduce the concentration of various pollutants due to physical, chemical, and microbiological processes. Suspended solids are filtered out; biodegradable organic compounds are decomposed; microorganisms are adsorbed, strained out, or die because of competition with other soil microorganisms; nitrogen concentrations are reduced by denitrification; synthetic organic compounds are adsorbed and/or biodegraded; and phosphate, fluoride, and heavy metals are adsorbed, precipitated, or otherwise immobilized.

In the case of SAT the recharge – reclamation process is based on intermittent flooding and drying of the spreading basins to provide oxygen, controlled passage of the effluent through the unsaturated zone and part of the aquifer, and subsequent pumping of the reclaimed water by means of production wells surrounding the recharge area. SAT uses the soil and groundwater as treatment and seasonal or longer-term storage (Bouwer and Rice, 1984). SAT technology is used also to store high quality water to replenish the

diminishing groundwater supplies and also to prevent sea water intrusion. Currently SAT renovated water is being used in USA as a non-potable resource (e.g., municipal and golf course irrigation) and in Israel the water treated to potable levels is used in unrestricted irrigation.

Fig. 1 shows a surface spreading infiltration basins where the basins are located close together in a cluster and the wells are on a circle around this cluster. Different types of surface spreading SAT system are shown in Figure 4 and will be discussed in Chapter 2.2.

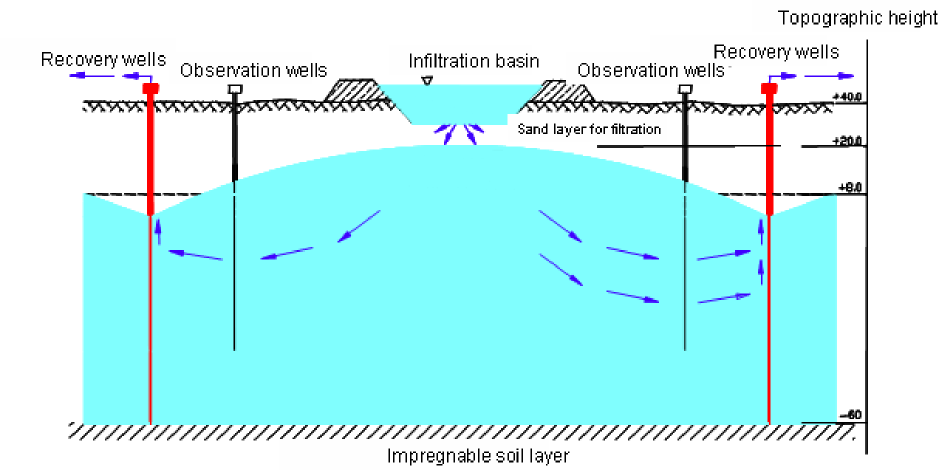

Figure 1 - Schematic Diagram showing the layout of the Soil Aquifer Treatment System and wells (Bixio and Wintgens, 2006)

In order to treat primary, secondary and tertiary effluents by SAT, a separate zone is created within the regional aquifer, which is located beneath the recharge basins and is hydrologically separated from the rest of the aquifer by the production wells surrounding the recharge zone. This zone is dedicated to treatment and seasonal storage of the effluents. In the aquifer, the recharged effluent is monitored by means of observation wells located at various distances from the recharge basins, in all directions. Because of its important function in water quality improvement, this recharge-recovery type system is particularly referred as SAT.

SAT provides an effective step in the treatment train for water reuse. On the other hand the actual surface spreading SAT systems have the surface clogging and manganese dissolution problems and for indirect potable reuse non satisfactory micropollutants removal that have to be taken care of. But it has to be emphasized that the SAT system produces very high quality water for unrestricted irrigation.

For this purpose, in recent years, new hybrid treatments have been proposed, including advanced pre-treatment methods like:

1. Polishing of the secondary effluents before SAT by the use of UF, rapid infiltration of the UF effluents in a Dug-well and recovery of the water after a short SAT (15-20 m. travel distance and around 30 days residence time) to obtain very high quality water for unrestricted irrigation. EU RECLAIM WATER project[2] (Gaus et. al., 2007; Cikurel & Aharoni, 2011).

2. Surface spreading infiltration of tertiary treated effluents (sand filtered secondary effluents) in a short - SAT system (15 m.-20 m. travel distance and around 30 days residence time) as pretreatment for NF to polish the SAT effluents to indirect potable reuse quality water. EU SWITCH project[1] (Cikurel et al., 2010).
3. Flocculation-aeration-filtration and AOP (ozone-hydrogen peroxide) pretreatment prior to dug-well infiltration and short- SAT process for the degradation and removal of micropollutants and prevention of manganese solubilization. Pre ozonation –SAT project (Maman et. al, 2010).

A schematic configuration of the conventional SAT and all three Hybrid SAT processes studied in different pilot plants in the Dan Region Project, Israel (Shafdan) is given in Figure 2.

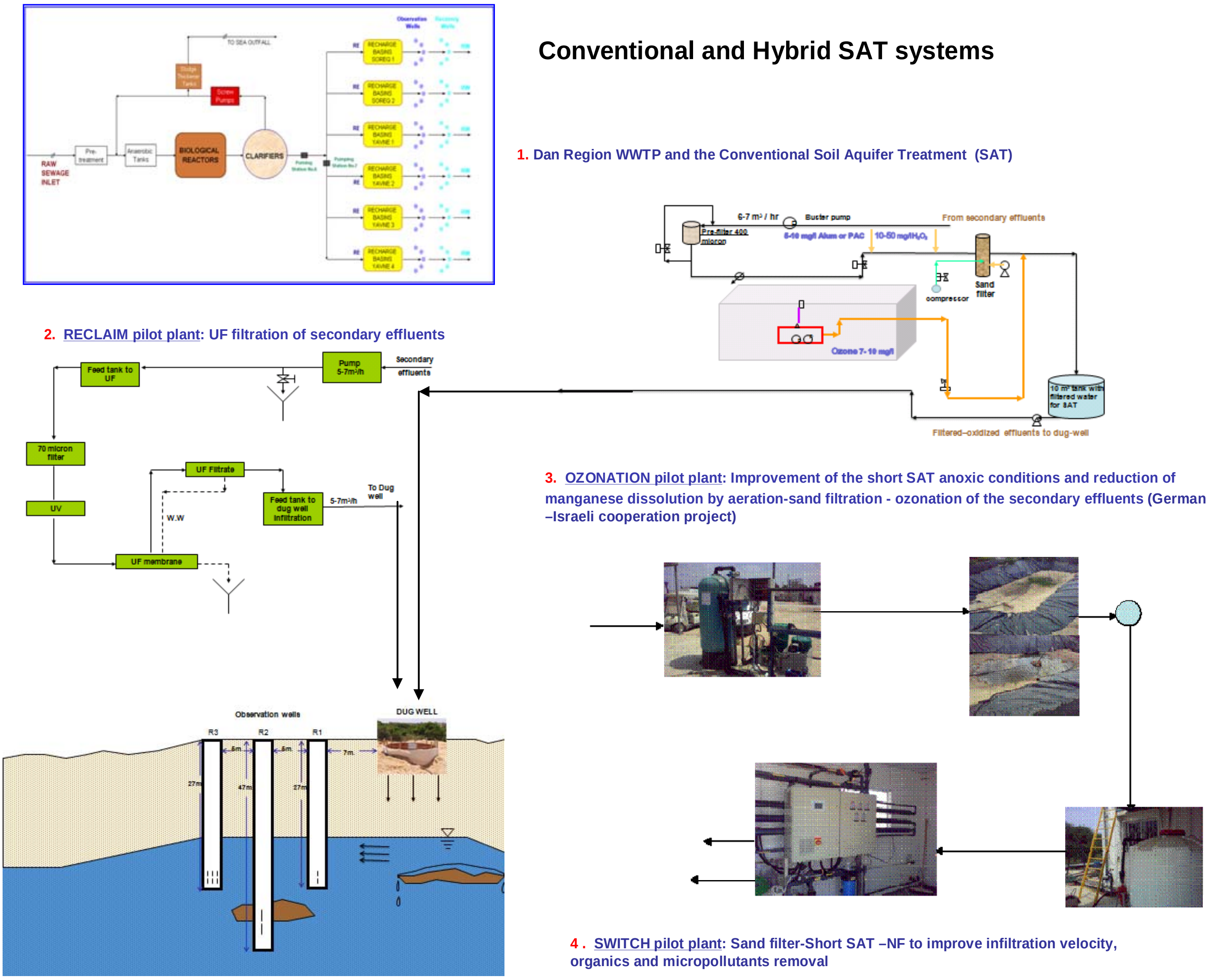

Figure 2 - The Conventional SAT system in the Dan Region Project and the hybrid SAT systems studied in different pilot projects (Aharoni & Cikurel, 2011)

These preliminary treated secondary effluents are infiltered by Dug-well infiltration technique (as intermittent or continuous infiltration) at high velocities and the water is pumped out after a relatively shorter than conventional retention time in the aquifer (one to two months instead of 6-12 months). Very good microbial quality, low DOC, low nutrients and low micropollutants containing water is obtained by this SAT system using a much less infiltration area and relatively lower retention times in the aquifer due to the pre or post treatments that are used (Aharoni et. al., 2007).

For both SAT and well - recharge artificial recharge processes, experience has shown that within the limitations of the conventional toxicological testing (the effect of micropollutants are being investigated lately), the recovered water does not pose greater health risks than currently acceptable potable water supplies (Bouwer, 1999).

SAT has been applied for further treatment and reuse of primary, secondary and tertiary effluents from wastewater treatment plants (Wilson et al., 1995; Nema et al., 2001; Fox et al., 2001; Crites et al., 2006; Sharma et. al, 2010).

Other hybrid treatments that were also experimented at pilot stage are:

a. SAT pre-treatment and NF polishing (Fernando et. al, 2009)
b. Effect of SAT pretreatment of effluents on performance of MF/UF/NF (Sharma et. al,2009)

After the Primary effluents (PE) or Secondary effluents (SE) are treated in passage through the vadose zone and reach the groundwater, they usually flow some distance through the aquifer before they are collected (Figure 3). This additional movement through the aquifer can produce further purification (removal of microorganisms, precipitation of phosphates, adsorption of synthetic organics, etc.) of the sewage. SAT is essentially a low-technology, advanced wastewater treatment system. It also has an aesthetic advantage over conventionally treated sewage in that water recovered from a SAT system is not only clear and odour-free but it comes from a well, drain, or via natural drainage to a stream or low area, rather than from a sewer or sewage treatment plant. Thus, the water has lost its connotation of sewage and the public see it water more as coming out of the ground (groundwater) than as sewage effluent.

SAT systems are **natural, inexpensive**, **simple to operate**, **reliable** systems and also allows **seasonal storage of the water to be store in periods of low demand** and used in periods of high demand. SAT has an excellent capacity for removing from the effluent a wide range of contaminants by a variety of processes. The soil-aquifer system should be viewed as a huge reactor where both **biological and physico-chemical processes** occur. The biological and physico-chemical processes perform in conjunction with one another. Consequently, the purification capacity is not affected with time. With proper operation and maintenance

and adequate monitoring, the SAT system should be considered as attractive and reliable method for effluent reclamation and reuse in areas where suitable conditions exist for groundwater recharge via spreading basins (Idelovitch et. al, 2003)**.**

2. TYPES OF SAT AND INFILTRATION RATES

2.1 SAT for water reclamation and reuse

Soil aquifer treatment (SAT) provides wastewater purification during flow through unsaturated soils (Fig. 3) and the aquifer and the purified water is recovered by means of recovery wells.

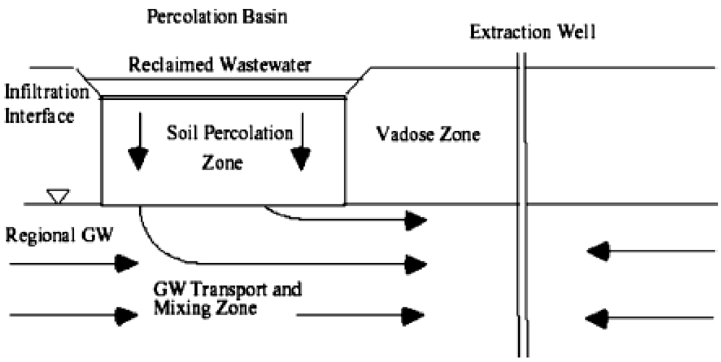

Figure 3 - Schematic of Soil Aquifer Treatment System (Amy & Drewes, 2006)

Due to this slow sand biofilter treatment, the upper layers (1-2 m.) of the vadose zone can be an effective and low energy step in the SAT technology to obtain water for reuse.

The bacteria and viruses are inactivated as a function of retention time and temperature in the soil. Bacteria and parasites are removed by filtration along with other mechanisms. Viruses can possibly survive six months at low temperatures. One of the reasons for relatively long SAT for secondary effluents treatment is that at least the effluents have to stay 6 months in the aquifer to completely remove the viruses (Fox, 2010). If proper pretreatment is applied (disinfection or membranal treatment) shorter SAT can still be suitable.
The DOC conversion depends on the effluent organic matter characterization (EfOM). If the humic acids are high in concentration (mostly in Europe) the DOC can be removed up to 50% depending on the travel time (retention in the soil), but in desert areas (example, Israel) where the effluents do not contain much humic acids the removal can be up to 80 - 85% for a travel time of around 30 days.

Since the main activity is in the first few meters of soil after infiltration in a surface spreading basin oxygen is quickly depleted and the Redox conditions become anoxic. The wet/dry cycles help improve the redox situation. During the **wetting** the oxygen is depleted since it is consumed by organics. During the **drying**

oxygen enters soil as wetted front moves to groundwater. During this period the ammonia consumes oxygen and nitrate is produced. This also means that the infiltered water organic matter and ammonia content effects strongly the Redox and will need adaptation of wetting/drying cycles to introduce more oxygen.

According to Fox (2010) secondary effluents without nitrification contain BOD<20 mg/L but Nitrogenous BOD >80 mg/L. On the other hand nitrified effluents also contain BOD < 20 mg/L but nitrogenous BOD around 5 mg/L and nitrified/denitrified effluents contain BOD<10 mg/L and nitrogenous BOD around 2-3 mg/L. So that pretreatment can strongly affect the Redox conditions. Although a change in wetting/drying cycle to help compensate for the lost oxygen is possible this is more theoretical. Since, depending on the clogging rate on one hand and the increase in the quantity of effluent to be treated by SAT (due to population increase) the wetting/drying cycle can only be shortened and not extended. This causes anoxic conditions further causing Mn dissolution (Cikurel & Aharoni, 2011). This is the reason that oxygen supply from outside source has to be brought (besides the wetting/drying cycles). This can be done by applying different oxidation methods (air pumping or hydrogen peroxide – ozone introduction to effluents) and pretreatment to reduce DOC and nitrogen concentrations.

The main problem with aquifer and vadose zone wells is clogging mainly by organic matter around the well, especially for vadose zone wells, which can not be pumped or rehabilitated after clogging (some times even chemical and mechanical treatment is not enough). On the other hand surface spreading SAT systems have the surface clogging problems. Organic matter from the recharged effluents readily alters the original hydraulic properties of the upper layers of the basin due to hydrophobicity that develops (Arye et al., 2010). That may be improved by changing the wetting – drying cycles (Nadav et al, 2010) or can be taken care of by mechanical treatments (Paricio & Carrera, 1998).

For both SAT and well recharge artificial recharge processes, experience has shown that within the limitations of the toxicological testing (as known today), the recovered water does not pose greater health risks than currently acceptable potable water supplies.

According to Bouwer (1996)**,** with surface infiltration systems considerable quality improvements can be obtained as the water flows through unsaturated zone to the aquifer, in particular with soil aquifer treatment (SAT) less pretreatment of the infiltered water is needed due to the bioprocesses that occur including particulate matter, microorganism organic matter and nutrient removal.

Examples of existing SAT systems from USA and Israel are presented in Chapter 11.

2.2 Types of SAT

SAT can be achieved in three different ways (Fig. 4):

(i) Infiltration basins

(ii) Vadose zone wells

(iii) Direct injection well.

Infiltration by surface spreading in basins can be operated only in sandy soils and should not contain too many clay layers or other soils that could restrict the downward movement of water.

Vadose zone wells are used where the surface infiltration is hard due to hydro-geological properties of the soil and where available land is expensive.

Direct recharge to the aquifer through wells is done where permeable surface soils are not available, vadose zones have restricting layers, and/or aquifers are confined.

In case of unfavorable local hydrological conditions when permeable top soil surfaces are not available, vadose zone wells can be used, and in case vadose zones have restricting layers and/or aquifers are confined, then, direct injection wells can be used (Bouwer, 1996).

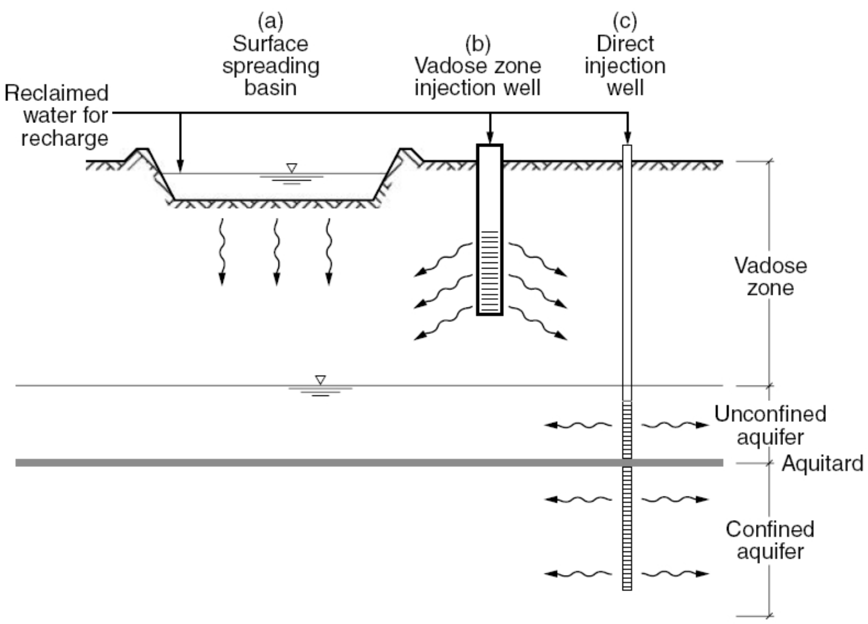

Figure 4 – SAT types: Surface spreading, Vadose zone well, Direct injection well (USEPA, 2004)

(i) Surface spreading basins (Infiltration basins):

This infiltration method is suitable for runoff water as well as for treated effluents that will be reused for indirect potable reuse purposes or agricultural irrigation depending on the degree of purification of the effluents before infiltration.

Where the top soil and aquifer conditions are favorable for artificial recharge of groundwater through infiltration basins, a high degree of upgrading can be achieved by allowing partially-treated sewage effluent to infiltrate into the soil and move down to the groundwater. The unsaturated or "vadose" zone then acts as a natural filter and can remove essentially all suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms. Significant reductions in nitrogen, phosphorus, and heavy metals concentrations can also be achieved (Bouwer and Rice, 1984).

Various types of surface spreading SAT system are shown in Figure 5, the simplest and the oldest is the bank filtration where the sewage effluent is applied to infiltration basins on sandstone ridges where it moves downwards to the shallow aquifer and flows to a lower depression (Figure 5 A) that can be a natural depression or seepage area, a stream or lake, or a surface drain. SAT systems as in Figure 5 A also serves to reduce the pollution of surface waters. Instead of discharging wastewater directly into streams or lakes, it is applied to infiltration basins at a higher elevation so that it receives soil-aquifer treatment before entering the stream or lake.

The system shown in Figure 5 B is similar to that shown in Fig. 5 A, but the wastewater treatment plant (WWTP) effluent, after SAT, is collected by underground, agricultural-type drains. Systems like the ones in Figs. 5 A and 5 B have the advantage that the entire SAT process is accomplished without pumping.

The method in Figure 5C shows two parallel strips of dug wells, and on the line midway between the two strips, a series of recovery wells that create an hydraulic depression which forces the infiltered treated water to flow from the dug wells to the, recovery well. The system of Figure 5 C can be designed and managed so that the wells pump mainly reclaimed water without any native groundwater from the aquifer outside the SAT system.

In Figure 5 D, the infiltration basins are located close together in a cluster and the wells are on a circle around this cluster. Systems as in Figure 5 D are more likely to deliver some mixture of reclaimed water and native groundwater at the outer reclamation wells on the border of the confined reclaimed water aquifer (Shafdan, Israel). In systems like in Figure 5D some reclaimed water might leak to the surrounding aquifers. For this reason the recovery system area is confined by peripherical reclamation wells ((Shafdan, Israel)

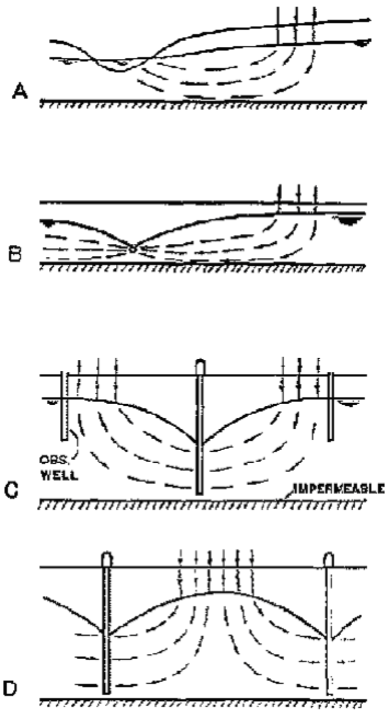

Figure 5: Schematic of soil-aquifer treatment systems (Bouwer 1987)

Systems 5 C and 5 D can be used both for seasonal underground storage of sewage water, allowing the groundwater mound to rise during periods of low irrigation water demand (winter), and for pumping the groundwater mound down in periods of high irrigation water demands (summer) (Bouwer, 1987). The type of SAT system shown in Figure 5 C would be suitable for small systems where there are only a few basins around a centrally located well (Figure 6).

In case of surface spreading, the vadose zone should not contain too many clay layers or other soils that could restrict the downward movement of water and form perched groundwater mounds. Aquifers should be deep and have high enough permeability to prevent mounding (rise of the groundwater level). This is the case in the SAT system in Shafdan, Israel. Otherwise other infiltration methods like Vadose Zone wells or direct injection wells can be used.

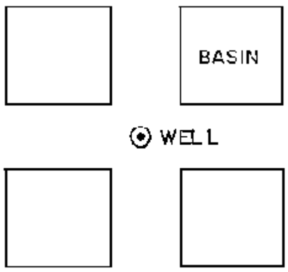

Figure 6 - Schematic of four small infiltration basins with well in centre for pumping renovated sewage water from aquifer (Bouwer, 1987)

(ii) Vadose zone wells:

Recently, interest is rising for use of larger diameter dry wells or vadose zone wells for recharge of unconfined aquifers. The main problem with aquifer and vadose zone wells is clogging around the well. This is particularly a problem for vadose zone wells, which can not be pumped, and hardly rehabilitated by using mechanical and chemical methods after clogging. This method too is suitable for indirect potable reuse method.

In cases that the available land for infiltration is scares or is near inhabited areas and is expensive, it is advantageous to pretreat the effluents to a high purity degree (by micron filters or MF or UF systems) and to infiltrate the water in the vadose zone if the zone is relatively deep (15-30 m.). As it was explained in 2.1 the main removal of organic matter, N and P occurs in a 1-2 m. biofilter zone in the soil. So that if the very good quality **effluents are well aerated before infiltration** and infiltered in the vadose zone, there is still enough biological activity to reduce the organic load and not to cause anoxic conditions. Case studies for such vadose zone wells (Water World, 2011) are given in Chapter 11.2.

Vadose- zone are boreholes in the vadose zone, usually 10-50 m. deep depending of the depth of the vadose zone and about 1 -2 m. in diameter (see Fig. 7).

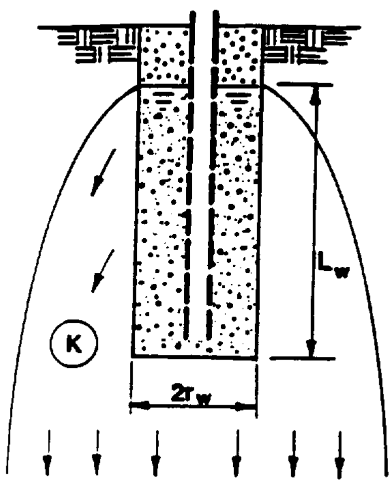

Figure 7 - Vadose Zone Recharge Well with sand or gravel fills and perforated supply pipe, (Bouwer, 1996)

These wells are commonly used for storm run-off disposal in areas of relatively low rainfall that have no storm sewers or combined sewers (Bouwer, 1996). These wells are similar to groundwater recharge wells. To prevent clogging, very good pretreatment of the effluents (for example UF filtration or flocculation – sand filtration followed by advanced oxidation) must be performed.

(iii) Direct injection wells:

Direct injection wells are used when injecting recycled or reclaimed water directly into deep aquifer. If the water will later be used for drinking, the recycled water will receive advanced treatment prior to injection. The direct injection can be for potable reuse or non-potable reuse. In case of Soil- Aquifer-Treatment this is mostly for non-potable purposes but the quality can reach potable quality.

The direct injection is mostly applied in drought regions where the geological and hydrological conditions do not enable either surface spreading or vadose zone wells (no porous or semi-porous soil, shallow vadose zone). In **direct potable reuse**, the liquid waste or sewage of a wastewater treatment plant is sent directly into the intake of a drinking-water treatment and distribution plant. Although this process involves the most technologically advanced water treatment processes (UF-RO-AOP), and the water that enters the distribution system must meet drinking-water standards, it is the one most argued against by community citizen groups, calling it "toilet-to-tap". It is presently used only in water-critical situations, such as those that frequently occur in drought areas.

Indirect potable reuse is the addition to a water supply of reclaimed water derived from pretreated municipal wastewater. This often is done through the medium of an existing stream or river or by injecting directly to the aquifer and, as a result, the highly treated wastewater generally is diluted significantly. Many communities use this method inadvertently because their drinking-water intake lies downstream of the collective discharges of other municipalities' wastewater plants. Indirect potable reuse also is called **non-potable reuse** because the technologies used for each are the same. Direct potable reuse may involve the most advance technologies (membranal filtration and AOP) and usually uses an additional set of water pipes (alongside drinking-water pipes) that carry treated wastewater back to large irrigation sources, such as city gardens, golf courses, and industrial or municipal parks (Asano, 2007)

2.3 Infiltration rates in SAT

The performance of SAT systems is affected by different parameters described in Chapter 4, but the influence of the infiltration rates to the final water quality is separately described here since it determines a major parameter: The retention time in the biofilter (which is located in the upper layers of the vadose zone) that has a major influence to the final water quality. Besides, the amounts of water that can be recharged in a given basin by surface spreading depend mainly on the geological profile (absence of impermeable layers in the unsaturated zone) and the rate of infiltration.

For a given vadose zone depth and wastewater quality, lower infiltration rates enable more retention time for bio-treatment but also, the high rate application of different grades of treated wastewater enable to have longer rest periods (one day flooding, 2-4 days rest) allowing more oxygen to penetrate the vadose zone and

help enhance the biological activity removing more biodegradable organic matter and also reduce the anaerobic conditions in the aquifer and prevent manganese dissolution.

Studies show that during surface spreading infiltration, the relatively high concentrations of biopolymers in the secondary effluents can be effectively removed by biofiltration in the upper soil layers (Sperlich et al., 2008). However, large filtration areas are required since natural bio-filtration processes like slow sand filters and also some SAT systems are normally operated at low filtration rates (<0.05 m/h or <1.2 m/d). To reduce area requirement the systems can be operated at higher filtration rates (0.1-0.5 m/hr or 2.4 -12 m/d). The pilot study performed during the EU SWITCH project[1] showed (Cikurel et al., 2010) that at 4-6 m/d infiltration rates still the upper layers' biofiltration could remove the biopolymers effectively. But, much higher rates similar to rapid sand filters (rate>5 m/h) do not remove DOC or biopolymers due to the short retention times (Zheng et. al, 2009)

.

Different qualities of wastewater (primary settled wastewater, secondary effluents, tertiary treated wastewater or UF-RO treated secondary effluents) can be infiltered at different velocities depending also of the SAT types. From different SAT types in the USA and Israel it can be seen that for surface infiltration the infiltration rates are 1-3 m/d, for vadose zone infiltration, due to well-treated water it can go up to 10-12 m/d and for direct injection wells, depending on the soil characteristics, it can be even higher.
Other factors that influence infiltration rates and soil aquifer treatment are (Fernando, 2009):

a. Soil type and permeability

b. Surface clogging material (the type of wastewater effluents applied)

c. Pond depth

d. Duration of wetting/drying cycles

a) <u>Soil type</u>

The soil type can affect the infiltration rate. Since the hydraulic conductivity or permeability can be different and even for the same type of wastewater applied to different soils different infiltration rates will be obtained. The biological activity will be affected and different DOC removals can be obtained. Results from Quanrud et al. (1996) indicate that significant differences in removal efficiencies were obtained during through-column removal of non-purgable dissolved organic carbon (NPDOC) for columns containing sandy loam (56%), sand (48%) and silty sand (44%). No significant differences in the removal of UV- absorbing organics were observed in the same experiment for columns containing sand (22%) and sandy loam (20%).

El-Hattab et al. (2007) evaluated SAT for the removal capacity of zinc, iron as heavy metals and magnesium and sodium. They evaluated the different soil types' capacities for removal of these wastewater constituents assessing optimum soil matrix for good removal of these constituents. The results concluded that sandy loam

soil was better than clayey soils for Magnesium and Sodium removal through SAT and sandy soil was not recommended for effective removal of Magnesium and Sodium. Sandy soil was better than clayey soil for Zinc and Iron removal through SAT system, and sandy loam was not recommended for Zinc and Iron removal.

b) Surface clogging material

The hydraulics of wastewater infiltration basins are affected by the formation of a low conductivity clogging layer on and within the upper few millimeters of the surface soils (Bouwer, 1996b) as cited by (Houston et al., 1999). Surface clogging phenomenon is also present even in freshwater recharge basins. This clogging layer impedes wastewater infiltration (Quanrud et al., 1996). As particulate material (depending on the particulate matter content of the effluents to be infiltered) accumulates on the bottom of the basin to form the clogging layer it exists in a loose, compressible state. An increase in water column translates to compression of this loose material because of the action of the seepage forces exerted by the infiltrating water, eventually resulting in the reduction of hydraulic conductivity of the clogging layer and the infiltration rate (Houston et al., 1999). As mentioned in Chapter 2.1 Organic Matter (OM) from the recharged effluents readily alters the original hydraulic properties of the upper layers of the basin due to hydrophobicity that develops (Arye et al., 2010). In this study, the role of treated wastewater (TWW) in inducing soil water repellency was checked in a sandy infiltration basin of SAT, in the Dan Region Reclamation Project (Shafdan), Israel. Based on measured parameters (like water drop penetration time and molarity of ethanol droplet) and calculated hydrophobicity indexes, the authors deduced that the development of hydrophobicity is more likely to occur in the upper soil layers where most of the particulate OM accumulated and the soil is more readily exposed to drying processes during the Wetting/Drying Cycles.

c) Pond depth

Increased pond depth increases the hydraulic gradient across the clogging layer, which tends to increase the infiltration rate if all other factors are the same. This effect competes with that of the surface-clogging effect. The net effect depends on the relative importance of the two phenomena and increasing the pond depth may either raise or lower the infiltration rate, or maintain the same rate if the effects compensate each other (Houston et al., 1999).

d) Wetting/drying cycles

During soil aquifer treatment, cyclic flooding/drying of the basins is necessary for improvement of infiltration rates and to control aerobic/anoxic conditions in the soil (Kopchynski et al., 1996). Recharge basins function under wet and dry cycles, alternately. A clogging layer called schmutzdecke develops at the soil surface during flooding due to the combined effects of algal growth, suspended solids deposition, and bacterial growth in soil pore spaces and slows down the infiltration rate. However, infiltration rates are

restored during the drying cycles by allowing the soil surface to dry and develop cracks (Quanrud et al., 1996). Wet-dry cycle operations consist of filling the pond to a certain depth, stopping the inflow (loading) and allowing the water to infiltrate into the ground. After all the water has infiltrated into the soil, the pond is left to dry for a period so that natural aeration can take place. During the drying period, water percolates and the infiltration potential for the next application period increases. When clogging occurs, the recharge basin can be cleaned and possibly restored to their original capacity by draining, drying and scraping. Another method of wet-dry cycle operation is to maintain a full pond, i.e., the influent water is maintained at a rate equal to the recharge rate. When the recharge rate reaches an unacceptable value, the operation is stopped so that the clogging layer can be removed (Li et al., 2000).

Continuing their research on the hydrophobicity of upper layers of infiltration basins in the Shafdan SAT system (Arye et al., 2010) found that the consequences of the initial condition with the hydrophobic top soil layer during the subsequent recharge may result in inhomogeneous Treated Wastewater (TWW) distribution during the initial phase of the flooding of the basins and due to the initial retardation in TWW infiltration. This issue is currently under investigation (Nadav et al., 2010) and methods to enhance the infiltration rate are being examined in conjunction with the development of the hydrophobic soil layer and the different wetting/drying cycles.

3. ADVANTAGES AND LIMITATIONS OF SAT

3.1 Advantages of SAT

The advantages of groundwater recharge by surface spreading can be (Harun et. al, 2007):

1. Microbiological: Total removal of bacteria and viruses.
2. Nutrient removal: Very high removal of Ammonia, P, C
3. Very efficient removal of DOC
4. Efficient removal of most of the micro-pollutants

Besides these, other advantages can be mentioned:

(a) Groundwater recharge using the aquifer as a storage in the vicinity of metropolitan and agricultural areas where groundwater is in over-exploited condition..

(b) Surface spreading provides added benefits of the treatment effect of soils and transporting facilities of aquifers (Asano and Cotruvo, 2004).

(c) Very efficient removal of organics, nutrients, microorganisms and good micropollutants removal are obtained by a completely **natural** system.

3.2 Limitations of SAT

1. After 30 years of infiltration in Shafdan -Israel there are indications of deterioration in the infiltration rate (less than 1 m/d), with no ability to recharge all the available effluents.
2. Due to anoxic conditions, signs of manganese dissolution appear in the aquifer below the infiltration basins.

Other disadvantages include:

(a) Big land requirement

(b) Clogging on the infiltration interface caused by biological and physical processes.

(c) Chemical process caused by algae photosynthesis change the pH in soil leading to precipitation of carbonate, gypsum, phosphorus and other chemicals in the soil cause clogging below the infiltration area.

4. FACTORS AFFECTING PERFORMANCE OF SAT SYSTEM

Table 1 summarizes the conditions for different parameters for the three stages of SAT (Infiltration interface, Soil percolation and groundwater transport) that effects the performance of the overall SAT process.

The parameters are:

1. (Residence) Time and travel distance
2. Wastewater quality
3. Redox conditions (oxidation-reduction)
4. Maintaining infiltration (hydraulic loading)

Other parameters that affect the performance are: pH, temperature, soil type and operating schedule.

Table 1 Comparison of Typical SAT Zones (Amy, 2009)

PROCESS/ PARAMETER	INFILTRATION INTERFACE	SOIL-PERCOLATION	GROUNDWATER TRANSPORT
Treatment Mechanisms	Filtration ✓, Biodegradation	Biodegradation ✓, Adsorption	Biodegradation, Adsorption, Dilution ✓
Transport	Saturated	Unsaturated	Saturated
Residence Time	Minutes	Hours to Days	Months to Years
Travel Distance	Centimeters / Inches	3 – 30 m / 10 – 100 ft	Variable
Mixing	No	No	Yes (regional G.W.)
Oxygen (O_2) Supply	Recharge Water	Unsaturated Zone	Regional G.W.
Biodegradable Org. Carbon Availability	Excess	Excess/Limiting	Limiting
Redox Conditions	Aerobic	Aerobic to Anoxic	Anoxic to Aerobic

According to Sharma et al. (2008) the main parameter that affects SAT performance (mainly for DOC and micropollutants, heavy metals, phosphate removal) is the residence time/ travel distance.

Sharma et al. (2008), using literature sources, performed a correlation analysis to determine how different parameters influence the contaminants removal. . They also calculated the removals of DOC at different residence times and travel distances during SAT of primary, secondary and tertiary effluents using statistical techniques. The residence times/travel distances are more related to horizontal residence time in the aquifer and the distance of the recovery well from the infiltration point than the infiltration rates and the residence time/travel distances in the vadose zone, since the higher residence time is due to the lower horizontal travel velocities in the aquifer and not during the vertical travel in the vadose zone. The data available from literature sources were grouped in bins in order to designate the travel distance and residence/travel time ranges to be used in guideline development**.**

A typical correlation analysis matrix of main process parameters for DOC removal from secondary effluent is presented in Table 2. Correlation analysis showed that for all the water quality parameters (DOC, nitrogen species, trace organics and microbes), among others **residence/travel time** in the soil layer was **the main parameter governing the effluent quality from SAT for all primary, secondary and tertiary effluents**. It is evident that longer travel times will allow breakdown of slowly biodegradable organics (Idelovitch and Michail, 1984)

Other important factors that affect the removal efficiency of Effluent Organic Matter (EfOM) during Soil Aquifer Treatment are (Saroj et al., 2007, Harun, 2007):

a. Wastewater Quality (primary or secondary effluents to be infiltered)
b. Process Parameters (hydraulic loading rate and Redox conditions in the soil, the pumping rate at extraction well and the distance of the extraction well from the infiltration basin).

Also the depth of the vadose zone influences the DOC removal.

Table 2 Correlation analysis of DOC removal during SAT of secondary effluents (Number of data = 58) (Sharma et al., 2008)

	Influent DOC (mg/L)	Effluent DOC (mg/L)	Infiltration rate (m/day)	Travel distance (m)	Travel time (day)	DOC removal efficiency (%)
Influent DOC (mg/L)	1					
Effluent DOC (mg/L)	0.03	1				
Infiltration rate (m/day)	-0.23	0.43	1			
Travel distance (m)	0.30	-0.60	-0.15	1		
Travel time (day)	0.31	-0.62	-0.21	1.00	1	
DOC removal efficiency (%)	0.58	-0.75	-0.54	0.65	0.67	1

Some conclusions from Harun's (2007) study are:

1. The removal of contaminants during SAT is case specific and may not be presented using one kinetic model.

2. A higher removal of about 50% and 80% for DOC and ammonia respectively during field SAT of secondary and tertiary effluents takes place in the top 1.5 m of soil which is mostly under predominant **oxic** condition.
3. Biodegradation is the main mechanism for removal of DOC which makes its removal sustainable.
4. Generally, the removal of contaminants increases with **residence/travel time and travel distance**. **Travel time** has more influence on DOC removal than **travel distance**.
5. Typical influent DOC for primary, secondary and tertiary SAT was 24-35 mg/L, 10-15 mg/L, 5-12 mg/L respectively. Typical effluent DOC for primary, secondary and tertiary SAT was 14-18 mg/L, 2-8 mg/L, 2-10mg/L. respectively.
6. DOC removal efficiencies during SAT of secondary and tertiary effluents at a travel distance of 5.0 m are comparable as 15-73% and 19-72% for secondary and tertiary effluents respectively. DOC concentration of SAT product water was <2 mg/L for long term SAT of both secondary and tertiary effluent which is below the average DOC found in drinking water supply which is 2.2 mg/L in field sites, therefore tertiary treatment prior to SAT may not be needed.
7. Hardly biodegradable micropollutants like Primidone and Carbamazepine were persistent during SAT of secondary effluent but were removed during SAT of tertiary effluent which suggests that contaminants persistent to one SAT system are not likely to be persistent to another.
8. Phosphorus removal during SAT is not sustainable since its removal mechanism is mainly adsorption and breakthrough condition is most likely when the soil adsorption capacity is exceeded.
9. There is no need to reduce nutrient load from wastewater where water is used for unrestricted irrigation. Where direct portable reuse is needed, nutrient should be significantly reduced. Therefore design of SAT system depends on intended reuse of SAT effluent.
10. Sandy loam soil is most likely to be the best soil for SAT systems since it has demonstrated better DOC removal efficiency as compared to other soil types.
11. Generally average bacteria removal was >4 log at travel distance <10 m and virus removal was >2 log at travel distance <10 m.
12. Some SAT systems removed microbes below detection. This implies that disinfection of effluent prior to SAT is not needed.

As mentioned before special attention is given to residence time/travel distance relationship.

1. Residence time /travel distance:

As mentioned in Chapter 2.3 the **residence time/travel distance** in the soil layer (which is a function of travel distance and infiltration rate) was found to be the main parameter governing the effluent quality from SAT for all primary, secondary and tertiary effluents (Sharma et al., 2008). This factor is specially discussed below.

Since the biodegradable matter is easily removed at the upper layer of soil infiltration the less biodegradable DOC, excess phosphates, heavy metals and micropollutants degradation/adsorption is much dependent on travel time first in the vadose zone that the depth of the zone affects DOC (Cha et al., 2005) and then the aquifer residence time/travel distance. Also for complete microorganisms removal including viruses a minimum of one-two moths travel time is necessary for Conventional Activated Sludge treated secondary effluents or tertiary treated effluents (otherwise the minimum retention time in the soil is 3 months).

As will be explained in Chapters 8 and 9, proper pretreatment of secondary effluents by membrane treatment (MF/UF/NF), or even good tertiary treatment by flocculation-sand filtration (either with or without disinfection), or Advanced Oxidation Processes (AOP) on tertiary treated effluents (ozonation-hydrogen peroxide) residence time of up to one month can be enough to produce a low DOC (1-2 mg/l DOC), microorganisms free and relatively low micropollutants containing water.

In case of AOP use for tertiary treated effluents before infiltration (Maman, 2010) the water obtained after one month retention time is expected to contain less than 100 ng/l of antibiotics, or Carbamazepine, or Diclophenac. This project is still on-going.

2. Wastewater quality:

According to Harun (2007) one of the findings from their literature review is that the average DOC concentration of SAT product water in field sites was <2 mg/l for both long term SAT of secondary and tertiary effluents (this is below the average DOC found in drinking water supply which is 2.2 mg/l). So it was stated that tertiary treatment prior to SAT may not be needed if only water quality improvement is at stake. The typical influent DOC for secondary and tertiary SAT was 10-15 mg/l and 5-12 mg/l respectively and after SAT it was 2-8 mg/l and 2-10 mg/l respectively. The higher DOC removal occurs in Mediterranean countries (Israel as an example) where the soil is sand or sand-loamy soil and there are less humic acids content in the wastewater. In Dan Region WWTP, Israel, in case of UF pre-filtered secondary effluents as compared to secondary effluents with no treatment, the DOC removal after 5 m. distance (or 10 days retention time) was for both secondary effluents almost similar. This is probably due to the bioactivity in the upper layers of the SAT and the absence of high concentrations of non-biodegradable DOC.

Sharma et al.(2007) investigated the effect of water quality and process parameters on the removal of wastewater EfOM)during SAT by conducting soil column and batch tests at laboratory-scale using primary and secondary effluents from a wastewater treatment plant at different hydraulic loading rates (HLR) and redox conditions.. They concluded that:

- Average primary effluent DOC was reduced from 35 mg/L to 15 mg/L and 18 mg/L at HLR of 1.25 m/day and 2.5 m/day, respectively.

- There was only slight change in DOC removal for secondary effluent (from 10.3 mg/L to 11.6 mg/L) when HLR was increased from 1.25 m/day to 2.5 m/day.
- Oxygen concentration decreased from 8 mg/L to less than 2.5 mg/L in the **top 1 m** implying that most of the bioactivity, especially the biodegradation process, takes place in this upper part of the soil column.
- It was found that both nitrification and denitrification can be achieved during SAT when proper process conditions are provided.
- Batch studies showed that for the given primary effluent, aerobic DOC removal was about 10% higher than anoxic DOC removal.
- DOC removal behavior followed first order kinetics and a three-term model fitted to measured data showed that primary effluent has a higher BDOC.

When adequate depth (travel time) and appropriate process conditions are provided, SAT is equally effective in treatment of primary effluent from wastewater treatment plants as in the case of treatment of secondary effluent. The implication is that, rather than just being a secondary effluent polishing step, SAT may also provide the equivalent of secondary biological treatment.

3. Redox conditions:

In the first infiltration stage and passage through the soil interface to the upper layer biofilter, there is enough oxygen but also biodegradable organic carbon. The residence time/travel distance in this layer is short. In the vadose zone the oxygen is depleted the residence time/travel distance is longer (hours to days/3-30 m.) and most of the organic matter is biodegraded. The third groundwater transport stage depends of the recovery well distance from the infiltration point. The transport is horizontal while the two other stages are vertical. The mixing ratio with the regional groundwater determines the chemistry and the redox conditions.
In this third stage the oxic/anoxic conditions may determine the types of micropollutants that will be removed.

As an example of how redox conditions affect SAT performance the Dan region SAT system can be sited.
After more than 30 years of infiltration and due to diminishing infiltration rates (due to bio-fouling) there is less relaxation time that introduces oxygen to the vadose zone and helps the oxic conditions in the ground. Due to the lack of oxygen anoxic conditions developed in the groundwater when in the presence of excess organic matter and lack of oxygen the nitrate is consumed (Oren et. al., 2007). This new redox conditions caused the manganese precipitation problem causing clogging of the irrigation systems.
As mentioned before oxic/anoxic conditions affect DOC and micropollutants removal efficiency.

4. **<u>Hydraulic loading rate (HLR)</u>**:

This also was discussed in previous chapters related to infiltration rate. If the hydraulic loading rate is high more effluents are infiltered at a given time leaving more relaxation time and more oxygen introduction to the soil. On the other hand more organic matter is infiltered at a given time may be impairing the bio-activity at the upper layers. Still the longer relaxation time enabling the oxygen introduction is a dominant mechanism.

5. SITE SELECTION FOR SAT

According to Harun (2007), site selection for SAT system involves investigation of:

a. Depths to groundwater.
b. Redox conditions.
c. Soil characteristics
d. Groundwater flow pattern (Fox et al., 2001).

Proximity to conveyance channel and/or wastewater reclamation facilities is also a practical factor to be considered when selecting a site for SAT (NCSWS, 2001).

However, to design a system for artificial recharge infiltration rates of the soil must be determined and the unsaturated zone between the land surface and the aquifer must be checked for adequate permeability and absence of polluted areas (Bouwer, 2002). The best surface soils for SAT systems are in the fine sand, loamy sand, and sandy loam range. Materials deeper in the vadose zone should be granular and preferably coarser than the surface soils (Pescod, 1992). The land requirement depends on the quantity of reclaimed wastewater to be treated, type of soil and method of groundwater artificial recharge. Recharge via shallow basins requires more land than recharge via direct injection to groundwater aquifers. Permeable soils with high infiltration rates minimize land requirements (Bouwer, 2002). A typical example is given below for how the experimental site for UF-SAT pilot for the EU - Reclaim project[1] was selected (Cikurel & Aharoni, 2011).

The Shafdan main facilities (including the UF plant) are located in one of the coastal aquifer depressions. At this depression there is a thick clay layer overlaid by a sandstone layer. The depression is bordered by two elongated sandstone ridges. This clay layer separates the regional aquifer (located below the clay layer) and a perch aquifer located above the clay layer, in the upper sandstone layers.

From the **geological point of view**, **the favorite site should be located outside of this depression**, at a place where the clay layer is absent (zero thickness). At this point, there is a continuous sand sequence from the surface up to the water table.

For the UF-SAT pilot experiment, after preparing the structural and the isopach maps of the clay layer, four proposed places for the test site were chosen. At those places auger wells were drilled near the border of the depression up to the regional water table (depth of the wells were between 16-20 m) in order to learn about the lithological sequence (Figure 8). The samples were taken every 2 m or when the lithology had been changed. The wells penetrated about 2-4 m below the groundwater. According to the drilling results the initial map was updated.

The result of the drilling indicated, that in three places the clay layer is missing and there is a continuous sequence of sand from the surface up to the regional water table which was found at a depth varying between 12.5-18.4 m. (Figure 8). The selected site is located on the western edge of the eastern calcareous sandstone ridge and about 250 m east to the UF plant (Figure 9).

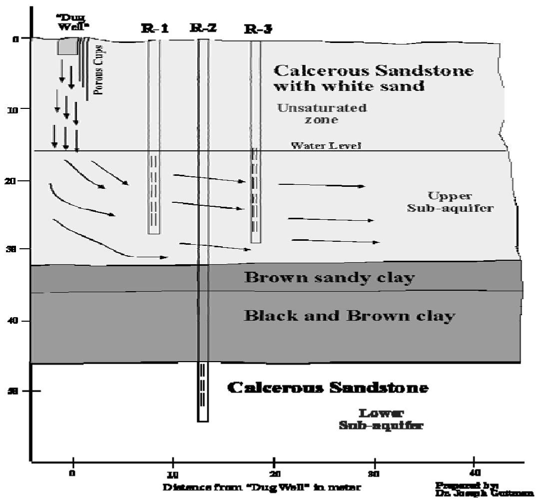

Figure 8 - The results of the 4 bore holes. R-2 is the area where the Dug well was located (Guttman, 2007)

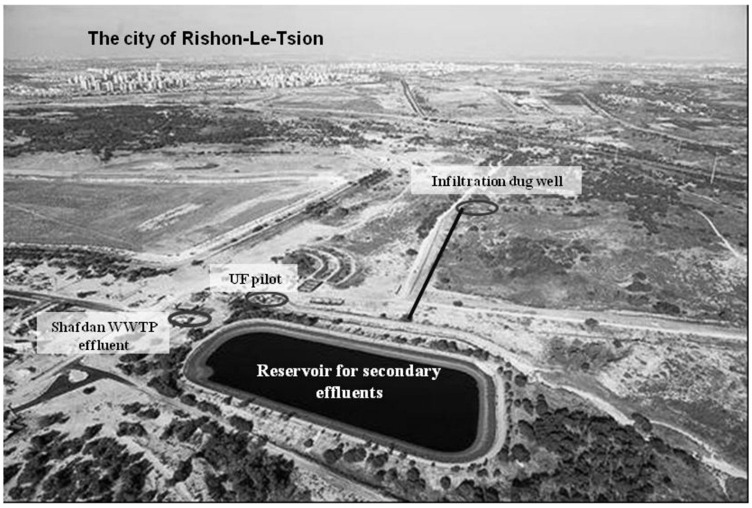

Figure 9 - Location of the EU Reclaim pilot and infiltration site (Cikurel & Aharoni, 2009)

Site R2, which is close (400 – 500 m) to the pilot UF pilot plant, showed a good permeability to aquifer. The other locations were less favourable. After this drilling the hydro-geological map was corrected, in a positive

aspect: The clay layer ends closer to WWTP than it was thought. The same procedure was applied for the EU SWITCH project[2] for the selection of the SAT system before the NF. In that case the spreading basins had to be located very close to the location area and the depth of the vadose zone was only around 4 m. Figure 10 shows the location of the spreading basins which was chosen after systematic study as mentioned above and Figure 11 shows a cross-section of the basins and observation and recovery wells after a tracer test was performed to determine the residence time/travel distance relation ship which in this case was (20 days) / 13.3 m. from the middle of the basins) for well 1 and (35 days) / (23.3 m. from the middle of the basins) for well 2 which was used as a production well for 1.5 m^3/hr that was sent to the nano-filtration (NF) polishing step.

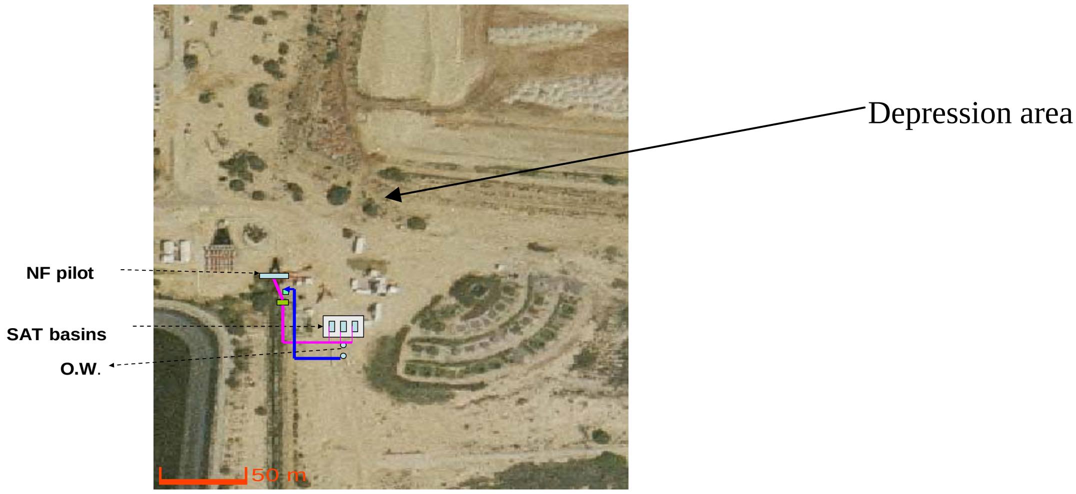

Figure 10 - Location of the spreading basins in the EU SWITCH project pilot (Cikurel & Aharoni, 2009)

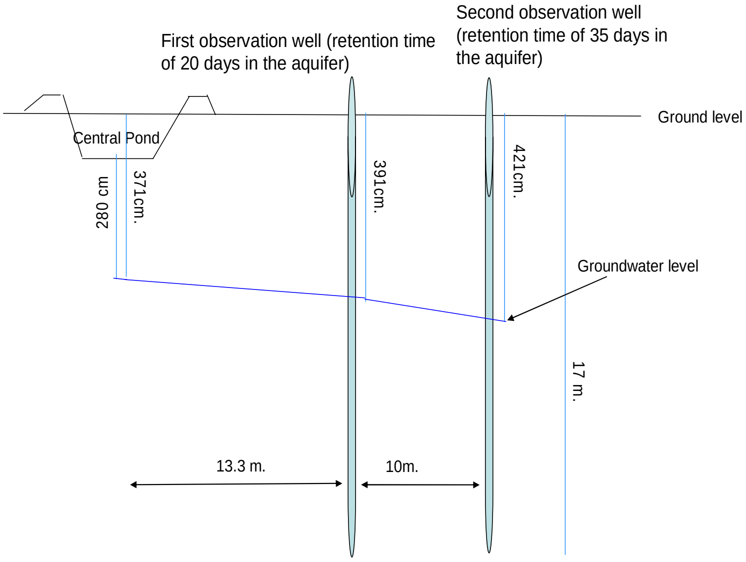

Figure 11 - Schematic diagram of the infiltration fields and ground water levels in each observation well (Cikurel & Aharoni, 2009)

6. SAT PLANNING AND DESIGN

6. 1 Design criteria for SAT systems (Guttman, 2007)

As explain in chapter 2 there are different recharge techniques in the SAT method. Evaluation of the viability of a SAT project and of its effectiveness requires an understanding and predictive capability of the hydraulic and chemical effects. Field survey and pilot testing should always be done to see if the method is working satisfactorily and how they should best be managed before large projects are established and considerable amount of money are invested.

The SAT system is a combination of spreading pond infiltration technique with ASR (Aquifer Storage and Recovery) subsurface recharge technique. The pre-feasibility studies and the pilot tests should be concentrated on the two topics: The unsaturated zone and the saturated zone.

Different steps in designing a SAT system are:

1. The first activity is to select the sites that are suitable for spreading infiltration (detailed in Chapter 5), and to see that the system is close to the water (effluent) sources and that the aquifer below the infiltration ponds can be used as a seasonal underground storage.

   Surface infiltration basins are used instead of vadose zone wells or direct injection wells in cases where the aquifer to be recharged is relatively shallow (to minimize pumping costs). The amounts of water that can be recharged in a given basin depend on several factors. The most important factors as mentioned in Chapter 2.3 are the geological profile (absence of impermeable layers in the unsaturated zone) and the rate of infiltration. It also depends on the nature of the top soil.
   Therefore, the first action is to study in detail the unsaturated section by constructing drilling a series of shallow and deep observation wells. The results of the drilling are maps that show the distribution of the sand and clay layers, their depth, their thickness and their composition.

2. The amount of water and the rate of infiltration in any pond depend also on the infiltration rate (percolation rate) and the clogging rate. Therefore, infiltration tests should be carried out in the drilling wells and afterward in several ponds that are acting as a pilot test ponds. At the surface of the infiltration ponds clogging occurs due to the existence of clay or silt on the top soil, deposition of particles carried by water in suspension or in solution, by algal growth, colloidal swelling and soil dispersion, microbial activities etc. These issues should be investigated prior to the decision of building the plant.

3. The recharge is most effective where there are no impending layers between the surface and the aquifer. But in cases where the top soil is composed of clay or silt material and its thickness is about 2-3 m only, removal of this top soil is a good solution (cost considerations have to be taken before the decision).

In conclusion: The aquifer is serving as a seasonal storage. Therefore, studying the aquifer properties and its capability to serve as a seasonal storage is crucial in operating the SAT system.

Design criteria for sizing a typical SAT spreading field (10 MCMY) system is as follows (Mekorot, 2006):
1. Unconsolidated aquifer, minimum clay layers < 10%-20%
2. Infiltration area: 10 hectare
3. Divide to sub basins, apply cycles of flood and dry regime
4. Total reclamation area: 100 hectare
5. Vadose Zone depth: 10-30 m'
6. Saturated layer :> 50 m'
7. Reclamation Wells: 12 wells of 150-200 m3/h each (20 hours/day pumping with an excess capacity)
8. Post - treatment devices against sand entrainment: Hydro - cyclone, Sand master, flow controllers
9. Monitoring and prevention of contamination of adjacent drinking water wells
10. Design of the supply system to consumers pump stations with net wires against algae or floating covers and pipes.
11. Seasonal storage reservoirs (months)
12. Operational reservoirs (hours up to few days)

More than 115% can be recovered, since 15% more than the infiltered water (which is back ground-water) can be recovered.

Wetting /drying cycles: 1 day recharge 2 - 4 days drying.

Typical design range for hydraulic loading rates ($m^3/m^2/d$): 120 m/yr or 0.3 m/d.

6.2 Design of production wells (Guttman, 2007)

In order to design the production and observation wells, investigation wells have to be drilled in a radius of about 1 Km from the proposed infiltration site. The wells must be drilled up to the bottom of the aquifer in order to study on the whole aquifer section (the existing of sandstone and clay layers).

Geological cross sections should be constructed in order to learn about the sub-aquifer layers, their thickness, distribution in space and the interconnection among themselves. In addition, pumping tests have to be carried out for getting the hydraulic properties of the aquifer and to study on the initial water quality.

Pilot test for studying the resident time that takes from the infiltration pond to the selected well is important for the final design of the well construction and the location of the ring wells (production wells).
In the Shafdan reclamation plant two rings of wells were drilled around each infiltration site. The first ring well pumps mostly reclaimed water whereas the second ring wells pumped mixture of reclaim water and fresh water. The second ring well creates a low water level buffer zone between the reclamation water body and the fresh water body.

Observation wells are located between the infiltration ponds and the first ring well.
As said before, the data obtained from the field survey, the wells and the recharge trials were used to define the configuration of the treatment plant, its dimensions and operation procedures. An example of a production well can be seen in Fig. 12.

Flow model -This data can be used as an input for a flow modeling. The model helps improve the selection of the proper operational scenario, deciding on the amount of recovery wells and their distances from the infiltration ponds.

Later on, after several years of operating a new flow model is required. The main purpose of the second model is to improve the daily operation of the system (from the hydro-geological point of view) and to solve different operational problems that arise during all these years.

6.3 Hydrogeological issues related to SAT operation (Shafdan case)
As mentioned in the introduction, the Shafdan plant is located on the Israeli Coastal plan. The hydrogeological system is taken as a singular unconfined aquifer, which is subdivided into four sub-aquifers near the coastline, and up to about 3-4 km away from it. Subdivision is due to marine shale intercalations, which merge westward below the coastal shelf and therefore, at least the lowest sub-aquifer are probable isolated and have minimal contact with recent seawater.

The recharge of the sewage as well the major pumping (reclamation and drinking water) occurs in the second sub-aquifer (sub-aquifer B). In some places the recharge reaches also to a lower sub-aquifer (sub-aquifer C). In some wells these two sub-aquifers are connected and the pumping is from both of them.
One of the unique hydrological situations in the Shafdan plant is the ability **to pump simultaneously fresh water and reclamation water from the same sub-aquifer and at the same region without any artificial barrier**. To avoid any mixture and contamination between the two water bodies and to minimize any potential damage to existing fresh groundwater production fields, a buffer zone (artificial low water level depression) is created between the second recovery ring wells and the closest fresh water pumping wells.

Over most of the time, the shape of the water level depression at the buffer zone is asymmetric, with sharp gradients toward the infiltration site and low gradients towards the aquifer area, upstream. Controlling the shape of the water-level depression minimizes the freshwater losses required for the efficient and reliable isolation of the reclaimed effluents from the main aquifer body.

In some sites (especially in the northern part - Soreq sites) over-pumping of fresh water that is carried out since 2004 by the local municipality caused a decrease in the water level of the fresh water body. In order to maintain the buffer zone, extensive pumping of reclaim water is carried out nearby the buffer zone. The total over-pumping (fresh water + reclaim water) at this point lowered the water level in the buffer zone to a level of 3 to 4 meter below sea level. The effect of this extreme low water level affected the nearby areas too. Some of them close to the sea shore. In order to bring the water levels in the aquifer to a more hydrological reasonable situation, Mekorot's hydrologists recommended to the regulator (Israeli Water Authority) to cut the pumping licenses of the fresh water operators.

The occurrence of high concentration of manganese (above 500 ppb) in few sites forces the system to change the pumping regime. It means, to shut down wells with high concentration of manganese. The problem of high concentration of manganese appeared after over 20 years of operation (Goren, 2009). Detail investigation found that the high concentration of manganese is limited to the area where the water contains 100% of reclaim water (Goren, 2009). These areas are close to the infiltration ponds and there the water level is higher than in the buffer zone (outside ring). From the hydrological point of view, these areas with the higher water level have the priority for reclaim water pumping. Because it is impossible to supply reclaim water with high concentration of manganese, the company (Mekorot) was forced to pump only water containing low manganese levels from wells that many of them are located in the water level depression.

This is an example that the overall management of the SAT system in the Shafdan plant is part of the whole aquifer management (MAR) with special insight combining several aspects such as: Geology, hydrology, water quality, climate change (drought), consumption and regulation. Proper SAT system management should take in consideration all of these aspects.

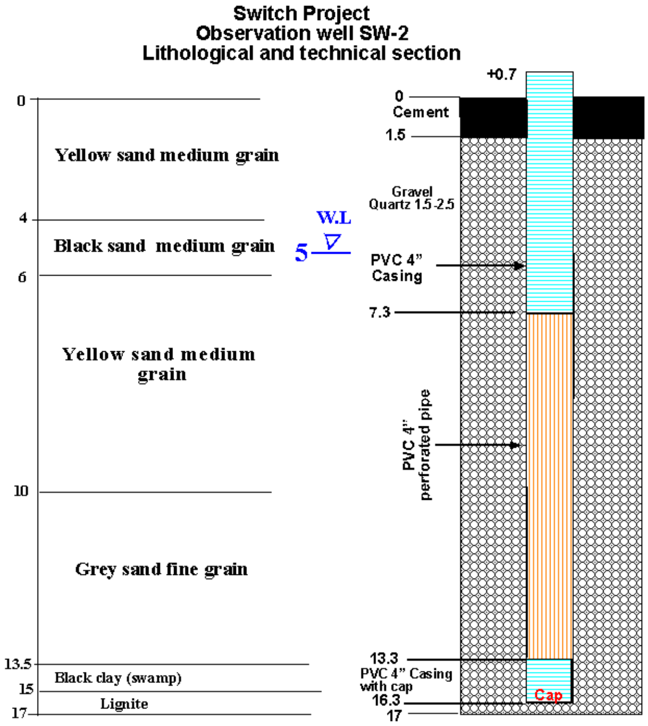

Figure 12 – Profile of the production well for the EU SWITCH project pilot experiment (Cikurel & Aharoni, 2009)

7. OPERATION AND MAINTENANCE OF SAT SYSTEMS

The Dan Region WWTP, the 6 infiltration areas and the production wells are schematically represented in Figure 13.

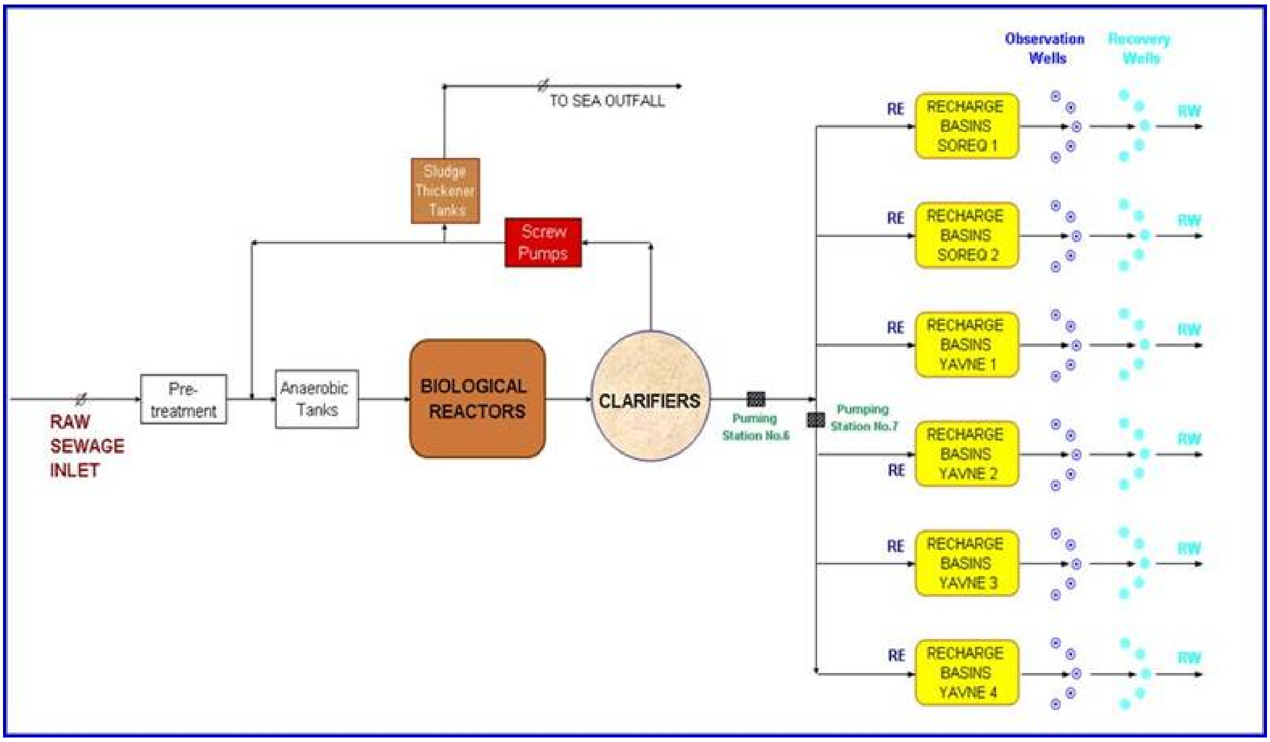

Figure 13 – Dan region WWTP and SAT system unrestricted irrigation reuse (Cikurel & Aharoni, 2009)

The SAT system can be divided in 5 parts (Cikurel & Aharoni, 2006):
1. The pumping system and effluent carrying pipe -lines to the infiltration fields
2. The infiltration fields and SAT system
3. The recovery system
4. The main distribution and storage system (with all seasonal and daily operative reservoirs)
5. The pumping system after the reservoirs and the distribution system to end – users

Each part has some specific aspects that have to be taken care of to maintain the system in good operational mode.

1. **The effluents (secondary or tertiary treated) pumping system and pipelines from the Wastewater Treatment Plant (WWTP) to the infiltration fields:** Due to the organic matter in the effluents and microorganisms, especially in hot weather (semi arid and arid countries) there is intensive biofilm development in the pipe-lines (see Fig. 14). Periodic disinfection -cleaning (chloro or bromo amines, chlorine..) of the pipe lines is carried when continuous disinfection (lately with UV while it used to be chlorine or chloramines in the past decades) is not applied.

Figure 14 – Biofilm formation in secondary effluent carrying pipelines (Aharoni, 2007)

2. **The infiltration fields and the SAT system:** As it is mentioned in Table 1 during the surface infiltration phase a high rate infiltration maintains oxic conditions so that the main purpose for maintenance of the SAT system is to maintain a good and constant infiltration rate or hydraulic loading and to avoid anoxic conditions. The infiltration into the groundwater is carried out by alternate flooding (1-2 days) and drying 2-4 days), a method designed to maintain aerobic conditions in the soil aquifer treatment. For efficient nitrification during SAT, infiltration periods should be short enough (<7 days) to prevent ammonium ion from breaking through surface soils. Drying periods should be long enough (> or equal to 4 days period) to permit the oxygen to oxidize ammonia. If anoxic conditions prevail, for long SAT systems (few months to more than a year retention time in the aquifer), denitrification occurs and there is effective nitrogen removal. In order

to maintain high hydraulic loading surface clogging must be avoided. Systematic cleaning of the fields every 15 to 30 days can keep the fields from being clogged (see in Figure 15 the cleaning operation. As mentioned in part 1 UV disinfection of the infiltered effluents can prevent clogging and not produce THM or NDMA

Figure 15 – Cleaning operation of an infiltration basin in SAT system (Cikurel & Aharoni, Aquarec, 2005)

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3. **The recovery system:** Reclaim water pumped from the production wells located at different at different travel times from the infiltration basins may contain sand, dissolved iron (Fe) and manganese (Mn) that are oxidized to ferric and manganese oxide and show up as particulate matter and also other inorganic salts (Calcium, Barium, Strontium, Magnesium) that can cause fouling in the distribution lines. A monitoring system including on-line sand detectors (Figure 16) and irrigation system clogging detectors (Figure 17) is used to operate preventive systems like hydrocyclones, wire filters or oxidation/disinfection systems (chlorination) and final sand filtration systems.

Figure 16 – (a) On-line sand detector **(b)** Hydrocyclone for sand measurement (Aharoni & Cikurel, 2009)

Figure 17 – Monitoring clogging irrigation systems (Aharoni, 2007)

<u>Treatment alternatives for the Mn and Fe clogging problem include</u>:

a. Wells shut off in case of high Mn conc' (more than 500 ppb)

b. Flushing of the major pipe-line at the beginning of the irrigation season

c. Mechanical cleaning of the pipe-line (pigging)

d. Automatic control of the flooding – drying cycles to ensure aerobic conditions in the vadose zone

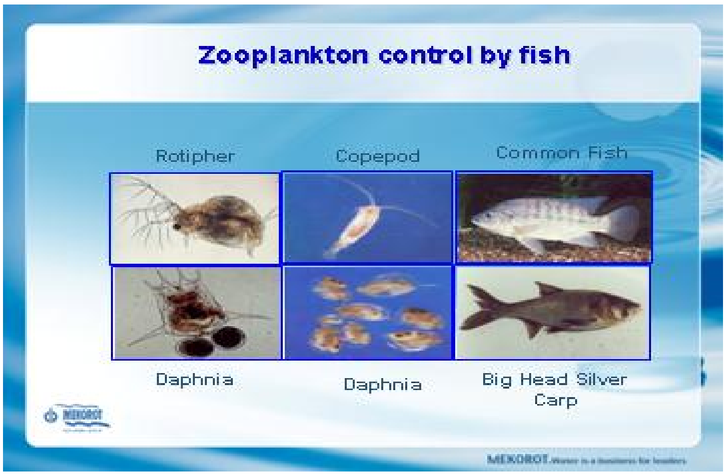
d. Manganese oxidation and filtration

4. The main distribution and storage system (including the seasonal and daily operative reservoirs):

The main problems in these daily and seasonal operative reservoirs are: Algal bloom and zooplankton that grow in the reservoirs. To control algal blooms either the reservoirs are covered (Figure 18a) or copper sulfate is sprayed using airplanes (Figure 18 b) or different ultrasound devices used (Figure 18 c). Different Zooplankton is controlled by fish (Figure 18 d).

(a) Floating cover reservoirs against algal bloom.

(b) Copper sulfate spraying from planes



(c) Ultrasound devices to prevent algae bloom **(d)** Zooplankton control by fish

Figure 18 – Different growth control methods for algae and zooplankton in SAT water reservoirs (Aharoni & Cikurel, 2009)

5. The pumping system after the reservoirs and the distribution system to end – users:

Chlorination follows the pumping of water from reservoirs to prevent clogging of the main distribution lines till the farmers' irrigation system. The monitoring device in Figure 17 is used to monitor biofouling.

8. PRE-TREATMENT FOR SAT

As mentioned in previous chapters 1, 3 and 7, and based on the longest experience (more than 30 years) in the biggest scale SAT (Shafdan, Israel) the following conditions have been identified as affecting negatively the good operation of SAT systems:

1. Reduction in recharge capacity
2. Bio-fouling of effluent pipelines
3. Clogging as a result of Mn and Fe oxides

Besides, in the last decade, there is more concern for the micropollutants that are not completely removed even in the long SAT (6-12 moths residence time).

In order to:

1. Decrease the reduction of the recharge capacity.
2. Reduce the bio-fouling of the effluent pipe-line to the SAT basins
3. Prevent organic matter and heavy metals accumulation in the soil
4. Prevent manganese dissolution
5. Remove micropollutants more effectively

advanced pretreatments like flocculation - sand filtration and Advanced Oxidation Processes (Maman et. al, 2010) or advanced pre-treatments like UF (Gaus et. al., 2007; Cikurel& Aharoni, 2011), direct NF or powdered activated carbon (PAC)/NF (Kazner et. al, 2008) can be applied.

An advantage of using UF membranes as pre treatment to SAT can be, the removal of suspended and colloidal solids and prevention of clogging. This can help increase the infiltration rate. But the persistent micropollutants are still not completely taken care of, since UF does not remove soluble micropollutants. Although, as the pilot experiments conducted in the context of EU RECLAIM WATER[2] showed, UF- short term SAT could remove almost all the micropollutants except some persistent non-biodegradable micropollutants like; Carbamazepine, Sulfamethoxazole and Adsorbable Organic Iodine (AOI). Also it was found that there is not enough dissolved oxygen to be able to maintain oxic conditions during the 30-35 days retention time of the SAT effluents in the aquifer.

The addition of the AOP step or using Nanofiltration (NF) or PAC/NF can help to the further removal of micropollutants during the SAT. Direct nanofiltration as well as powdered activated carbon combined with nanofiltration can produce high quality water from tertiary effluents (sand filtration – disinfection). DOC values below 0.5 mg/l (removal rates above 90%) have been obtained. This process can produce a water quality suitable for direct injection.

If the purpose is to only increase the infiltration rate, an effective tertiary treatment including pre-filtration (wire filtration) followed by flocculation-contact filtration can increase the infiltration rate significantly (Cikurel et. al, 1999). A shallow – bed traveling – bridge (SBTB) filter used as a contact filter with the addition of 10-15 mg/l alum and 0.5 mg/l of medium cationic high molecular weight polymer has been able to effectively remove particles down to 10 micron and also 80-90% of phosphate was removed. This helped increase the infiltration rate from 2 m/d in case of infiltered effluents with no treatment to 10 m/d after flocculation –contact filtration. Figure 19 shows test infiltration fields without any treatment (a) and with contact –flocculation-filtration (b).

In field pilot experiments (Gaus et. al., 2007; Cikurel& Aharoni, 2011) conducted during the EU RECLAIM[1] project secondary effluents from the Dan Region WWTP were first preliminary treated by wire filtration (400 micron) and followed by a 70 micron disc filter before a 0.01 micron Poly Sulphone UF membrane operating at a dead-end mode (at around 40-50 LMH). The effluents from the UF filter were infiltered in a 3m. diameter and 2.5 m. depth dug-well (see Figure 20) at 10-12 m/d as compared to the 2 m/d conventional SAT (the soil in the pilot site was pristine as compared to the old conventional SAT sites so as a conventional type pilot surface spreading field in such a sand enabled to infilter at 2 m/d rate for comparison).

(a) (b)

Figure 19 - Infiltration improvement experiments in pristine sand near the Dan Region WWTP using 20 m^2 surface - area SAT fields (Cikurel & Aharoni, 2009)

The UF filtration almost completely removed (see Figure 21) the Extra-cellular Polymeric Substances (EPS) that are mainly responsible for soil clogging and enabled the high rate infiltration to the dug well.

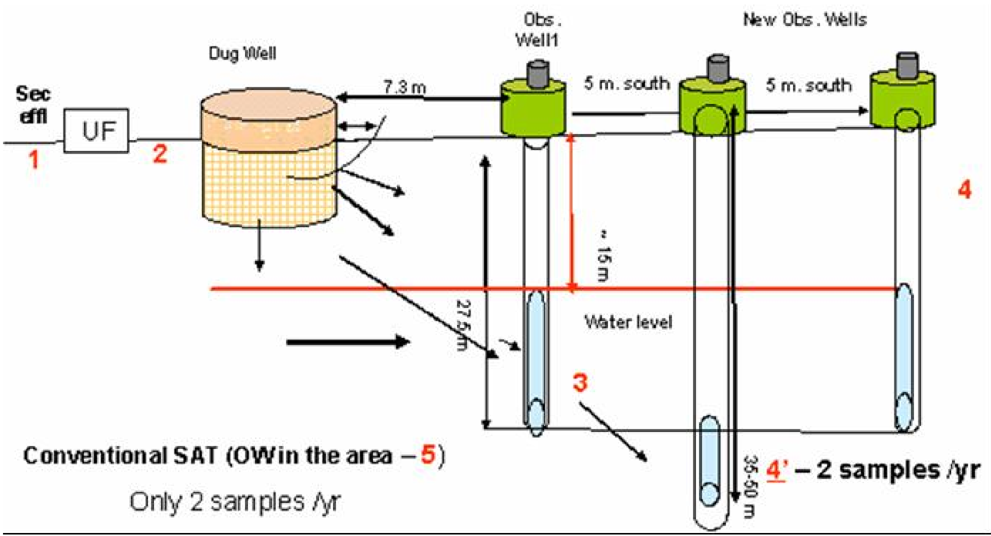


Figure 20 – The UF Prefiltration of secondary effluents before Dug Well infiltration and recovery at short travel distance/retention time (Cikurel& Aharoni, 2011)

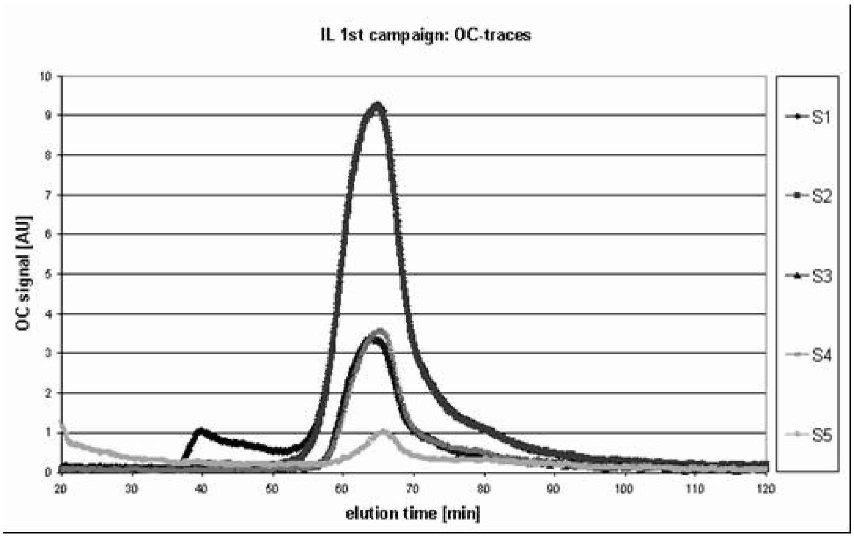


Figure 21 - Graph showing the removal of the EPS fraction that causes bio-fouling during SAT by the UF (Cikurel & Aharoni, 2009)

Analysis of the final results with secondary effluent treatment by UF and short SAT (35 days) compared to conventional SAT results can be summarised as follows:

1. Efficient removal of micro-organisms can be obtained by the short SAT similar to conventional SAT.
2. Efficient removal of total DOC (from 10 mg/L to 2-3 mg/L) was obtained in the short SAT, but slightly less effective then in the conventional long SAT system (1-2 mg/L DOC).
3. Efficient removal of Nitrogen (from around 6-7 mg/L total N to <0.5 mg/L) almost similar to conventional long SAT was obtained in the short SAT.
4. Relatively low phosphorous removal (from 2-4 mg/L Total P to 1.3-1.5 mg/L).

The redox conditions were oxic in a sample taken from 10 days retention time - well but anoxic after 35 days retention time. Based on these redox results and in order to prevent Manganese dissolution, in the context of a new research, it is planned to enrich the filtered secondary effluents with oxygen. The idea is to produce, by pretreatment of the secondary effluents, conditions for maximum organic removal before the infiltration and maximum oxygen supply to improve the Redox conditions.

The technique based on UF and short term SAT only, produced a good chemical (DOC 1.8-2.3 mg/l, very low phosphate and ammonia content) and microbiological quality water (no fecal coliform, enterococci, clostridium and MS2 phages) but did not remove all the measured micropollutants effectively due to the short retention time in the aquifer before the water is pumped out (Kazner et. al., 2009). In this system the objective was to remove the biopolymers that clog the SAT by UF pre-filtration and to reach a relatively high infiltration velocity (10-12 m/d). Short term SAT (with 30-35 days retention time as compared to the 6-12 months in conventional SAT system) is then used as polishing step to remove the dissolved organic matter (from 10-12 mg/l to 1.8-2.3 mg/l DOC). It was found that some micropollutants (sulfamethoxazole, carbamazepine) although in minimal concentrations, prevail after short term SAT systems (Kazner et. al., 2009). The high rate infiltration introduced more oxygen helping to maintain some positive redox conditions that decreased the manganese dissolution.

In another pre-treatment method for groundwater recharge that was investigated (Kazner et al, 2008) tertiary treated effluents were directly filtered on a Nanofilter (NF) and recharged and the water quality obtained from this process was compared to the water quality of another process that used powdered activated carbon and NF before the infiltration of the same tertiary effluents.

The investigation results showed that direct nanofiltration as well as powdered activated carbon (PAC) combined with nanofiltration can produce high quality water from tertiary effluent. DOC values below 0.5 mg/L and removal rates above 90% confirmed the excellent quality suitable for direct injection. Direct nanofiltration partly rejected the molecules with low molecular weights As PAC tends to adsorb the humic and fulvic substances as well as smaller size molecules. Thus the PAC/NF process allows the fairly accurate adjustment of the permeate quality according to the site specific requirements through proper selection of the adsorbent and the dosage.

9. POST TREATMENTS FOR SAT INCLUDING HYBRID SAT SYSTEMS

As was shown in the last chapter, if non-potable or potable reuse of treated wastewater is sought as an alternative source to natural water and at the same time a natural, energy efficient process is required as an alternative to conventional UF-RO processes, pretreated secondary effluents and SAT is not always sufficient.

On the other hand, it was shown that SAT can effectively remove biodegradable organics and mainly polysaccharides. So that combinations of short (30-35 days residence time) SAT as pretreatment for membranal processes NF polishing may result in UF-RO comparable water.

Sharma et al.(2009), using laboratory -scale soil column experiments for secondary effluents (SE) and a mixture of SE and Delft canal water and stirred cell and flat sheet membrane (MF/UF/NF) with or without SAT pre-treatment analyzed the performance of MF/UF and NF membranes in terms of DOC removal as well as fouling potential. They observed that SAT pre-treatment helps to improve DOC removal from wastewater treatment plant effluents, especially removing non-humic substances, as shown by an increased value of SUVA after SAT.

SAT pre-treatment of WWTP effluents increased the DOC removal by MF/UF membranes by 30 to 46%. Protein-like organic matter removals during SAT pre-treatment was more than 90% for both types of effluents tested which increased to almost 100% with subsequent membrane filtration. SAT pre-treatment improves the performance of MF/UF/NF membranes by reducing the fouling measured as Modified Fouling Index (MFI), as protein-like organic matter is preferentially removed during SAT. As expected, the MFI

reduction was higher for membranes with a smaller Molecular Weight Cut - off (MWCO). In case of NF membranes, there was not any significant increase in DOC removal with SAT pre-treatment, however the flux decline was considerably reduced (up to 18%) with SAT pre-treatment.

They concluded that, SAT membrane hybrid systems are effective for removal of DOC and provide additional barriers for microbes and organic micropollutants. Therefore, such systems have high potential for wastewater reuse applications.

Aguilar et al. (2008) used different NF filters to polish water from an aquifer recharged with wastewater. They compared nine nanofiltration membranes to treat water coming from an aquifer recharged with wastewater and used as municipal supply in the Tula Valley, Mexico. The comparison was made based on (a) the amount of water produced; (c) the capability to produce a 1 mg TOC/l effluent without entirely eliminating salts, (b) the removal of specific organic and microbiological pollutants, and (c) the reduction of toxicity and mutagenicity from water. From the tested membranes, only four produced an effluent with 1 TOC mg/L, and three totally retained dibutyl phthalate, diethyl phthalate and hydroxytoluene butylate. Influent mutagenicity (Ames test) was negative but there was a certain degree of toxicity when Tetrahymena pyriformis was used as indicator. Toxicity was partially reduced by some of the NF membranes. The best membrane had a flux of 95 LMH and removal efficiencies of 98% for TOC, 92% for AUV254, and 92% for TDS. The permeate had a final hardness of 76mg/L and an alkalinity of 124mg/L. Additionally, this membrane removed totally specific organic compounds, total and fecal coliforms and almost all the somatic coliphages. The NF270 membrane also had a high TOC retention. This membrane was also characterized by having the highest flux of all the membranes.

Wintgens et al (2008) highlighted that nanofiltration can be considered as an alternative to reverse osmosis technology where a lower degree of desalination is required. They elaborated that, with a molecular weight cut-off (MWCO) of around 200 g/mol it is a promising treatment option for a variety of emerging trace contaminants, e.g. contrast media.

However several studies (Kazner et al. 2008b; Verliefde 2008; Bellona et al. 2004) clearly revealed that loose nanofiltration membranes (such as the DOW NF 270) cannot fully retain the whole range of organic micropollutants. New concepts thus propose multi-barrier systems combining nanofiltration with pre- or post-treatment for additional removal of contaminants of concern. Hybrid nanofiltration processes combining for example NF and activated carbon adsorption (Kazner et al. 2008b) can thus be regarded as a valuable alternative to UF/RO as they provide a comparable barrier against pathogens and also micropollutants to a large extent while the NF brine is less saline and thus easier to treat. Nevertheless pharmaceuticals with a molecular weight similar to the MWCO of NF membranes cannot be completely removed by the membrane system alone.

As mentioned in the previous chapter in the Dan region WWTP a series of pilot experiments were conducted. A hybrid UF-SAT system was studied in the context of the EU RECLAIM WATER[1] project at the Shafdan site.

Although the water obtained by this process is suitable for unrestricted irrigation according to all regulations as of today in Israel and other parts of the modern world, since the regulations are being stringent and in the prospect of future regulations, better micropollutants removal processes were sought in the context of the EU SWITCH[2] project. Another concern was that in cases of indirect potable reuse of tertiary effluent treated by managed aquifer recharge the trace organics, such as pharmaceuticals and endocrine disruptors, are causing concern due to potential harm to the users (Asano and Cotruvo, 2004).

In the context of the EU project SWITCH[2], Fernando et al. (2009) analyzed the effect of SAT pre-treatment on the performance of NF membranes (NF 270 and NF 90) at bench scale.

In parallel, the study of the SAT-NF treatment of secondary effluents at pilot scale in Shafdan aimed to obtain a more effective removal of micropollutants by using SAT pre-treatment before NF membrane as polishing step. The purpose of this pretreatment was to verify if the polysaccharides and other clogging material had been retained by the sand filter and the short-term SAT. The study was performed at a field pilot plant with 5 m^3/hr pretreated secondary effluents for SAT infiltration and a 0.5 m^3/hr NF as polishing system. The short SAT was used as pretreatment to an NF polishing step to remove the biopolymers and ease the organic load on the NF. In the actual demonstration scale plant, new concepts were tested. Travel distance/time relationships required for elimination of different contaminants were checked and pretreatment to reduce infiltration basin clogging was also addressed.

The details of the experiment are mentioned below as part of the work done in EU SWITCH project[1] (Cikurel et. al, 2010).

Experimental set-up of the NF pilot system

This study was conducted using the treated effluent from Shafdan WWTP and using the pilot plant. Different stages and components of the study were:

1. Pretreatment - Sand filtration of 6 m^3/h of secondary effluents without flocculant addition at 8 m/h, the filter was backwashed every 8 h. No chlorine was used during the air-water backwash. This pretreatment is optional and was applied to obtain a higher infiltration rate, in order to increase the infiltration rate of the SAT system and save infiltration area. This does not have to be part of the short SAT – NF process.

2. SAT - 5 m^3/h filtered secondary effluents were intermittently infiltered in 3 SAT fields, operated at a 1 day infiltration - 2 days relaxation mode and at 3-4 times higher infiltration rate than conventional (1 m/d).

3. Wells - Observation well (5 m from the SAT fields) and a recovery well (located 15 m from the SAT fields and reclaiming water after 30-35 days retention time in the aquifer) which extracts only 15 m^3/d of water. The recovered water was sent to a hydrocyclone and micron filter before a polishing step by NF to remove most of the loamy sand (calcareous and iron containing).

4. NF membrane treatment - DOW NF270 or NF90 polyamide thin film composite NF membranes were operated (NF270 for 10-11 months and NF90 for 3-4 months). Operating conditions are detailed further in the paper. Fig. 22 shows the three stages of the NF membrane system. The SAT treated water is fed first to the 2 stages and the concentrates of these two stages go for further polishing in the third stage. The NF270 membrane was operated for 4000 hours with no special problems while after this time gradual clogging occurred due to inorganic fouling from the short SAT pretreatment.

The NF membranes were both backwashed only with acid water since the clogging was not organic, due to complete biopolymers removal during the soil passage. Water analyses results for samples of the feed water to NF agreed with other studies that showed almost complete removal of biopolymers during soil passage (Fernando, 2009). On the other hand inorganic pollution occurred during the same soil passage. Besides, the acid backwash every 4-6 hours, once a week the membrane was washed with alkali.

Characteristics of the membranes used

The two types of membranes used in this pilot experiment were DOW FilmTec NF270 and NF90. Table 3 shows the characteristics. The same membranes were used in a parallel laboratory work by UNESCO – IHE as part of their work in EU SWITCH project[1] (Fernando et. al., 2009). Both membranes consist of very thin polyamide active layer while NF270 (MWCO: 150-200 g/mol) is slightly more open than the NF90 (Fernando et. al.; Aguilar, 2008). According to the same sources, NF90 has a MWCO of 100-150 g/mol. The NF270 membrane is more hydrophilic and has smoother surface and a higher surface charge than NF90. The nominal salt rejection percent is given based on 2000 mg/L of MgSO4 at 25 °C and is given as 97% for NF270 and 98% for NF90. Actually different salt rejection results for each membrane were obtained in the pilot, using as feed to the membranes the short SAT water.

Table 3 - Properties of the NF membranes used in this study (acc. to Nghiem et al. 2008)

Membrane	Pure water permeability	Average pore diameter	Roughness	Contact angle	NaCl rejection	$CaCl_2$ rejection	TOC rejection
	L/m²·h·bar	nm	nm	°	%	%	%
NF-90	6.4	0.68	76.8	42.2	85.0	95.0	92.7
NF-270	13.5	0.84	8.55	23.4	40.0	43.0	88.9

The NF pilot system as depicted in Fig. 22 consisted of three passes each, containing either an NF 270-2540 or a NF 90-2540 element 2.5 inches diameter and 40 inches length.

During the pilot experiments 500 L/hr of short SAT effluents were passed through the NF270 and 400 L/hr effluents were passed through the NF90 system (see Figs 23 and 24). Analyses were performed at different laboratories. The standard chemical and microbiological analyses were conducted at Mekorot, Israel. The emerging pollutants that were represented by some Macrolides and sulfonamide antibiotics, organic iodine compounds (AOI) and dissolved organic matter characterization were analyzed by Technical University Berlin (TUB), Germany and UNESCO-IHE in Delft, Netherlands.

4 sampling campaigns were conducted during the one year pilot. The sampling for the SAT effluent, the NF inlet and NF permeate was performed continuously during 24 hrs. The samples were sent to the Mekorot Central Laboratory for SPE and the cartridges were sent by courier to the different laboratories for analysis. The analytical method for detection of Macrolides and sulfonamide antibiotics was developed in TUB using LC-MS/MS measurements after solid phase extraction. For detailed analysis of the bulk organic compounds in IHE, size exclusion chromatography was applied (LC-OCD system).

Figure 22 - The nanofiltration system

Effect of the short SAT pretreatment on the removal of organic matter, nutrients, microorganisms and micropollutants

In early 2008 the first tracer tests were conducted to determine the retention time of the infiltrated effluents in the aquifer, before being sampled at the observation and reclamation wells. The tests were conducted with water recovered from conventional SAT ("third line" water) with bromide (Br) addition as tracer. Two tracer

tests were conducted while the first was static (no recovered water), in that case 120 m^3/d of third line water was infiltered intermittently to each field while letting the others rest for 2 days. A retention time of 20 days to the observation well (5m away from the SAT) and 30-35 days retention to the reclamation well (15 m. away from the SAT) were obtained. After the completion of these tests and the installation of the sand filter and NF, the first infiltration tests with sand filtered secondary effluents started. The results for the efficiency of organic matter and nutrients removal by the short SAT can be seen in Table 4. The COD was removed by an efficiency of 78-83% and the DOC by 78-81% (from around 10 mg/l to 1.8-2.3 mg/l). The ammonia removal efficiency was 76-87% and the phosphates were almost completely removed.

Table 4 - Organic matter, ammonia, phosphates and salt removal efficiencies at different stages of the pilot.

Parameter	Unit	Sec. Effl.	After Short SAT*	Rem. Eff. % Aftr.short SAT	After NF 270	Rem. Eff.% (from short SAT to NF)
COD	mg/L	29 - 40	5.0 - 9.0	78-83	2.0 - 3.0	60-67
DOC	mg/L	9.5 - 10.3	1.8 - 2.3	78-81	0.2 - 0.3	87-89
UVabs.	1/cm* 1000	209 - 224	46 - 68	70-78	6.0 - 7.0	87-90
Ammonia	mg/L	3.17-4.2	0.4-1.0	76-87	0.03-0.1	90-93
Phosphorous	mg/L	0.66-1.4	0.03-0.08	94-96	<0.03	>63
TDS	mg/L	864 -900	786 - 897	-	687 - 755	13-20

* After 1 year infiltration. The analyses results relate to 30 days retention time in the aquifer

Table 5 shows the microorganisms' removal efficiency by the short SAT. The microorganisms are effectively removed at the short SAT stage. 5-6 logs of E. Coli, 4-5 logs of Enterococci, 4-5 logs of Clostridium, 4-5 logs of MS2 phages and complete removal of enteroviruses were obtained.

Table 5 - Microorganisms removal after short SAT (up to 35 days retention time)

Sample	Secondary Effluents	OW1*	OW2** (after short SAT
Date FC (/100 ml)	05.02.09 $2x10^5$	05.02.09 0	05.02.09 0
Enterococci (/100ml)	$1x10^4$	0	0
Clostridium (/100 ml)	$4x10^4$	0	0
Phages F+ (/10 l)	Negative	Negative	Negative
PhagesMS2 (/1 l)	$2.6x10^4$	Negative	Negative

***** Observation well 5 m. from the infiltration fields (15 days r.t.)
** Observation well 15 m. from the infiltration fields (35 days r.t.).After short SAT

The measured micropollutants removal efficiencies by the short SAT are given in Table 6. The results of two campaigns (November and December 2008) showed that there was a complete removal of clogging material by the sand filter and the short SAT (30-35 days retention time). Most of the investigated micropollutants (Clarithromycin, Erithromycin-H_2O, Sulfamethazine and Trimethoprim) were effectively removed by the short SAT since they are easily biodegradable (see Table 6). Roxithromicin was partly removed and sulfamethoxazole although partly removed prevailed at a concentration of more than 100 ng/L (according to

the German recommendations the maximum allowable concentrations of antibiotics in drinking water).The organic iodine compounds (AOI) concentrations in the water decreased from around 13.4-47.3 µg//L to 13-17.3 µg//L during the short SAT passage.

Table 6 - Micropollutants concentration after short SAT -NF270 or NF90

Micropollutant	Sample point/ Membrane	Raw sewage[1]	Before short SAT*	Before NF**	Before NF**	After NF	After NF
				NF-270	NF-90	NF-270	NF-90
	Unit			(range)	(range)	(range)	(range)
Clarithromycin	**ng/L**	385-2922	39-500	< 10-25	< 10-25	< 10-25	< 10-25
Erythromycin-H20	**ng/L**	399-1515	93-594	< 10-25	< 10-25	< 10-25	< 10-25
Roxithromycin	**ng/L**	629-1839	55-787	< 10 - 98	< 10-25	**< 10-25**	**< 10-25**
Sulfamethoxazole	**ng/L**	215-1367	173-657	< 24 - 316	48 - 65+	**< 10 - 43**	**< 10-25**
Sulfamethazine	**ng/L**	6-135	< 1-5	< 1-5	< 1-5	< 1-5	< 1-5
Trimethoprim	**ng/L**	27-105	62-349	< 1-5	< 1-5	< 1-5	< 1-5
AOI	**µg/L**		13.4-47.3	13 - 17.3	11.1 - 11.2+	**0.6 - 3.5**	**0.4 - 0.5**
DOC	**mg/l**		9.8-13.8	1.8 -2.2	1.8-2.4	**0.2-0.3**	**0.1-0.2**

[1] Data from (Kazner et. al., 2009)
* Before short SAT or activated sludge system (CAS) effluent
** Before NF or after short SAT (the pretreatment of short SAT water before NF did not change the micropollutants conc.)

Nanofiltration as polishing step:

Operational conditions for NF270 and NF90. The NF270 membrane system was operated for almost one year (from February 2009 to January 2010). The denser NF90 membrane was operated from end January till end April 2010 to optimize the operation conditions, the micropollutants and salinity removal. Although the micropollutants and salt removal rates (in case of NF90) were similar to RO membranes the work pressure (6-7 bars) was lower than RO system for effluent desalination used at Shafdan (18 bars), but was higher than NF270 (4-5 bars). The operational parameters that were monitored for both membranes and their results were:

a. Flow rates NF 270 and NF 90

The inlet flow rate and the change at almost constant TMP during the whole experimental period were monitored. Special mention was made when a cleaning method or pretreatment method change occurred. The inlet flow rate over the whole experimental period for NF270 and NF90 can be seen in Figs 23 and 24. The inlet flow rates for the NF-270 (Fig. 23) were stable till 4000 hours, then slowly decreasing from around 450 to 350 L/h. Although regular membrane washes (every 4 hours acid wash with hydrochloric acid) were performed the irreversible inorganic fouling caused flow rate decrease. The flow rates for NF90 were stable for 1000 hours (Fig. 24) after a small decrease at the beginning. The permeate flow was more or less stable at around 300 L/h.

b. The percent recovery for both membranes

The total water recovery for NF270 was rather high at around 90% (Fig. 23). Recovery in the single stages (2 stage system) was around 70%. The total water recovery for NF90 was significantly lower than NF270 (the effect of scaling although some anti- scaling measures were taken). The total recovery was around 70% and in single stage it was around 50%.

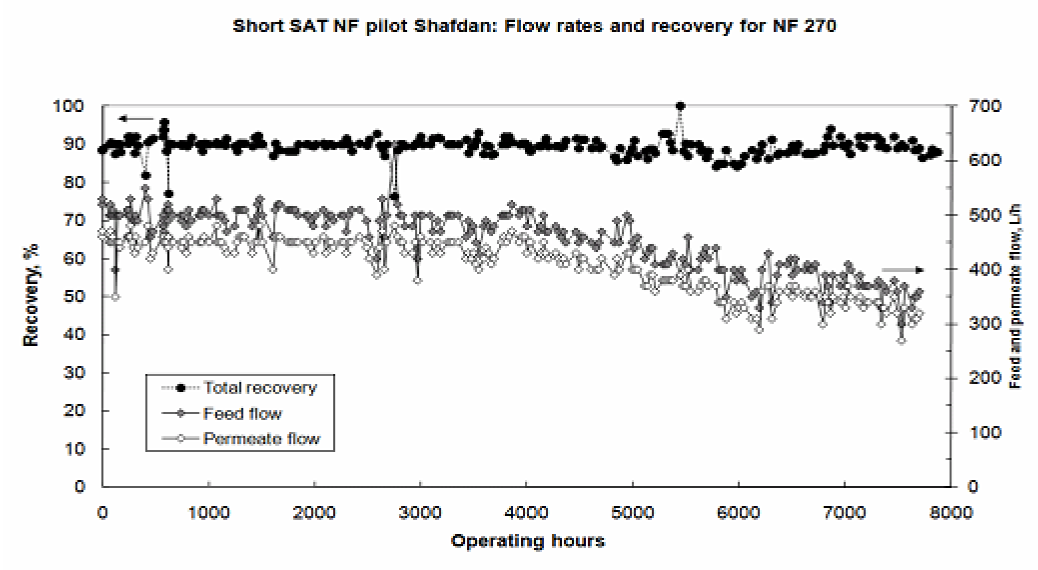


Figure 23 - Flow rates and percent recovery for NF-270

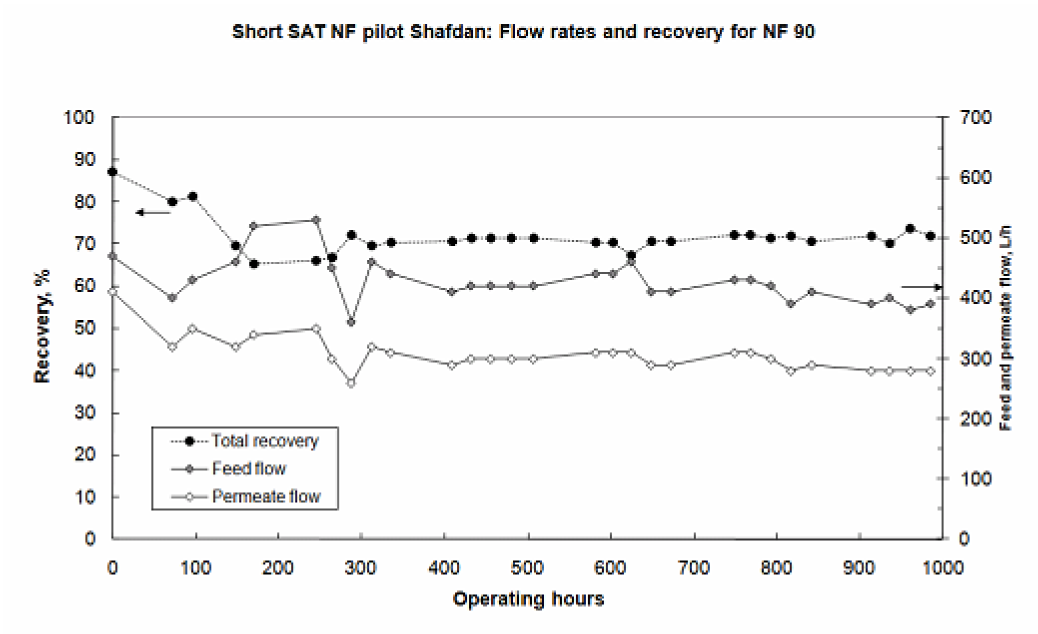


Figure 24 - Flow rates and percent recovery for NF-90

c. The trans-membrane pressure (TMP) for both membranes

The TMP's of the 1st and 2nd stages for the NF270 and NF90 are given in Fig. 25.

NF270 is operating at relatively low TMP. For the first stage the TMP was rather stable at around 2.5 bars for around 4000 hours, increasing afterwards to 2.8 bars maximum due to fouling. The second stage which had lower TMP (1.8 bars) increased above 2 bar after around 4000 hours operation. The operation after the start of the fouling phenomena was in the overall less stable than during the first 4000 hours.

NF90 is operating at relatively higher TMP than NF270. For the first stage the TMP started at around 3.5 bars and quickly rose to 4 bars, due to fouling. The second stage TMP was 3 bars. The overall duration of the tests for the NF90 was too short for a sound evaluation of the performance. But even from this short operation period it can be concluded that the system is less stable then NF270.

d. Flux for both membranes

The flux for NF270 (Fig. 26) till 4000 hours was 19-20 LMH then, it started to decrease to below 15 LMH. The flux for NF90 (Fig. 26) started at 15 LMH and went down to 13 LMH. In 1000 hours of operation

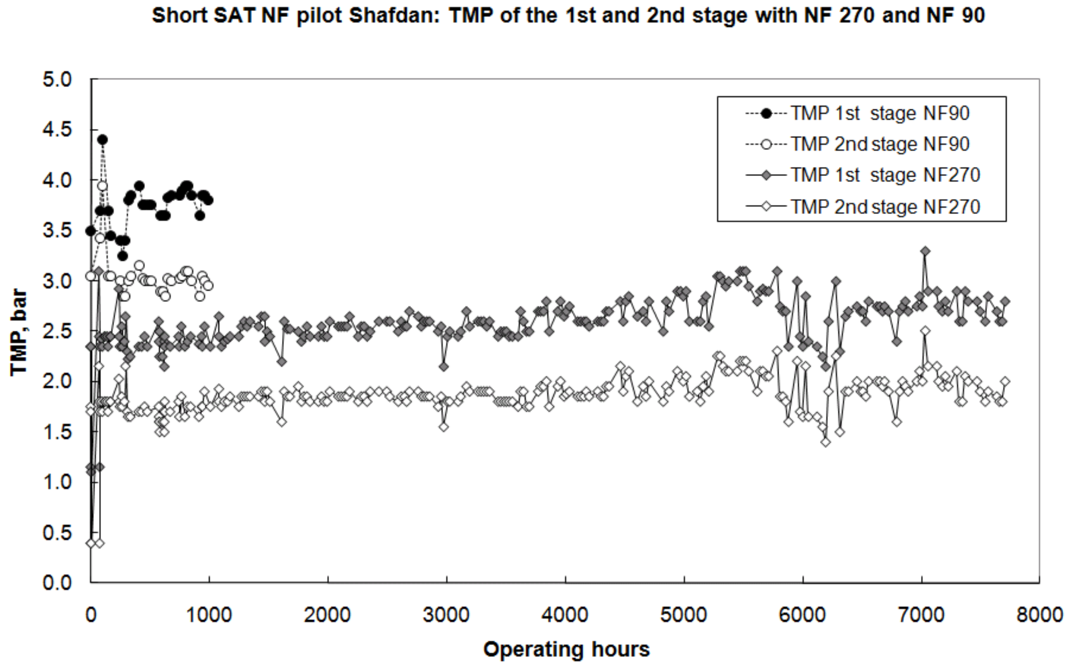


Figure 25 - TMP for NF270 and NF90 during the experimental period

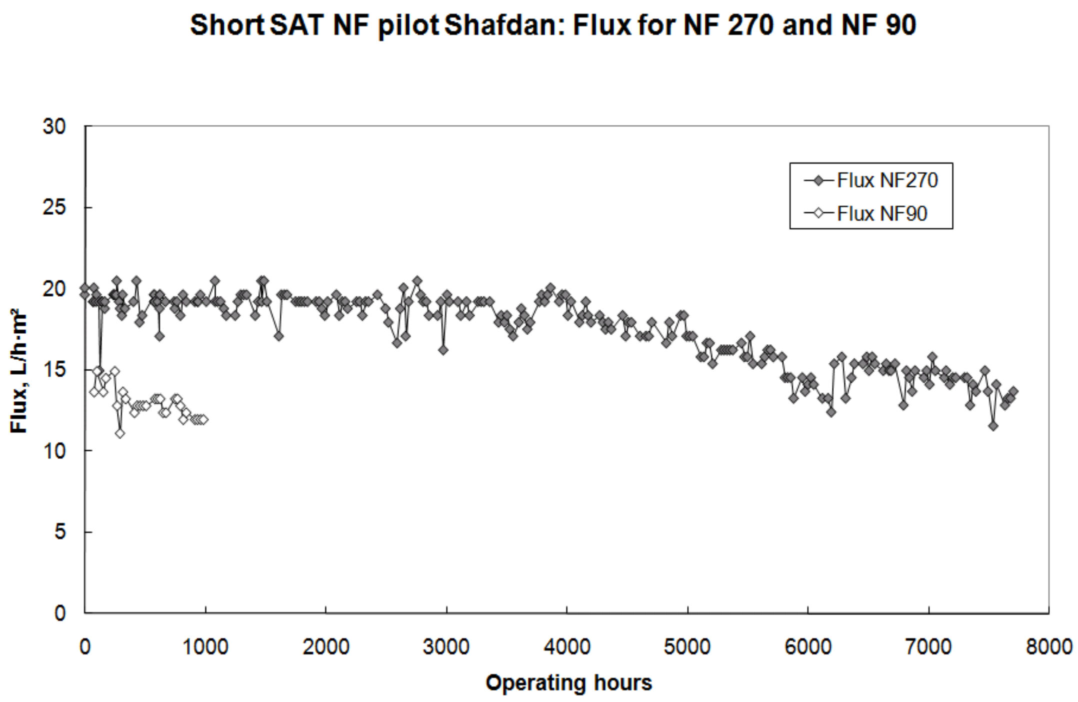


Figure 26 - Flux for NF270 AND NF90 during the experimental period

The NF-270 permeate salinity was (see Table 7) in the average 1333 µmhos/cm. The average salinity of the water entering the membranes was 1601 µmhos/cm, so that in the average around 17% salinity was removed by NF 270. For the NF 90 the salinity of the permeate was 225-235 µmhos/cm, so that 85-86% salinity was removed.

Operational problems during the pilot run:

The main reason for the flux decrease for NF270 and NF90 was the inorganic fouling due to dissolution and mainly entrainment (during the rainy season) of iron (571µg/l), manganese (705µg/l), calcium (106 mg/l), barium (204 mg/l) and strontium (575 mg/l) during the short Soil Aquifer Treatment of the water before entering the membrane. The anoxic process mainly due to lack of oxygen and consumption of nitrates caused the dissolution of manganese. The DO most of the time at the end of the SAT process was less than 1 mg/l. The ammonia was oxidized for the first 20 days retention time in the SAT (well No.1) to nitrates but due to anoxic conditions after 30 - 35 days retention time the nitrates were depleted. Particulate iron is entrained but there was no excess soluble iron so the filtration or precipitation was easier. Contrary to what was obtained in EU RECLAIM project[2] and contrary to the known fact that P is not readily biodegraded or easily absorbed, in case of the actual pilot there was a very good removal of P. This can be due to the formation of insoluble iron phosphate due to the excess iron. .A solution to the fouling was experimented by pre-treating the short SAT water before entering the NF. A softening process was proposed, including pH change to 10, precipitation of the formed solids (calcium carbonate, iron hydroxide, manganese hydroxide etc.) and fine filtration. This process produced feed water to the NF membranes that were low in iron, manganese, barium,

calcium and strontium content. Since the hydrocyclone, precipitation tank, feed tank and the 5-50 micron filters were present originally, the only addition was the pH change. The total iron decreased by 90-92%. Also there was a 70-80% manganese concentration decrease, a 60% Barium and around 50% Calcium concentration decrease after the pretreatment.

Organic matter, nutrients and micropollutants removal by the combined short SAT-NF system (mainly based on NF270):

During the NF270 operation three sampling campaigns were performed. The results for standard parameters are given in Table 4 and for micropollutant removal in Tables 6 and 8. From Table 7 it can be seen that after the NF polishing the organic matter removal is comparable and even better than the long SAT results (Third Line – Ashdod junction sample) while nitrogen and phosphorus are removed efficiently.

Furthermore, the microorganisms were already completely removed by the short SAT process (see Table 5).

Micropollutants - Table 8 compares the different Macrolides and Sulfonamide antibiotics and organic iodine (AOI) removal efficiencies for the following tertiary treatment systems:

a. Conventional SAT- Conventional Activated Sludge effluent (CAS) + long SAT

b. CAS-UF-short SAT (EU RECLAIM WATER project[2])

c. CAS - Short SAT-NF (EU SWITCH project[1])

d. CAS-UF-RO

All secondary effluent data (CAS Shafdan) relate to 4 years' (2007-2010) average taking into account that the EU RECLAIM WATER project[2] experiments were performed during 2007 and the EU SWITCH project[1] experiments were performed during 2009-2010. The results obtained within the framework of EU RECLAIM WATER project[2] included analysis at a specific well (D9) in the conventional SAT (CAS + long SAT). From Table 6 it can be seen that higher than 100 ng concentrations for sulfamethoxazole were obtained even after long SAT process. The UF as pretreatment to SAT and the subsequent short term SAT did not effectively removed the sulfamethoxazole. The short SAT-NF method produced a water quality comparable to UF-RO by almost completely removing the micropollutants.

Table 7 - Comparison of third line water quality (conventional 6-12 month retention time SAT) with short SAT (one month retention time) NF-270 or NF-90 filtered water quality

Parameter	Units	Third line (Ashdod jncn)	NF-90	NF-270				
Cl	mg/l	250-290	57	284		259	263	260
Ca	mg/l	80-100	2	76.8		74.4	76.8	80
COD	mg/l	3-5		3	2	2	<2	3
COD (f)	mg/l	2-3	< 2.0	< 2.0		2	<2	
DOC	mg/l	0.6-0.8	<0.2	0.3	0.2	0.2	0.3	0.2
EC	μmhos/cm	1395-1500	235	1399	1410	1284	1277	1294
Fe*	μg/l	25-30	17	18	22	10	21	33
Fe (f)*	μg/l	5-8	10	18	18	10	18	13
HARD as $CaCO_3$	mg/l	344-365	4	237.1		224.9	230.9	240.5
K	mg/l	12-15	4	14.8		12.8	11.8	12.5
Mg	mg/l	24-33	< 1.0	11		9.5	9.5	9.9
Mn*	μg/l	15-20	< 3.0	54	48	42	44	49
Mn(f)*	μg/l	5-10	< 3.0	42	44	31	44	48
Na	mg/l	152-200	40	187		176	171	170
NH_4	mg/l	< 0.03		0.14	0.09	< 0.03	0.03	0.33
NO_2	mg/l	< 0.01		0.51	0.11	0.03	0.01	0.14
NO_3	mg/l	4-5		< 1.0	< 1.0	4	<1	4
pH		7.3-8.0	6	7.9	7.75	7.72	7.48	7.4
PO_4	mg/l	0.02-0.03		0.01				0.03
Ptot	mg/l	0.02-0.04		< 0.03	< 0.03	< 0.03	<0.03	<0.03
SO_4	mg/l	76-91	< 1.0	9		5	na	7
TDS	mg/l	815	106	755	721	707	718	687
UV 254 Abs.	$cm^{-1}x10^3$	23-30	2	7	7	5	6	7

* Due to dissolution of iron and manganese (anaerobic conditions) during the short SAT passage the values are higher in the entrance of the membranes after the short SAT

Table 8 - Comparison of antibiotic and AOI concentrations in different hybrid SAT –membrane treatments in Shafdan WWTP (short SAT-NF results are for NF-270 only)

Micropollutants / Process	Unit	CAS (Shafdan)	CAS+long SAT (conventional)**	CAS+ UF +RO (desalination)	CAS+ short SAT +NF (SWITCH)*	CAS+UF + short SAT (RECLAIM)*
Clarithromycin	ng/L	39-500	0-61	<10-25	<10-25	<10-25
Erythromycin -H_2O	ng/L	93-594	0-43	<10-25	<10-25	<10-25
Roxythromycin	ng/L	55-787	0-108	<10-25	<10-25	0-118
Sulfamethoxazole	ng/L	173-657	10-363	<1-5	0-43	24-120
Sulfamethazine	ng/L	<1-5	<1-5	<1-5	<1-5	<1-5
Trimethoprim	ng/L	62-349	0-18	<1-5	<1-5	<1-5
AOI	μg/L	13-42	11-12.6	-	0.6-3.5	13-22.7
DOC	mg/L	9.8-13.8	0.5-0.6	0.1-0.3	0.2-0.3	1.6-2.3

*After one year infiltration. The analyses results relate to 30-35 days retention time in the aquifer
**After 30 years infiltration. The analyses results relate to 300 days retention time in the aquifer
Note: German recommendation for maximum allowable concentrations of antibiotics in drinking water is 100 ng/l

Innovative features:

The importance of removal of micropollutants in drinking water and reclaimed unrestricted irrigation water is increasing more and more as new detection methods with lower level of detection are available. Of major concern are the endocrine disruptors, antibiotics and pharmaceuticals. The EU SWITCH project[1] is part of recently checked hybrid SAT treatments - membranes and SAT combination (Sharma et. al, 2009) to give an answer to these problems and at the same time reduce the GHG emissions (smaller carbon footprint) as compared to the UF-RO systems. This study clearly shows that SAT pretreatment followed by NF would be an effective technology for water reuse applications.

There are few open questions to be better investigated:

1. Can a relatively small (around 700 m^2 surface area and 10-15 m. depth) SAT soil core (in the case of Shafdan SAT-NF pilot where the aquifer was very high) with a high organic loading be effective on the long run? Although 1-2 years of 4-5 m/d loading of Shafdan effluents which is equal to 10 years loading of the current SAT (1 m/d) did not show any adverse effect. This has still to be checked.

2. Can a feasible pretreatment to the SAT effluent be designed before reaching the nanofilter, in order to prevent inorganic fouling? This also has to be further optimized.

If the solutions to the above questions can be found a short SAT system which can be almost an isolated core of soil (by wells over pumping around the chosen 15-20 m. radius area) can be used as a natural bioreactor (and still conform the non-pollution of the natural water courses that the EU requires). This bioreactor comes before NF polishing, to remove organic matter, ammonia and phosphates, particulate matter and microorganisms better than UF pretreatment applied in RO systems for effluent reuse in indirect drinking water purposes.

10. CAPITAL AND OPERATIONAL COSTS FOR A TYPICAL INFILTRATION FIELD AND DISTRIBUTION LINE

10.1 Capital costs, O&M, labor, energy calculations

1. If an area **A** m^2 for only SAT infiltration is available the total area needed for planning the whole system, including infrastructure, is **2A** and the hydrological area under the SAT (Vadose Zone) will be **10 A** to a **60 - 100 m** depth.
2. **345 €/m**. pipe for 36-44" SS pipe and **862 €/m**. pipe for 70" cement coated SS pipes.
3. **Useful Life: 40 years** for piping, for cement and infiltration ponds for the SAT system. **15 years** for pumping stations

a. For a 20 Mm^3/yr infiltration field that was operated in 2003, including excavation equipment, sand replacement, pipe - lines, electro-mechanical parts, valves, pumps. **0.2 €/m^3** effluent treated.

b. 15 years return on investment on pumping stations and wells and **40 years** for piping and infiltration fields. The total cost of **0.23 -0.25 €/m^3** will be divided **30% investment 70% labor and operation maintenance costs**.

c. Operation and maintenance for infiltration (including treatment for the clogging problem), recovery and distribution would cost **0.1 - 0.15 €/m^3**

d. Labor: For 140 Mm^3/yr for Dan Project In the distribution system 5 people in direct contact with the end – users. For the SAT system one field person, 2-3 in the controlled room, 1-2 for field cleaning, for O & M, 2 -3 man for mechanical and 1-2 man for electrical , for distribution system another 10 persons for different O & M all this does not include the administrative staff and engineers that can put the whole project manpower to almost 70 .

e. Energy consumption: 4 W - hr m^3/m head Total energy for secondary WWT, SAT, extraction and for distribution **1.42 kWhr/m^3.** The SAT system does not generate any sludge. No chemicals are used.

10.2 Capital and O&M costs for an SAT system (infiltration field and distribution line)

The operation and maintenance cost of an infiltration site including the distribution system for recovered tertiary effluents for agricultural irrigation is given below for the **YAVNE 4** site (Shafdan) that is a very new site (Cikurel and Aharoni, 2006).

The purpose for constructing this new infiltration field was the inability to treat 130 Mm^3/yr of effluents in the existing infiltration fields due to clogging that slow down the infiltration rate during the 25years operation of the fields.

The **cost of reclaimed water including infiltration** is about **0.21 –0.25 €/m^3**, to which the cost of storage and conveyance (DISTRIBUTION) to the irrigation points in the south in the case of the Third Line needs to be added (**0.23-0.25 €/m^3**). Thus the total cost for reclaimed water is about **0.45-0.50 /€m^3**.

These costs include the following 5 stages:

2. The pumping system and effluent carrying pipe -lines to the infiltration fields
3. The infiltration fields and SAT system
4. The recovery system
5. The main distribution and storage system (with all seasonal and daily operative reservoirs)
6. The pumping system after the reservoirs and the distribution system to end – users.

Operational Reservoirs: 150, 000 m^3 cost 1 Million **€** (not including the land price and indemnities for the growers). In hilly regions the cost is 2 –3 times more expensive. Construction in regions based on clay soils is more expensive than loess soils.

The cost of reclaimed water including infiltration and distribution to the storage reservoirs is about – 0.21 0.25 **€**/m^3 not including the secondary wastewater treatment.

Energy use: For every m^3 of effluent pumped to 1 m. electrical power consumption is: **4 W-hr**. not included loses.

Effect of weather conditions: Serious decrease of infiltration velocity affected by rainfall.

Investment and operational costs: Example for a new infiltration field: YAVNE 4

The mass balance in (2003) before the operation of the YAVNE 4 field was:

1. Raw wastewater treated in the secondary system: 122 Mm^3/yr
2. Sludge disposed 5 Mm^3/yr
3. .Available for SAT 117 Mm^3/yr
4. Alternative disposal due to infiltration constraint 9 Mm^3/yr
5. Total effluents pumped to SAT system 108 Mm^3/yr
6. Total recovered effluents 127.9 Mm^3/y

After the new YAVNE 4 infiltration field for 20 Mm^3/yr was constructed at this stage only 5 Mm^3/yr of effluents are still not reused since only 15 Mm^3/yr are recovered through YAVNE 4 system bringing the recovered water amount to 135 – 140 Mm^3/yr.

This is true for the following hydro – geological conditions.

"East - west section across the Yavne recharge basins. The aquifer is made of calcarenite with alternating units of sand, loams and clays (marked). The aquifer overlies a thick shale sequence, which forms its base".

From "Short description on the Hydrogeology in the Shafdan Reclaim area” Prepared by Dr. Joseph Guttman Chief Hydrologist Mekorot **YAVNE 4 reservoir general data**:

• Land area requirement for infiltration: 340,000 m^2. Out of it, 47% or 160,000 m^2 net area (without the infrastructure around the fields).

•SAT system water production capacity: 20 Mm^3/yr

•Single recovery well production capacity: 1.75 Mm^3/yr

•Pipe line total length:

From Pump station 7 (Main pipe – line): 3 km. to Yavne 2 and 3 junction, 44" and to the fields 4km. 36" Pipes stainless steel 316. Another 3 km. is taken for topography and internal lines.

COST: Piping - 2000 NIS (or as 5 NIS/EU) 400 **€** /m or on the total 3.5 M **€** piping

Pumping station for 20Mm^3/yr - 1.72 M **€**

11. CASE STUDIES FOR SAT SYSTEMS

Different large/medium scale (>2000 m^3/d) water reuse projects using SAT around the world are given in Table 9.

Table 9 - Large/medium scale (>2,000 m3/d) water reuse projects using SAT around the world (Cikurel and Aharoni, 2006)

Location	Size (m^3/d)	End-use	Start up and end of project	Comments/referemces
Shafdan, Israel	330,000	Unrestricted irrigation	1977	Surface infiltration of secondary effluents Retention times 3-12 months
Water Campus, Scottsdale, Arizona, USA	108,000	Indirect potable recharge and unrestricted irrigation	2002 (extention 2008-2012	The process based on MF/RO and AOP (lately added) and vadose zone well infiltration
Mesa, Arizona USA	12,000	Indirect potable recharge	1990	Retention times several days to 5 years
West Basin, California, USA	30,000	Ground water recharge for salt intrusion	1997	Deep bed infiltration of RO prefiltered and AOP polished effluents

The Shafdan reuse project using SAT since 1977 is the biggest SAT project in the world (more than 350,000 m^3 /d) and the abstracted water are used in agricultural irrigation in the South of the country.

In the USA the Mesa Northwest Water Reclamation Plant Arizona, has recharge basins that receive nitrified/denitrified effluent with low dissolved organic carbon and the vadose zone is negligible. As mentioned in Table 9 the retention time in the aquifer varies from several days to 5 years in some places. The water is reused mainly for non-potable purposes.

Other Artificial recharge for indirect potable reuse in the United States of America are West Basin and Orange County, CA; Mesa and Tucson in AZ. Details can be found in (Asano, 1998), Bixio and Wintgens,

(2006) and Cikurel and Aharoni (2006) . The recharge should not degrade the quality of the groundwater nor impose any additional treatment after pumping.

In the US new vadose zone infiltration systems using advanced (MF-RO-AOP) technology are being developed the last decade (starting in 2005). As mentioned in Chapter 2 this technology is useful in cases where the available land for infiltration is scares and expensive, it is advantageous to pre-treat the effluents to a high purity degree and to infiltrate the water in the vadose zone. In Phoenix city and Scottsdale, Arizona such projects are being developed. In Scottsdale, Arizona, when completed in 2012, the system will treat up to 108,000 m^3 /d. More details are given in Chapter 11.2 (Water World, 2011; Marsh, 2008; Luria et al., 2009; Nunez and Mata, 2009)

11.1 Dan Region water reclamation scheme, Israel – Infiltration basins

Israel is a semi-arid country with a long history of water reclamation. It started in the 70's with the Dan Region Project (Shafdan) that over the years expanded into other reuse projects. Currently over 75% of municipal wastewater effluent is reused for irrigation. The Dan Region Reclamation Project (Shafdan) is the largest wastewater treatment and reclamation project in Israel. Today it treats and reclaims more than 130 Mm^3/yr of wastewater from the Tel-Aviv Metropolitan area and several other neighboring municipalities (2 million p.e.). The Shafdan WWTP is operated by Mekorot, treats the sewage by mechanical – biological process with single – stage simultaneous nitrification – denitrification. The good quality secondary effluents (see table 11) are further refined by a tertiary treatment using the classical Soil-Aquifer Treatment (SAT) technology (infiltration of the secondary effluents in open fields while each field receives effluent over 24 hrs. then rests for 48 hrs). High quality water is reclaimed by pumping from the aquifer after 6-12 months retention time. The water produced by this technology is used for unrestricted irrigation in agriculture in the south of Israel (Negev), enabling the country’s economic development (Aharoni et al., 2010).

<u>Historical background</u> (Cikurel & Aharoni, 2011)

The Shafdan Wastewater Treatment Plant (WWTP) is located on the sand dune ridges near the town of Rishon – Le Zion, on the South of Tel-Aviv on the sand dunes of Soreq near the town of Rishon – Le Zion. The biological treatment mode was chosen to be oxidation ponds.

In 1972 the first ponds were ready to receive 20 Mm^3/yr wastewater (out of 80 Mm^3/yr produced that year). Since the beginning of operation, the wastewater has been treated biologically in re-circulated facultative oxidation ponds (Figure 27), followed by high pH lime-magnesium chemical treatment and final maturation in polishing ponds. But since the oxidation ponds required large surface area (200 hectares were required to treat the 20 Mm^3/yr of wastewater) planning for building a mechanical-biological activated sludge (MBAS) plant started mid 70's.

Figure 27 - Shafdan WWTP first oxidation ponds (Aharoni, 2007)

In 1977, in order to comply with the above - mentioned aims (proper disposal of effluents and replacing potable water being used for agricultural irrigation with treated effluent, thereby reclaim additional potable water for urban use) the recharge of the effluents into the regional aquifer was started. The construction of the first infiltration site (Soreq - was delayed due to the stiff opposition from the Major of Rishon Le-Zion, the city where the project was constructed at the end. A mechanical – biological activated sludge (MBAS) plant with nitrogen removal was put into operation in 1987 and was later expanded in 1996 (see Fig. 28).

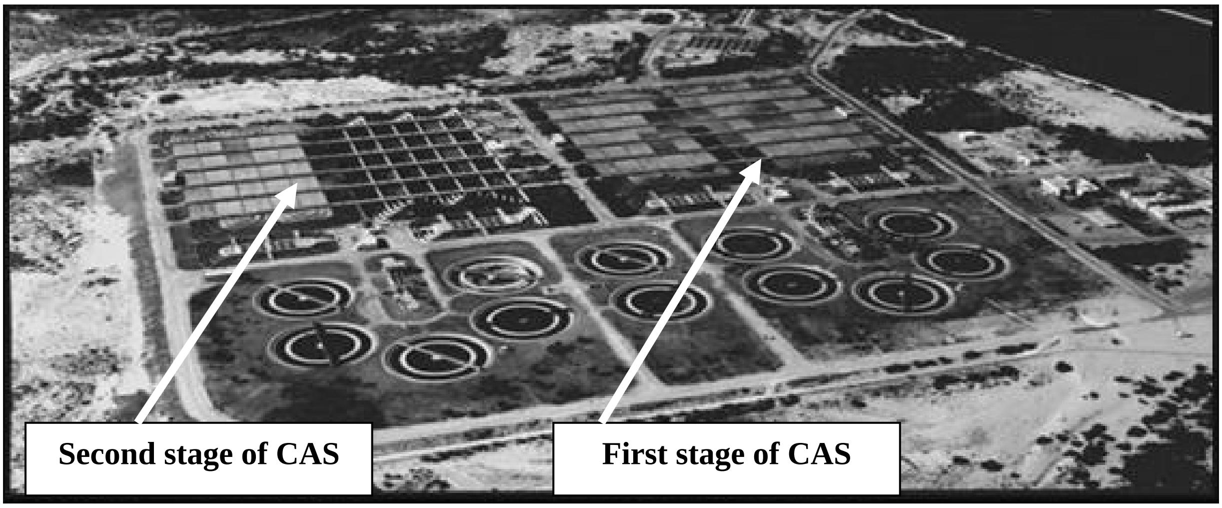


Figure 28: First stage of a modern conventional activated sludge (CAS) plant (1987) (Aharoni, 2007)

Until 1999, 7% of the wastewater was treated in the oxidation ponds. At the end of 1999, the system of recirculated oxidation ponds was closed and all the wastewater, 130 Mm^3/yr, is treated in the mechanical – biological plant. In 1987 Yavne 1 (Figure 29) and 1988 Yavne 2 infiltration fields were operated.

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In November 1989 the operation of the “Third Line” the distribution system for the soil aquifer treated effluent from the Dan Region WWTP was started. Since that time the reclaimed water of almost drinking water quality is used for unrestricted agricultural irrigation in the southern part of the country. In 1989 the magnesium treatment after oxidation ponds was terminated.

In 1996 the second stage of the MBAS plant was operated. At the same year the Yavne 3 fields were also operated to cope with the increasing available effluents for infiltration. With the operation of the second stage MBAS, in 1999, the operation of the oxidation and polishing ponds was stopped.

In response to ever increasing available secondary effluents for infiltration and gradual clogging tendencies in the existing infiltration fields, two additional sites (Yavne 4 in 2003 and Soreq 2 in 2006) were operated (see also Figure 13). Today 135 -140 million cubic meters per year (Mm^3/yr) are being treated by the SAT system. There are no more available infiltration fields due to growing population and housing construction around the available sites.

Figure 29 shows a typical recharge basin (Yavne 1) at the flooding (a) and drying period (b). The advanced treatment plant meets all the EC Drinking Water Directive’s limits.

The hydro-geological structure of the soil in the Yavne recharge basins area is characterized in Figure 27

(a) (b)

Figure 29 - Recharge basin during flooding period (a) and drying period (Idelovich, 2003)

Hydrogeology issues in planning and operating SAT system (The Shafdan Plant, Israel as an example)

For the recharge – reclamation operation, the Shafdan reclamation plant makes use of the coastal Quaternary sandstone aquifer that is one of the major freshwater resources of the country. The surface spreading infiltration basins are located in areas where the soil is mainly sand and sand-stone with some occasional clay lenses (Figure 30).

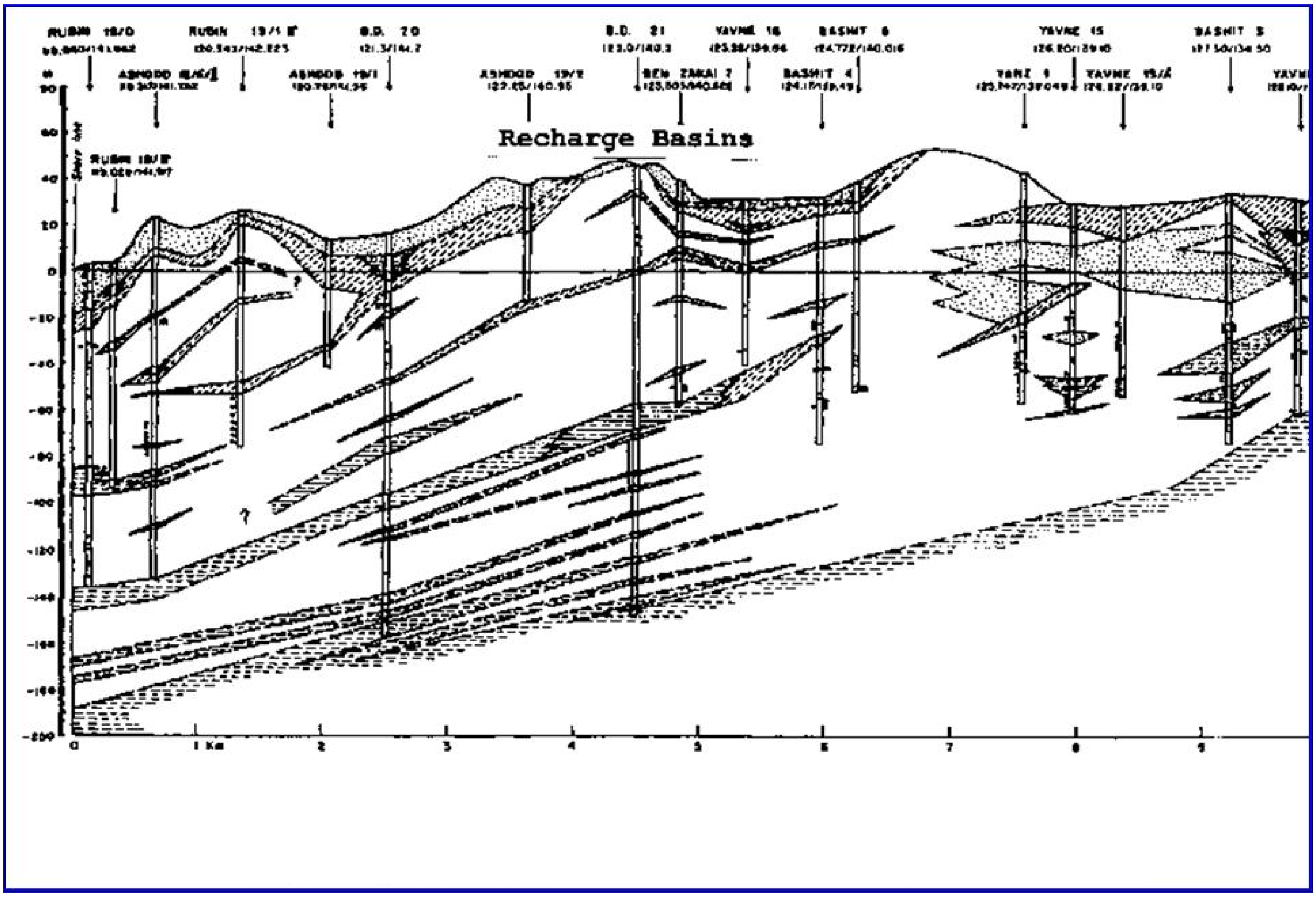

Figure 30– Geological cross-section through Yavne recharge basins (Aharoni, 2007)

The operating conditions for the Dan Region SAT system are given in Table 10

Table 10 Common operational parameters for SAT (Mekorot, 2004)

Parameter	**Units**	**Value**
Hydraulic loading	m/d	0.2 - 0.6+
Wetting cycles	days	1 - 7
Drying cycles	days	2 - 7
Cleaning cycle	days	< 15 - > 30
Retention time in ground	months	< 6 - > 12
Depth to ground water	m.	5 - 30 (max. 100)
Recovery	%	up to 100 %

Typical sewage water, secondary effluent and SAT recovered water quality is given in Table 11. For comparison to drinking water and unrestricted irrigation water quality (Inbar committee) the Israeli standards are also mentioned.

Table 11 Shafdan -Secondary effluent and SAT recovered water quality as compared to unrestricted irrigation standards (Inbar Committee) and drinking water standards (Mekorot, 2009)

Parameter*	Unit	Raw sewage	Secondary effluents	After Conventional long SAT**	Drinking water std.	Inbar Committee Effluents for unrestricted irrigation std.
TSS	mg/l	424	6	0.5		10
BOD	mg/l	407	7	<0.5		10
COD	mg/l	896	43	4		100
DOC	mg/l	86.3	10.6	0.8		
UV abs	$cm^{-1}10^3$	475	215	24		
Kjeldahl N	mg/l	66.4	5.3	0.3		25 (TN)
Ammonia as N	mg/l	44.1	3.7	0.005		20
Total Phosphorus	mg/l	11.4	1.1	0.04		5
Detergents	mg/l	3.1	<0.13	<0.1	1	2
Fe	µg/l	2327	77	27.8	1000	2000
Mn	µg/l	59	21	24.5	500	200
F. Coli	N/100 ml	9.5 E6	1.7 E4	0	0	10
T.Coli	N/100 ml	8.5 E7	2.6 E5	0	3	

* Based on 2009 annual average values
** After r.t. 6-12 months.Based on annual average values at Ashdod-Granot junction of the "Third Line"

It can be seen that at the main pumping station of the distribution line of the long term SAT treated water (the Third Line) at the Granot Junction the quality of water is suitable for drinking water purposes and largely surpasses the quality required for unrestricted agricultural irrigation (Inbar Committee Standards).

But the groundwater resources are fully utilized for many years due to many reasons (population growth, increasing in life standards, climate change, pollution etc.). The results are: Lowering in the water level in the aquifer and deterioration in the water quality (mainly increasing in the chloride and nitrate concentrations).

The full utilization of the aquifer as a result of lack of new infiltration areas and excess effluents that can not be treated and reused and flow to the sea were the main reasons to look for – dug well infiltration and shorter path SAT.

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For that purpose and also in order to reduce soluble manganese and micropollutants in the reclaimed water the above mentioned pretreatment to SAT (EU RECLAIM WATER project[2]) and post-treatment to SAT (EU SWITCH project[1]) and recently, sand filtration hydrogen-peroxide-ozone pretreatment before SAT (AOP –SAT project) technologies are being investigated.

11.2 Different SAT projects in the US leading to indirect potable reuse

a. Phoenix city, Arizona – Vadose Zone wells (Water World, 2011):

The greater Phoenix city, Arizona initiated in 2002 a comprehensive Water Resources Master Plan with the goal of determining future water demands and the resources needed to meet those demands. Treated effluent from the city's wastewater treatment plants were to be reused for irrigation or recharged to enrich the aquifer and fresh water saved. Since the excess water that was not used for direct irrigation had to be infiltered, the surface infiltration would be an expensive option considering the area occupied by these basins and cost of land in Arizona. Additionally, the recharge basins have low infiltration rates resulting from soil plugging due to total suspended solids composed mainly of organic materials. As a result, the city looked for an alternative recharge method to handle the added effluent capacity. In 2005, a technology called the **vadose zone recharge system** was proposed by Lockwood, Andrews & Newnam Inc. (LAN), a planning, engineering and program management firm and Hydro Systems Inc. (HSI), a firm specializing in groundwater recharge and other hydrogeologic applications to help achieve the city's water resource management goals. The technology, which works like a condensed drainage pit, uses a cluster of specially designed wells installed in the unsaturated zone of sand and gravel material above the groundwater table, commonly known as the vadose zone. Reclaimed water, treated to Class A^+ quality levels using advanced filtration methods (special stainless steel mesh screen down to 5 micron filtration capacity), is pumped into the wells and percolates through the clay, sand, gravel and silt layers laterally and vertically into the groundwater aquifer.

The vadose zone recharge technology takes less land area compared to other recharge methods.
To balance the volume of the reclaimed water coming out of the main WWTP and its subsequent recharge, the city decided to install the vadose zone wells in phases in conjunction with the expansion of the plant. Accordingly, the wells will be installed in four phases at two different locations in the city service area. The first location, which is adjacent to the WWTP, has an estimated recharge capacity of 40,000m^3/d of treated effluents and includes approximately 32 wells (see Figure 31). The first phase will consist of 15 wells and two subsequent phases will include 10 and seven wells, respectively. Other project elements include associated delivery pipelines, filtration systems, booster pump station modifications, and a control system.

The second location is approximately 6-7 km. from the WWTP with an estimated recharge capacity of 20,000m^3/d and will include approximately 21 recharge wells.

In September 2006, after studying the local geology and the groundwater flow direction at the two sites, the project team designed the recharge wells according to the site-specific soil and subsurface geologic conditions to enhance the flow-rate of the recharged water

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Figure 31 –Vadose zone wells in Maricopa County, Phoenix, Arizona (Water World, 2011)

Each well (see Figure 32) is 1.2 m. in diameter and drilled to approximately 55 m. The depth of groundwater in the city of Surprise normally ranges from 90 to 150 m. This means water from the recharge wells permeate through more than 35 m. of sand, clay, gravel and silt before it reaches the groundwater aquifer, thereby becoming further purified through natural soil percolation.

To achieve economy of space, the wells were placed in a rectangular formation with wells spaced just 100 feet apart from each other. This allows the wells to be tested individually or in clusters, based on which design or operational modifications can be made if required.

The footprint of a vadose zone recharge well is so small that an entire group of wells can be accommodated in a few acres compared to several acres that will be needed for recharge basins.

.A major issue that the design team had to address during the project was the quality of the water that will be recharged. While vadose zone recharge wells are less land-intensive and economical, they cannot be rehabilitated like other recharge technologies and therefore well lifespan is estimated to be only around five to 10 years. Consequently, the water being recharged into the wells has to be filtered to a very high level to prevent clogging due to particulates such as total suspended solids (TSS) and total organic carbons (TOC). In addition to slowing down the infiltration rates, these solid organic materials also affect the life of a well.

The biggest challenge in most cases is the microbiology and biological clogging caused by microorganisms. One of the things that were found was that typical reclaimed water has a high load of nutrients and this allows the bacteria already in the soil to flourish. So, disinfection and filtration at the surface helps to ensure that the water injected into these wells is of a very high quality.

To increase the longevity and productivity of the wells, the project team evaluated and recommended an innovative filtration system for subsequent phases of the project. This filtration system, which has a 98 percent sediment removal efficiency (AFR Series-8 internal back flushing filter from Eaton Filtration of Portage, MI), used a **stainless steel mesh screen** to filter the TSS, TOC and other organic material down to five microns. The construction of the first phase of the project, estimated to cost approximately $5.25 million.

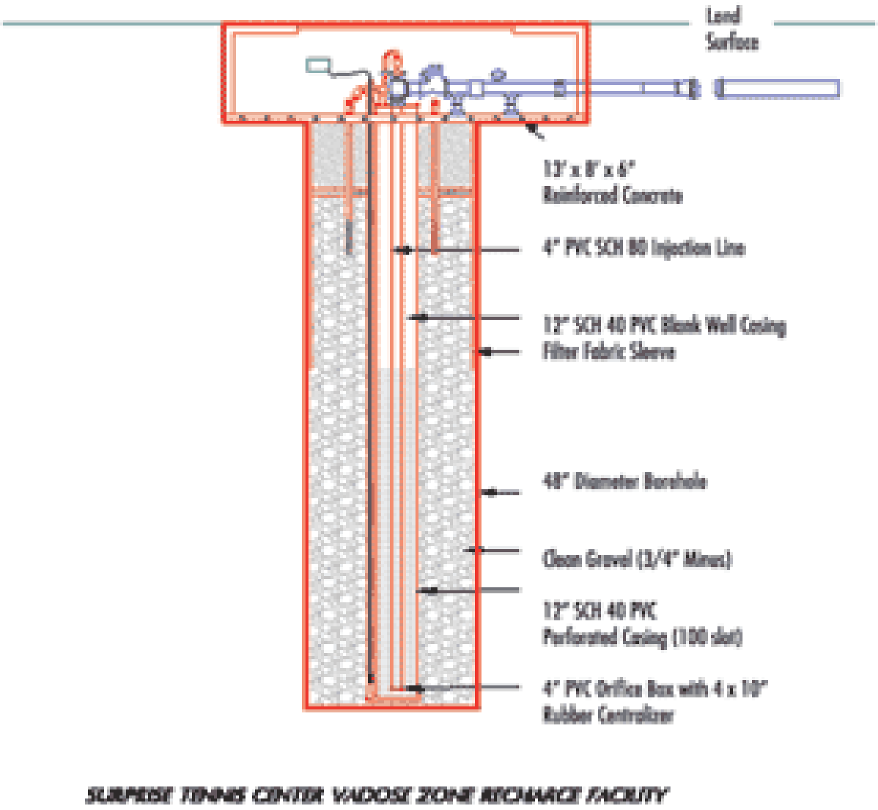

Figure 32 – Vadose zone well design (Water World, 2011)

b. Scottsdale Water Campus advanced water treatment (AWT) facility:
(Marsh, 2008; Luria et al., 2009; Nunez and Mata, 2009)

The City of Scottsdale is currently conducting conceptual design efforts for the expansion of the Water Campus Advanced Water Treatment (AWT) Facility (Figure 30) to be followed by full design and construction of the expanded facility (Marsh 2008). The expansion will increase reliable capacity of the AWT from approximately 8 MGD (32,000 m^3 /d) to 27 MGD (108,000 m^3 /d). The expansion will also **include additional vadose zone recharge wells** and an **advanced oxidation process to address compounds of potential concern**.

This project is split into three phases:

1. The first phase consists of the conceptual efforts to determine the most cost effective means to approach the AWT expansion, with the final product being a Conceptual Design Report expected to be completed in the summer of 2009.
2. The second phase of the project will encompass full design of the expanded facility expected to be completed late in 2009. The third phase of the project is the construction of the expanded facility which is anticipated to reach substantial completion in the 2011 / 2012 time frame.

The City's primary Water Reclamation Plant (WRP) located at the Water Campus provides state-of-the-art technology to treat wastewater generated in North and Central Scottsdale for irrigation of turf, primarily golf courses associated with the City's Reclaimed Water Distribution System (RWDS). The WRP process includes Nitrification – Denitrification followed by tertiary treatment and disinfection which provides Class A^+ reclaimed water, as defined by the Arizona Department of Environmental Quality (ADEQ).
The City also conducts groundwater recharge at the Water Campus as part of the water supply program. The primary source water for this effort is Class A^+ reclaimed water from the WRP further treated through the Advanced Water Treatment (AWT) Plant (Figure 33) which is also located at the Water Campus. The AWT consist of **microfiltration, reverse osmosis, post treatment stabilization and vadose zone recharge wells**.

Figure 33 – Scottsdale Water Campus wastewater reuse project (Nunez and Mata, 2009)

The 2008 Wastewater Master Plan for the City of Scottsdale recommended increasing the capacity of the AWT to meet increased flow demands generated by growth and inflow and infiltration related to storm events. The City is also considering treatment technology beyond what is currently implemented at the

Water Campus to address recently identified compounds of potential concern (CPC) that can impact the quality of groundwater due to recharge. In addition, the RWDS golf course users have approached the City expressing a desire to change the water quality characteristics of the reclaimed water they receive.
The primary characteristic change involves a reduced sodium level of less than 125 mg/l. This reduction can be achieved through the AWT process.

The Current AWT Facility is comprised of the following components:

• **Flow Equalization** A seven million gallon reservoir (Reservoir B) provides reclaimed water storage volume for diurnal flow equalization prior to the AWT Facility.

• **Microfiltration** - Seven vertical turbine pumps piped in parallel with automatic backwash strainers provide feed pressure to 24 - **90M10C Memcor** continuous microfiltration (CMF) units. There is space for an additional 3 pumps. Installed pumping capacity is 40 MGD (160,000 m^3 /d) with a firm capacity at 33 MGD (132,000 m^3 /d). The current CMF units implement hollow fiber polypropylene modules with a pore size of approximately 0.2 microns. Maintaining the original CMF design capacity of 16MGD (64,000 m^3 /d) has not been possible due to redundancy issues, ancillary equipment limitations, and the membranes approaching the end of their useful life. The original membranes have been in service for approximately nine years and the maximum operating flux has declined. The current reliable capacity has been identified at approximately 8 MGD (32,000 m^3 /d). Five vertical turbine pumps transfer microfiltration filtrate to the high-pressure RO pumps. Installed pumping capacity is 27 MGD (108,000 m^3 /d) with a firm capacity of 18 MGD (72,000 m^3 /d).

• **Reverse Osmosis (RO) -** The RO system consists of chemical addition, cartridge filters, 14 high - pressure feed pumps, a clean-in-place system and 14 separate skids. The RO skids consist of 8-inch thin film composite membranes with 10 configured in a 24 x 10 x 5 array and 4 configured in a 20 x10 x 5 array. At the design flux of 10.6 GFD, the installed feed capacity is 14 MGD (56,000 m^3 /d) at 85% recovery to produce approximately 12 MGD (48,000 m^3 /d) of permeate. The existing 14 racks occupy all available space within the RO building. Concentrate flow from the RO system is conveyed from the facility in a dedicated line and ultimately disposed of in the sanitary sewer.
Advances in membrane technologies along with pilot studies and research suggest current expansion needs for the CMF and RO systems can be achieved within their current foot print.

• **Post Treatment** - Post treatment of RO product water includes de-carbonation followed by lime addition for product water stabilization.

• **Product Water Pump Station**

Four vertical turbine pumps deliver stabilized product water to the **vadose zone recharge well** system. Installed pumping capacity is 27 MGD (108,000 m^3/d) with a firm capacity of 17 MGD (68,000 m^3/d).

[1]**EU SWITCH Project -"S**ustainable **W**ater management **I**mproves **T**omorrows' **C**ities **H**ealth", FP6 EU research Program No. 018530 (2006-20011)

[2]**EU RECLAIM WATER Project** -Water Reclamation Technologies for Safe Artificial Ground Recharge", FP6 EU research Program No. 018309 (2005-2008)

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