TREATMENT OF DOMESTIC WASTEWATER USING SOIL AQUIFER TREATMENT SYSTEM

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ABSTRACT

TREATMENT OF DOMESTIC WASTEWATER USING SOIL AQUIFER TREATMENT SYSTEM

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Soil Aquifer Treatment (SAT) has been used as a viable alternative for wastewater reclamation and reuse. In this study, three soil columns are used to simulate SAT process performance. System inputs are: hydraulic loading rate, infiltration rate, aeration and system outputs are removal of Dissolved Organic Carbon, Chemical Oxygen Demand, Ammonia, Nitrite, Nitrate and Total Phosphorus. Hydraulic state of the soils is observed by measuring soil water potential with tensiometer/manometer setup. Dissolved oxygen concentration through the column profile and topsoil total organic content are measured to observe biological activity. The soils are artificially prepared by using sand and the soil sample taken from Gölbaşı, Ankara. Primary and secondary wastewater are influents of the study.

Primary step of the study is ripening of the soil columns. Primary and synthetic wastewater are used for this purpose. Second step is implementation of three different operational schedules: 7 d wetting/ 7 d drying, 3 d wetting/ 4 d drying cycles and slow rate infiltration. SCL and LS soils remove COD more efficiently in 3 d wetting/ 4 d drying cycles compared to slow rate infiltration. COD removal performances of the columns were observed to decrease significantly when COD concentration of influent wastewater decreased to 25 mg/l or lower values. 7 d wetting/ 7 d drying cycles have higher nitrate removal efficiencies compared to 3 d wetting/ 4 d drying cycles. LS and SL had better TP removal efficiencies compared to SCL under all of the operation conditions during this study.

Keywords: SAT, wastewater reuse, vadose zone, treatment, organics, nitrogen, phosphorus.

ÖZ

EVSEL ATIKSUYUN TOPRAK AKİFER ARITIM SİSTEMİ İLE ARITILMASI

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Toprak Akifer Arıtım Sistemi (TAAS) atıksuyun iyileştirilmesi ve yeniden kullanılmasında uygulanabilir bir seçenek olarak kullanılmaktadır. Bu çalışmada üç adet toprak kolonu TAAS'nin proses performansını simüle etmek için kullanılmıştır. Bu çalışmadaki sistem girdileri: hidrolik yükleme hızı ve havalandırma iken sistem çıktıları infiltrasyon hızı; Çözünmüş Organik Karbon, Kimyasal Oksijen İhtiyacı, Amonyak, Nitrit, Nitrat ve Toplam Fosfor giderimleridir. Toprakların hidrolik durumu ise topraktaki su basıncının tensiyometre/manometer düzeneğiyle ölçülmesi sonucunda belirlenmektedir. Kolon profilindeki Çözünmüş Oksijen ve üst topraktaki toplam organik içerik ölçülerek biyolojik etkinlik izlenmiştir. Kolonlarda kullanılan topraklar kum ve Ankara Gölbaşı'ndan alınan ince bünyeli toprak örneği karıştırılarak hazırlanmıştır. Çalışmada giriş suyu olarak birincil ve ikincil arıtım çıkış suları kullanılmıştır. Çalışmanın ilk basamağı toprak kolonların olgunlaştırılmasıdır. Birincil ve sentetik atıksu bu amaçla kullanılmıştır. İkinci basamak ise üç değişik işletim programının uygulanmasıdır: 7 gün ıslak/7 gün kuru, 3 gün ıslak/4 gün kuru döngüleri ve düşük hızlı infiltrasyon. SCL ve LS toprakları Kimyasal Oksijen İhtiyacı gideriminde 3 gün ıslak/ 4 kuru döngüleri sırasında düşük hızlı infiltrasyona oranla daha yüksek verim sağlamışlardır. Giriş suyunun Kimyasal Oksijen İhtiyacı 25 mg/l'nin altına düştüğünde kolonların Kimyasal Oksijen İhtiyacı giderim verimlerinin önemli oranda azaldığı gözlemlenmiştir. 7 gün ıslak/7 gün kuru döngüleri, 3 gün ıslak/4 gün kuru döngülerine oranla daha yüksek nitrat giderimi sağlamıştır. LS ve SL toprakları SCL toprağına oranla daha yüksek oranda toplam fosfor gidermiştir.

Anahtar Sözcükler: Toprak Akifer Arıtımı, atıksu geri kullanımı, vadoz zonu, arıtım, organikler, azot, fosfor.

To

My Deceased Grandparents

&

The Citizens who have sheltered the Republic

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AOX	Adsorbable Organic Halide
ACWTP	Ankara Central Wastewater Treatment Plant
APEC	Alkylphenolpolyethoxcarboxylates
AWWA	American Water Works Association
AWWARF	American Water Works Association Research Foundation
BDOC	Biodegradable Dissolved Organic Carbon
BOD_5	5-day Biochemical Oxygen Demand
CBOD	Carbonaceous Biological Oxygen Demand
CEC	Cation Exchange Capacity
COD	Chemical Oxygen Demand
DBP	Disinfection By-Product
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
EDTA	Ethylenediaminetetraacetic Acid
EPA	The United States of America Environmental Protection Agency
EU	European Union
ϕ	Porosity

HAA	Haloacetic acid
LS	Loamy sand
MLVSS	Mixed Liquor Volatile Suspended Solids
NDC	Napthalenedicarboxylic Acids
NH_3	Ammonia
NH_3-N	Ammonia-Nitrogen
NH_4-N	Ammonium Nitrogen
NO_2^-	Nitrite
NO_2-N	Nitrite Nitrogen
$NO_3^=$	Nitrate
NO_3-N	Nitrate Nitrogen
NOM	Natural Organic Matter
NTA	Nitrilotriacetic Acid
Org-N	Organic Nitrogen
PO_4^{-3}	Phosphate
PO_4-P	Phosphate Phosphorus
PVC	Polyvinyl Chloride
ρ_b	Soil Bulk Density

ρ_s	Average Particle Density
SAR	Sodium Adsorption Ratio
SAT	Soil Aquifer Treatment
SCL	Sandy Clay Loam
SL	Sandy Loam
SS	Suspended Solids
TDS	Total Dissolved Solids
THM	Trihalomethane
THMFP	Trihalomethane Formation Potential
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TOX	Halogenated Organics
TP	Total Phosphorus
US	The United States of America
USDA	The United States of America Department of Agriculture
UV	Ultraviolet
UV-254	Ultraviolet Absorption at 254 nanometre wavelength
WHO	World Health Organization
WWTP	Wastewater Treatment Plant

CHAPTER 1

INTRODUCTION

1.1 OVERVIEW OF SOIL AQUIFER TREATMENT SYSTEM

Water scarcity is an important problem for semi-arid or arid regions of the Earth. Therefore, integrated water management options are very vital to have sustainable water supply and effective wastewater treatment in these regions. Wastewater reuse is a viable water resource alternative among fresh high-quality run-off, brackish water and treated wastewater (Oron, 1996). Wastewater reuse is defined as the use of treated wastewater, for a beneficial use such as agricultural irrigation or industrial cooling (Tchobanoglous and Burton, 1991). However, even advanced technologies for wastewater (nutrient removal, reverse osmosis, activated carbon) suffer from lack of scientific information on health effects when treated wastewater is reused to augment potable supplies. Appendix A provides a list for categories of municipal wastewater reuse and potential constraints. In regions with limited natural water sources, treated wastewater is a relatively stable water source and can be utilized for agriculture, industry, recreation, gardening, industrial plant cooling, and recharge of aquifers. Negative public and industrial perception of drinking and using reclaimed wastewater has also been prevalent. Advanced cooling, and recharge of aquifers. Negative public and industrial perception of drinking and using reclaimed wastewater has also been prevalent. Advanced technologies have high capital and operational costs, require educated operators, and generally are not well suited for developing countries. Therefore, natural treatment (e.g. land treatment) options are frequently considered as a solution for wastewater treatment, reclamation, recycle and reuse needs. Effectiveness of all classes of land disposal techniques is given in Appendix B (Arceivala, 1998).

Groundwater recharge is an inexpensive instrument used in wastewater reuse among other alternatives; it can be effective in groundwater replenishment, salt water intrusion and subsidence control. The other wastewater reuse alternatives can be seen in Appendix A. Intermittent flooding of the spreading basins, controlled passage of the effluent through unsaturated zone and a portion of the aquifer and its subsequent pumping by means of recovery wells surrounding the recharge area is called as SAT (Kanarek *et al.,* 1993). During SAT, treated wastewater infiltrates into the ground from surface spreading basins, percolates through the vadose zone, and eventually mixes with native ground water (Quanrud *et al., 1996).* Infiltration basins (SAT systems) are by far the most widely used methods for groundwater recharge and municipal waste removal (US EPA *et al.*, 1981). Because of the economical attractiveness and low cost maintenance, many SAT systems have been installed or in planning stages in US and other countries throughout the world. There are flourishing full-scale SAT projects of US, Israel, Germany since 1970s.

During SAT application, special attention is required for nitrogen if drinking water aquifers are involved. Unless special measures are employed, it is unlikely that drinking water levels for nitrate nitrogen (*10 mg/l*) can be routinely attained immediately beneath the application zone with typical municipal wastewaters. If special measures are not employed, there must then be sufficient mixing and dispersion with the native groundwater prior to downgradient extraction points.

In the more humid regions neither recovery nor reuse is typically considered. In these cases groundwater impacts can often be avoided by locating the SAT site adjacent to a surface water body. The quality of the subflow entering the surface water will generally exceed that of which could be produced by an advanced wastewater treatment plant (Crites *et al.*, 2000).

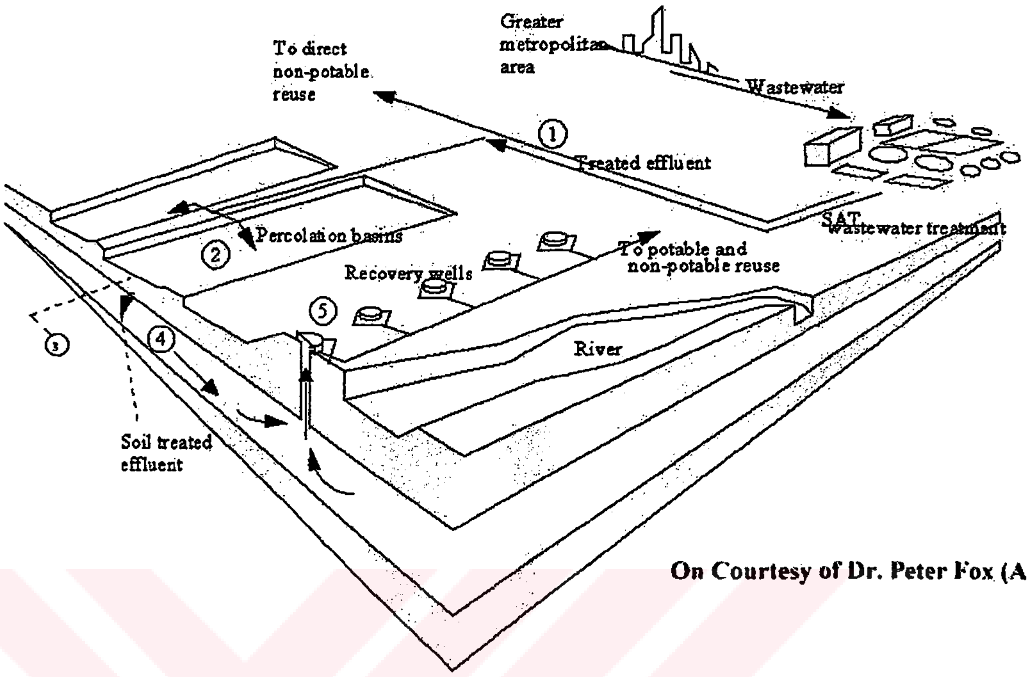
The main objective of SAT is secondary or tertiary wastewater treatment by removal of pollutants during flow through subsurface. Fate of the treated water can include (US EPA *et al.*, 1981):

1. Ground water recharge,
2. Recovery of renovated water by wells with subsequent reuse or discharge,
3. Recharge of surface streams by interception of ground water,
4. Temporary storage of renovated water in the aquifer.

High quality of reclaimed water obtained after SAT is suitable for a variety of non-potable uses such as unrestricted agricultural uses (including irrigation, livestock watering), industrial uses, non-potable municipal uses (such as lawn irrigation, and toilet flushing), and recreational uses. Other important functions of SAT system are: seasonal and multiannual storage, reliability, dilution, safety barrier and psychological effect (Kanarek *et al.,* 1993). A very important aspect of water reuse via artificial recharge of groundwater is that it also greatly enhances the aesthetics and public acceptance of water reuse, because the water has had SAT and it comes out of wells rather than out of the end of an advanced wastewater treatment if water is recycled with in-plant treatment only (Bouwer, 1996).

A SAT system consists of five major components: (1) pipeline that carries the treated effluent from the wastewater treatment plant; (2) percolation (infiltration) basins where the treated effluent infiltrates into the ground; (3) the soil immediately below the infiltration basins (vadose zone); (4) the aquifer where water is stored for a long duration; and (5) the recovery well where water is pumped from the aquifer for a potable or non-potable reuse (Fox *et al.*, 1998). A typical schematics of SAT application is shown in Figure 1.1.

It is observed that SAT systems can reasonably remove the following pollutants: organic species (DOC, COD, BOD_5, AOX, DOC, DBPs, HAAs, THMs), nitrogen species (NO_2^-, $NO_3^=$, NH_3), phosphorus, pathogens, enteroviruses, bacteriophages and trace metals (Kopchynski *et al.,* 1996; Kanarek *et al.,* 1993; Bouwer, 1996; Wilson *et al.*, 1995). On the other hand, SAT sites must be hydraulically confined because many xenobiotic organics have the capacity to penetrate into the depth of saturated zone and reach ground water (Bouwer *et al.,* 1984; Muszkat *et al.,* 1993); the organics, which have been successfully removed by land treatment, are given in Appendix C. The target pollutants studied in the literature are tabulated and given in Appendix D.



On Courtesy of Dr. Peter Fox (ASU/USA)

Figure 1.1: Typical SAT Application

The input variables of SAT include *soil type, water quality, operation conditions and aquifer characteristics*. The state of a SAT system is described by *soil moisture and concentration profile, level of oxygen, algal growth and soil hydraulic conductivity,* which controls the residence time of water and pollutants in the vadose zone and the level of microbial activity (Fox *et al.*, 1998). Several soil types were used in SAT studies: sand, sandy silt, silt, clay with low plasticity (Kopchynski *et al.,* 1996), sand, silt and clay (Wilson *et al.*, 1995), uniform fine sand (Idelovitch and Michail, 1984), loamy sand, poorly graded sand, poorly graded silty sand, silty sand (Quanrud *et al.*, 1996), cross-bedded sands and gravels usually cemented by gypsum and carbonates (Viswanathan *et al.*, 1999), poorly graded sand, poorly graded silty sand, silty sand, low plasticity clay (Fox *et al.*, 1998).

Effluent of various biological and physical-chemical processes are used in SAT systems; namely primary, secondary (e. g. activated sludge, pond processes and trickling filters) and tertiary wastewater (e. g. denitrified) with or without disinfection (e. g. chlorination and dechlorination) (Idelovitch, 1978; Bouwer *et al.*, 1974; Bouwer *et al.*, 1980; Wang *et al.,* 1981; Idelovitch and Michail, 1984; Amy *et al.,* 1993; Quanrud *et al.,* 1996; Fox *et al.*, 1998; Drewes and Fox, 1999; Viswanathan *et al.,* 1999; Westerhoff and Pinney, 2000; Reemtsma *et al.*, 2000; Fox *et al.*, 2000).

Operation of SAT system includes the following important items: wetting/drying cycles, schedule of pumping. During normal conditions, unsaturated soils contain pores filled by water and air. However, clogging layer development and reduced infiltration rates can dominate system performance. This is caused by the accumulation of biofilm, algae, and suspended solids reducing the void space. (Fox *et al.*, 1998). Continuous application of wastewater causes an intense clogging layer development, cease percolation and infiltration of the wastewater through the soil. Hence, wastewater is given to the systems intermittently. Wastewater is given to the infiltration basins during wetting period and wastewater application is stopped during drying period. Wetting and drying activities are cycled repeatedly; and this operation approach is called as *wetting/drying cycles*. Cycle times also influence the transport of oxygen with depth in the vadose zone. Therefore, cycle times may be critical for the control and efficiency of biological processes. Schedule of pumping is an important parameter that controls the mounding in the unsaturated aquifer; unsatisfactory pumping schedule results in mounding of the water table.

Environmental conditions include climatological factors, land slope suitability, land use suitability (Droste, 1997), vadose zones without restricting layers and absence of problem contamination zones (Bouwer, 1996). Application of wastewater to land is more subject to climatological factors than conventional treatment. Seasonal change in rainfall and temperature affect the rate at which wastewater can be applied to the soil. The design must take into account of wastewater generation rates against variable application rates throughout the year. Land properties include land slope suitability. SAT systems are most suitable for lands having 0-12 % slope, suitable for lands having 12-20 % slope and unsuitable for lands having more than 20 % slope. Open land or cropland is highly suitable for SAT application, partially forested land is moderately suitable, heavily forested land is less suitable and developed land is (residential, commercial, or industrial) least suitable (Droste, 1997). Vadose zones with restricting layers such as clay lenses or rock layers can impede vertical water movement, hence vadose zones without restricting layers are suitable for SAT application. Contaminated zones may be a source of contamination during SAT wastewater percolation during the operation; therefore, SAT site is required to lack problem contaminated zones. All of the above input variables have certain effects over the state of a SAT system. Studies on interactions between system variables of the SAT system are presently wide spread.

The major removal mechanisms in SAT systems include the following: filtration, biological degradation, physical adsorption, ion exchange and precipitation (Kopchynski, 1996). Kanarek *et al.* (1993) states additional removal mechanisms: nitrification, denitrification and disinfection. However, effects of the former mechanisms on pollutants degraded in SAT have not been explained fully and quantified explicitly. Moreover, denitrification of wastewater is an important problem in SAT system; complete denitrification can not be achieved due to lack of carbon source. Anoxic conditions prevail in the system and this may result in ammonia or nitrate spikes in the effluent of SAT system. (Bouwer *et al.,* 1974; Bouwer *et al.,* 1980; Idelovitch and Michail, 1984; Amy *et al.,* 1993; Fox *et al.,* 1998; Reemtsma *et al.*, 2000).

In some countries the main purpose of artificial ground water recharge is to increase ground water level in the coastal aquifer in order to prevent seawater from penetrating into the aquifer thereby increasing salinity (Rav-Acha *et al.,* 1996). However, SAT has more important objectives such as pollutant removal, as in several full-scale SAT implementations. Several full-scale projects have been undertaken in Arizona (USA) and Israel. For instance, the Dan Region Wastewater Reclamation Project, provides for collection, treatment, ground water recharge and reuse of the wastewater from the largest metropolitan area of Israel, which includes the city of Tel-Aviv-Jaffa and several other neighboring municipalities. The project serves a total population of about 1.3 million with an average municipal wastewater flow of 270,000 m^3/d. The Dan Region Project has two major objectives (Idelovitch, 1978):

a. To stop pollution of beaches in the Tel Aviv area resulting from wastewaters discharged into the Mediterranean Sea,
b. To recover large amounts of water in order to reduce the gap between the country's increasing water requirements and the limited capacity of its natural water resources.

1.2 SCOPE AND OBJECTIVES

1.2.1 SCOPE

Literature on SAT systems mainly comprise laboratory, field, modelling and optimization studies aspects of SAT system. This study focuses on laboratory scale operations under controlled conditions in order for better understanding of the SAT mechanisms. Soil columns are used to examine and assess behavior of SAT system under different hydrological conditions with different soil types. Three soil columns are constructed and these columns have *sandy clay loam, loamy sand* and *sandy loam*. Secondary wastewater is applied to the columns. The following pollution parameters are traced in the study: COD, DOC, ammonia nitrogen, nitrate nitrogen, nitrite nitrogen, total nitrogen and total phosphorus. Operation schedule of the SAT system includes different wetting/drying cycles (*7 days wetting/7 days drying, 3 days wetting/4 days drying*) and continuous wastewater application (slow-rate infiltration). Each operation schedule is applied to every column simultaneously. Sampling ports are located at varying depths of the three columns to have water samples at regular intervals. Samples are analysed to quantify the removal of pollution parameters. Tensiometers are located at varying depths of the columns to measure the soil-water potential. Volumetric water content distribution in the soil column is determined from moisture retention curves obtained for each soil type. The study firstly focuses on ripening and acclimation phases of the soil columns since the soil samples used in columns are not taken from a previously used SAT site. Therefore, the column soils are ripened and acclimated before SAT application. Effect of short-term primary and synthetic wastewater on ripening of the columns are observed. Removal efficiencies of the pollution parameters are measured and examined under the defined operational conditions. Nitrogen species, in particular nitrate is one of the most common reasons that groundwaters do not meet drinking standards (Fox *et al.*, 1998). Ammonia, nitrite, nitrate nitrogen and total nitrogen are measured so that development of nitrification, denitrification, ammonia adsorption and desorption can be followed at different depths of the soil columns.

DOC present in the recovered groundwater reacts with chlorine to form carcinogenic disinfection by-products (e.g. THMs) that are regulated by the US EPA; EU and WHO guidelines (Westerhoff and Pinney, 2000). DOC measurements are made to follow the ripening process of the soil because growth of microbial community results in degradation of DOC. Decrements of effluent DOC and infiltration rate decrement during the ripening phase indicates of microbial population. DOC removal, infiltration rate decrement and their relation with ripening of the soil columns are investigated and discussed in this study. COD is a commonly used parameter as an indicator for the pollution capacity of wastewaters; COD content of reclaimed wastewaters must meet regulations or standards. Developed countries have been successful in sustaining secondary treatment of wastewater; therefore, COD or BOD removal are not hot research topics there. However, developing countries have still deficiency of secondary treatment. Hence, BOD or COD removal is still a big concern. Idelovitch and Michail (1984) stated that in SAT systems, COD particulate removal efficiency is 100 %. While dissolved COD removal efficiency is given as 76 %. Viswanathan *et al.* (1999) reported a COD removal efficiency of 70 % in a pilot-scale SAT application. Recent laboratory scale SAT studies are concentrated on TOC and DOC removal efficiencies. In this study removal efficiencies of DOC, COD and total phosphorus are investigated under different operational conditions (i.e. wet/ dry cycles and continuous wastewater application).

Wetting/drying cycle and continuous wastewater application are two alternatives in SAT systems. Wetting/drying cycles can be useful both for prevention of topsoil clogging and provision of appropriate anaerobic conditions for denitrification of nitrate. Continuous wastewater application in SAT systems can be realised at relatively low hydraulic loading rates compared to SAT applications with wetting/drying cycle. Topsoil zones in the soil columns can be aerated continuously to aid nitrification process and deeper zones in the soil columns can be anaerobic to facilitate denitrification.

1.2.2 OBJECTIVES

The primary objectives of this study is given below:

1. Monitoring and assessing DOC, COD, NH_3, NO_2^-, $NO_3^=$, TP removal efficiencies. That is:

a. DOC removal efficiency of SAT during ripening phase,
b. COD removal efficiency of SAT during *3 d wetting/ 4 d drying cycles* and *slow rate infiltration,*
c. NO_2^-, $NO_3^=$, TP removal efficiencies of SAT during 7 d wetting/ 7 d drying cycles, 3 d wetting/ 4 d drying cycles and slow rate infiltration,
d. NH_3 removal efficiencies during 7 d wetting/ 7 d drying cycles and 3 d wetting/ 4 d drying cycles,

2. Establishing removal efficiencies as a function of soil types using three different soils; namely sandy clay loam (SCL), loamy sand (LS) and sandy loam (SL),

3. Comparing removal efficiencies of the pollutants during different SAT schedules: 7 d wetting/ 7 d drying cycles, 3 d wetting/ 4 d drying cycles and slow rate infiltration,

Other important objectives of the study are:

1. Determining hydraulic operational parameters of the soil columns in relation to removal efficiencies:

a. Hydraulic loading rates and outfluxes of the soil columns during the operational schedules,
b. Soil water potential measurement and volumetric water content calculation during slow rate infiltration,

2. Monitoring topsoil organic contents of the soil columns as an indicator of biofilm,

3. Effect of high/low DO on the removal efficiencies of the pollutants during 3 d wetting/ 4 d drying cycles through similar textured soils at a laboratory-scale SAT operation.

CHAPTER 2

LITERATURE SURVEY

2.1 SAT Process Dynamics

SAT has several processes involved in hydraulic behavior and pollutant removal. These processes and their interrelations during system operation are given in Figure 2.1. Soil type and operation schedule effects directly *soil moisture profile, algal growth* and *dissolved oxygen* in the system. Soil moisture profile effects infiltration rate; algal growth changes dissolved oxygen; and molecular oxygen in SAT water is used up during total organic carbon removal and nitrification (Fox *et al.,* 1998).

2.2 SAT POLLUTANT REMOVAL MECHANISMS

The ultimate goal of a ground water recharge project is to resupply the subsurface with water that does not impair the quality of the underlying resource. Thus, the role of the unsaturated or vadose zone in recharge systems is to help filter out or transform harmful constituents in the soil solution as recharge water moves through the soil matrix en route to the aquifer (Andelman *et al.*, 1994).

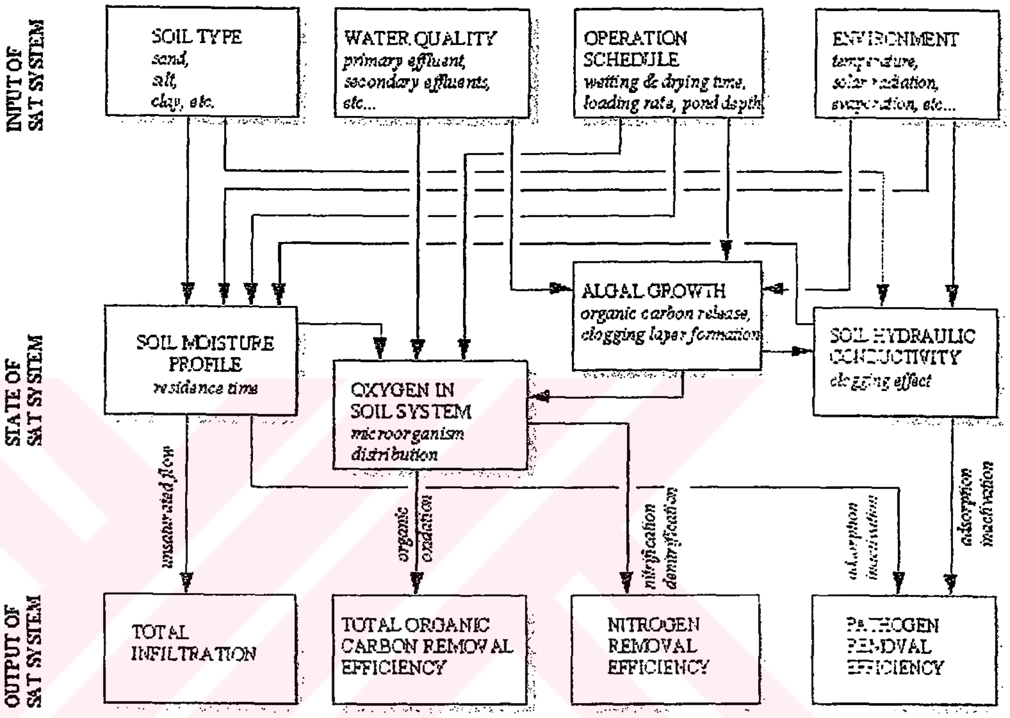


Figure 2.1: SAT Process Dynamics

The vadose zone is a much more complex transport medium than an aquifer, for several reasons. Because only part of the void space is filled with water, chemicals with a significant vapor pressure can move in the gas phase as well as in solution. The water flow rate can vary significantly. The resistance offered by the vadose zone to the flow of water through a given local soil volume is a nonlinear function of the water content, whereas in the saturated zone, it is a constant. The temperature varies in the surface regime in response to the cyclic inputs of radiant energy, and the composition of the air, solid, and solution phases of the soil is also dynamic, causing spatial and temporal variations in the chemical and biological reactions that transform chemicals in the vadose zone. Also, the amount of water retained against gravity varies significantly with soil texture. Coarse-textured, sandy soils may hold as little as *10 to 20 percent* of water-saturation after drainage becomes insignificant, while fine-textured silts or clays may hold up to *90 percent*. Restricting layers comprised of clay lenses or cementing agents can retard drainage greatly, even in otherwise permeable media. Soils that retain extensive water are prone to aeration problems (Andelman *et al.*, 1994).

There are many different processes that can remove chemicals or pathogens from the recharge water as it flows through the vadose zone. Some chemicals *volatilize* and escape to the atmosphere. They can be chemically or biologically transformed to a new form that may or may not be toxic. They can attach to stationary soil mineral or organic surfaces or *precipitate* out of solution. They can form complexes with dissolved constituents or particulate matter in solution, thereby reducing their attraction to the soil solid phase and enhancing their mobility in solution. Large pathogens such as parasites, some bacteria, and colloidal material containing contaminants can be *filtered* out of solution by narrow soil pores, a process that slowly clogs the medium and eventually reduces its permeability if the contaminants are not biodegraded. Viruses can be retained by soil solid phases and inactivated by reactions occurring in the soil (Andelman *et al.*, 1994).

Chemicals or pathogens that are still present in solution when the recharge water reaches the aquifer are subject to many of the same processes that occur in the vadose zone, with several exceptions. The biological activity in ground water is much slower than in the near-surface zone, so degradation is greatly reduced. Water fills all of the pore spaces within the ground water zone, so the only place where volatilization can occur is in the capillary fringe above the water table interface. Aquifers used for ground water recharge projects are generally much more coarse textured than soils, so colloids and large pathogens, should they still be present in ground water, are not as easily filtered out of solution as they are in surface soil (Andelman *et al.*, 1994).

Water quality improves from removal mechanisms in the soil that include *filtration, biological degradation, physical adsorption, ion exchange,* and *precipitation* (Kopchynski *et al.*, 1996). The major purification processes occurring in the SAT system are: *filtration, chemical precipitation/dissolution, organic biodegradation, nitrification, denitrification, disinfection, ion exchange,* and *adsorption/desorption* (Fox *et al.*, 1998). Then, the commonly accepted removal mechanisms of SAT can be given as follows:

a. Filtration,
b. Biological degradation,
c. Physical adsorption/desorption,
d. Ion exchange,
e. Chemical precipitation/dissolution,
f. Organic Biodegradation,
g. Nitrification,
h. Denitrification,

i. Disinfection.

The studies over critical pollutants and their removal mechanisms are still being conducted. However, the impact of the former removal mechanisms over the pollutants has not been explicitly determined explicitly yet.

2.3 LABORATORY SCALE AND PILOT SCALE SAT STUDIES

One of the recent extensive studies on laboratory and pilot scale SAT application is realised by Peter Fox and his colleagues in Arizona, USA (1998). This study provides important experimental findings and has well-designed experimental setup. Therefore, this study is described in detail in the latter part of Chapter 2. Soil characteristics, influent water quality characteristics and operating conditions of the soil columns are presented in Appendix E (Fox *et al.*, 1998).

2.3.1 SAT EXPERIMENTAL SETUPS AND THEIR OPERATION

Soil columns were used to show that they are good models of the field groundwater recharge system. They were previously used in various experiments with secondary effluent. In the study of Lance *et al.* (1980), the columns consisted of PVC pipes, *2.75 m* long and *15 cm* diameter packed with *loamy sand* from basins used for rapid infiltration of secondary wastewater effluent in the dry Salt River bed near Phoenix (Arizona, USA). Each column was filled with *6 cm* of pea gravel and *250 cm loamy* sand. The air-dried soil, which was *3 % clay, 8 % silt* and *89 % sand,* was packed so that bulk densities ranged from *1.5* to *1.7* g/cm^3. *An alternating schedule of 9 days of* *flooding with 5 days of drying was used for all experiments.* During the flooding period, 10 to 12 cm of water was ponded on the soil surface using a float that activated a pump by means of a solenoid switch. Common Bermuda grass (*Cynodon dactylon*) was planted in three columns and the other three columns remained bare. During all experiments, the wastewater and water drained from the columns were sampled daily and analyzed for NO_2-N, NO_3-N, NH_4-N and PO_4-P.

Fox *et al.* (1998) *used one-meter columns to investigate water quality transformation in detail.* Fourteen one-meter columns containing either repacked homogenized soils or intact soil cores were used. Columns consisted of 8.62-cm inner diameter acrylic tubes with a 0.64 cm wall thickness. Total column length was 130 cm; soil depth was 100 cm leaving a 30-cm headspace for ponding of effluent above the soil surface. Each column was equipped with a series of ports at multiple depths (2, 4, 6, 12, 34, 56, 78, 96, 98 cm) for the measurement of matric potential (via tensiometers), collection of liquid samples, and measurement of molecular oxygen. Tensiometers and liquid samplers consisted of 0.64-cm outer diameter stainless steel porous cups. The three intact core columns were equipped similarly. Soils used in the one-meter columns included the Sweetwater, North Pond Silt, and Agua Fria Sand. Several of the one-meter columns were inhibited with azide to minimize aerobic biological activity and determine upper limit for abiotic removal.

Kopchynski *et al.* (1996) constructed ten stainless steel pilot soil columns and are operated at 91st. Avenue WWTP in Phoenix, Arizona, USA. The columns are *2.44 m* in length, *30.5 cm* in diameter and they are composed of two *1.22 m* sections. The columns are insulated and are cooled by circulating cooling water temperatures exceed *28 °C.* The majority of sampling ports are located near the soil surface since most previous studies indicate most removal occurs in the top *two feet* of soil. Rows of sampling ports are located at depths of *5, 10, 15, 30, 61* and *127 cm* below the soil surface. Tensiometer ports consist of *ceramic porous cups* (1 bar bubble point), liquid sampling ports consist of *0.5 or 0.2 µm* stainless steel porous cups, and other ports contain septums that allow penetration into the column with needle attached to a syringe. All soils were packed to field density at field moisture content. Each column was packed with 15 cm of underdrain, 1.83 cm of soil, resulting in 46 cm freeboard in the columns. Overflow weirs allow the columns to be operated with *15, 30* or *45 cm of head.* The soils used represent a wide range of hydrological and physicochemical characteristics that exist at a proposed recharge site and the soils include a *sand, sandy silt, silt* and a *clay with low plasticity.* The three different effluents include *chlorinated secondary, chlorinated denitrifed,* and *dechlorinated denitrified* effluents. The columns have been operated for over 15 months and the majority of operation has been cyclic operation with wet/dry cycles of *seven days wetting/ seven days drying, three days wetting/ four days drying* and *three days wetting/ seven days drying.* Liquid samples were analyzed for TOC, NH_3, NO_2^-, $NO_3^{=}$, PO_4^{-3}.

2.3.2 INFILTRATION RATES, CLOGGING AND BIOMAT

In the study of Lance *et al.* (1980), the infiltration rates of the six columns flooded with primary wastewater did not change much during the first *208 days* of flooding. The average infiltration rate during the first flooding-drying cycle was only about *0.6 cm/d* more than that of the last cycle. It indicated that soil clogging was not increased with continued flooding, even though SS content ranged from *51* to *181 mg/l* for the primary effluent. The average infiltration rate of the six columns for the 9-day flooding periods was 17.5 cm/d as compared with an average rate of 21.1 cm/d for the same columns flooded with secondary effluent for 10 months during the previous year. Infiltration rates in the silt columns of Kopchynski *et al.* (1996) were reduced from a range of *55-36 cm/d* to a range of *23-14 cm/d* over the first several wetting/drying cycles at seven days wetting/ seven days drying. Infiltration rates through the sand and the silt/sand columns have been limited by pumping capacity and range from 183-305 cm/d (1996). Rice (1974) demonstrated that infiltration rate is *highly dependent* on SS concentrations; above *10 mg/l* SS infiltration decreased rapidly. However, the SS content of primary effluent reduced infiltration rates much less than did the SS content of secondary effluent, probably because SS of primary effluent degraded much more rapidly after they had accumulated on the soil surface than did those of secondary effluent. Kopchynski *et al.* (1996) state that *effluent pre-treatment did not have noticeable impact on clogging layer development.*

Nema *et al.* (2001) reported that each flooding cycle of operation of the SAT system, a layer of biomass developed on the basin bed as a result of settling of suspended and colloidal organics as well as microbial mass in the influent wastewater. This layer (referred to as biomat), gradually dries during the drying phase of the basin. By analyzing the volatile matter of the biomat at different depths below the infiltration basins, it was observed that the volatile matter content of the soil just beyond 5-10 cm of the basin bed was insignificant, implying that the travel of pollutants in the SAT system remained to the confined to surface layer only and perhaps the vadose zone underlying the riverbed remained fully aerobic.

2.3.3 NITROGEN REMOVAL

Effluent ammonia and nitrate concentrations from the sand columns of Kopchynski *et al.* (1996) indicate complete nitrification of influent ammonia and negligible denitrification of influent nitrate. Since the sand columns essentially mimic aerobic biological filters, the conversion of *1-2 mg/l* NH_3*-N to 1-2 mg/l* NO_3*-N* is logical. Also, the sand has a *very low cation exchange capacity (2.4 meq/100 g)* which makes the adsorption of ammonia negligible removal mechanism. Complete nitrification was not always observed in all columns when the wet/ dry cycle was three days wetting/ four days drying since reaeration of the soil during drying *was not always complete.* Elevated nitrite concentrations (*greater than 0.5 mg-N/l*) were often observed when nitrification was not complete. *Rapidly changing column effluent nitrate concentrations were observed during intensive sampling.* A nitrate peak was observed at the beginning of wetting cycles and nitrate concentrations would decrease to influent concentrations by the end of a wetting cycle. Nitrate peaks were typically below *10 mg-N/l* for column fed denitrified effluent but peaks greater than *50 mg-N/l* were observed in columns fed *secondary effluent.* Based on nitrogen mass balances, nitrogen removal efficiencies are less than *20 %* indicating that denitrification is not significant. Sufficient drying time allowed for aeration of the soil and efficient nitrification.

Fox *et al.* (1998) reported that attempts to establish denitrifying conditions by manipulating the wetting/drying schedule were not successful. Denitrification was observed when nitrate was blended with trickling filter effluent since sufficient BOD or BDOC and nitrate were available. Denitrified effluents were below the MCL for nitrate (10 mg-N/L) before SAT and remained below the MCL when drying cycles were long enough to promote complete nitrification and prevent extended accumulation of ammonia. Furthermore, short drying periods during cool weather were not sufficient to allow for complete nitrification, thus allowing ammonia to build up in the soil and nitrify under warmer conditions leading to increased nitrate-N concentrations. *This phenomenon was noticed for all effluent pretreatments, including denitrified effluents*. Extended wetting could eventually cause ammonia-N breakthrough in the coarser grained soils that had lower cation exchange capacities.

Nitrogen removal from three *bare* soil columns of Levine *et al.* (1978) averaged *45.6 %* for primary effluent as compared with *28.5 %* nitrogen removal from the secondary effluent. Nitrogen removal increased because the primary effluent contained more DOC, and thus supported more denitrification. The experiments suggested that nitrogen removal percentages would have been higher from a primary effluent with a higher organic C: N ratio than the 3:1 ratio found in the primary effluent used. Nitrogen removals of about *90 %* were reported for the Hollister (California, USA) land infiltration site where the C: N ratio of primary effluent was 6:1.

Other studies with small columns flooded with dextrose-enriched secondary effluent showed that the higher carbon concentrations supported a larger population of denitrifying bacteria than columns flooded with only secondary effluent and that these higher populations were needed for complete N removal at *high loading rates* (Gilbert *et al.,* 1979).

2.3.4 PHOSPHORUS REMOVAL

Van Cuyk *et al.* (2001) used four laboratory lysimeters packed with sand to evaluate phosphorus removal efficiency. During 48 weeks of continuous operation, each lysimeter was dosed with septic tank effluent four times daily (8, 12, 16, 20 h) and dose volume was 1.25 cm/dose. Average TP concentration was *4.6 mg/l* and each lysimeter had the following *average total phosphorus* removal efficiencies: *20.6 %, 41.6 %, 23.7 %* and *27.2 %.*

PO_4-P removal from primary effluent having average PO_4-P concentration of *7.2 mg/l* ranged from *66* to *72 %* as compared to a range of *58* to *73 %* from secondary effluent having *12.1 mg/l.* The PO_4-P removal increased as infiltration rates decreased as was previously reported for secondary effluent (Lance and Whisler, 1975; Lance *et al.*, 1980).

The removal of orthophosphate phosphorus in the 100 and 50 cm columns was 100 % initially. The removal in the 15 cm column was, however, relatively low. In the columns loaded at the rate of 10 and 50 cm/week, the removal percentages were 99 and 98 % respectively, and no decrease was observed with time. The rate of phosphorus removal remained almost the same for different column lengths and loading rates within the test period of 11 weeks (Billur, 1981).

2.3.5 ORGANIC REMOVAL

Most of the organic carbon was removed from the primary wastewater effluent as it moved through the soil columns. Average TOC concentration at the column outlet was *6.9 mg/l with* a range of *3.3* to *16.6 mg/l.* TOC of the water from the columns was about the same as when the columns were flooded with secondary wastewater effluent (Lance *et al.,* 1980).

In the study of Kopchynski *et al.* (1996), after ten wet/dry cycles TOC concentrations in the silt column effluents decreased to consistent values ranging from *8-10 mg/l.* For silt columns fed with denitrified effluent, there was negligible removal of TOC until cycle 17 when the wet/dry cycle was changed from seven days wetting/ seven days drying to three days wetting/ four days drying. TOC concentration decreased to *5-6 mg/l.*

Idelovitch and Michail (1984) measured *82 %* reduction in DOC (Initial concentration= 18 mg/l) in a 25-m sediment column composed of fine sands at the Dan Region Project in Israel using effluent treated sequentially in oxidation ponds and a two-stage high lime-magnesium reactor-clarifier. Quanrud *et al.* (1996) used repacked loamy soil in the columns and columns were fed with secondary and tertiary wastewater. Some columns are also inhibited to prevent aerobic activity by azide inhibitor. Average DOC reduction in the azide-inhibited column during the operation period was *10 %* for a mean effluent concentration of about *10 mg/l*, suggesting that biological degradation was the primary mechanism of DOC removal. In a single seven-day wet cycle, DOC reduction followed a steady trend. The biologically active column fed with chlorinated secondary effluent (Initial concentration= 11.0 mg/l) reduced DOC *about 54 %*, yielding effluent DOC concentrations of about *5 mg/l.* The biologically active column that received tertiary-treated wastewater reduced DOC concentrations by *30 %,* to an average of *6.5 mg/l* in the initial SAT periods; but later, performance was enhanced and tertiary wastewater fed column effluent began to have steady effluent concentration comparable to secondary effluent fed column (effluent concentration of the column fed with secondary effluent=4.8 mg/l and effluent concentration of the column fed with tertiary effluent=4.9 mg/l) (Quanrud *et al.,* 1996).

In the study of Fox *et al.* (1998), the influent TOC levels averaged about 10 mg/L. Effluent TOC values for the rest of the North Pond Silt columns at the 91st Avenue WWTP were similar indicating that *denitrification and dechlorination did not improve SAT performance in terms of organic removal.* During the beginning of Schedule 1 (seven day wet/seven day dry) *the effluent TOC concentrations exceeded influent organic concentrations. A significant quantity of soluble organic carbon was initially present on the soil as indicated by independent desorption tests on the soils.* In the laboratory column experiments of Kopchynski *et al.* (1996), clean water was used to leach the soluble organic carbon from the silts. These experiments verify that the majority of the organic carbon initially present in the soil was leached after *12 wet dry cycles.*

Fox *et al.* (1998) reported that during the shorter flooding and drying cycles in schedule 2, the effluent TOC values decreased as compared to schedules 1,3, and 4 in the North Pond Silt columns (schedule 1=7 days wetting/ 7 days drying, schedule 2= 3 days wetting/ 4 days drying, schedule 3= 3 days wetting/ 7 days drying, schedule 4= 12 days wetting/ 7 days drying)[1]. During schedule 2, characterized by short (four-day) wetting cycles combined with temperature-limited low algal growth, effluent TOC concentrations decreased to 5 mg/L. During schedules 1,3, and 4, TOC concentrations were often near the influent level (8-10 mg/L). These higher effluent TOC values were probably due to algal growth on the soil surface, which contributed significant levels of organic carbon in the North Pond Silt columns. Depth-dependent concentration profiles indicated the highest TOC concentration occurred near the soil surface immediately after the beginning of wetting period. *This is consistent with leaching of organic matter from dessicated algae.* Several temporal series of depth dependent profiles indicated that the initial pulse of leached organic matter was retarded by adsorption and biodegradation as it moved through the soil column resulting in relatively constant column effluent concentrations. Independent desorption tests on algae indicated that the algae could contribute 5-10 mg/L of DOC to the infiltrating wastewater.

DO measurements indicated a steep decline in oxygen levels near the soil surface where biological activity was apparently greatest (Fox *et al.*, 1998). After one day of wetting, the DO concentration decreases from near saturation to *1-2 mg/l* in columns fed with *denitrified effluent* and decreases to less than *0.1 mg/l* in columns fed with secondary effluent (Quanrud *et al.,* 1996). Since denitrified effluents typically contained only 5 mg/L of BDOC or BOD, there was insufficient BDOC to lower the dissolved oxygen levels to anoxic conditions. Hence, oxygen profiles were dependent on the quality of waters applied to the column; those with higher levels of DOC provided a more rapid decline in molecular oxygen with depth (Fox *et al.,* 1998).

Studies by Quanrud *et al.* (1996) and Fox *et al.* (1998) concluded that there was no strong relationship between organic carbon removal efficiency and

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[i] Additional information on the operational and soil characteristics of SAT study conducted by Fox *et al.* (1998) can be seen in Appendix E.

infiltration rate or detention time. This insensitivity was confirmed with different effluents and a wide range of flowrates during various column tests conducted at both Arizona State University and the University of Arizona. Appendix E.6 illustrates that there was relatively little difference in terms of organic removal between one-meter columns containing Sweetwater, Agua Fria and North Pond Silt despite *significant differences in infiltration rates*. Appendix E.6 also shows very little removal by adsorption. The results of azide inhibition experiments suggest that at least 80 percent of the DOC removed during infiltration of secondary effluent through surface soils results from *aerobic biochemical activity* (Appendix E.6). Residual removals in azide-treated columns could have resulted from abiotic mechanisms, presumably sorption, and O_2-independent microbial activity. Independent adsorption experiments under saturated conditions indicated that sorption capacities were rapidly exhausted and continuous removal of organics *could only be expected by biodegradation*.

Analysis of data using a one-way ANOVA test revealed that *six months to a year* was necessary to establish *steady SAT performance* (Fox *et al.,* 1998). The development of a microbial community capable of reproducibly degrading organic residuals was evident after *15 cycles* for DOC corresponding to 30 weeks of column operation (Quanrud *et al.,* 1996), which means that relatively long time may be necessary to develop *an acclimated culture* and to achieve *steady influence from adsorption*.

Billur (1981) has studied removal of COD using SCL soil in soil columns fed with METU Oxidation Pond effluent. Influent COD values were in range of *114 mg/l* and *127 mg/l*. The removal of COD at 5 cm/week loading rate was *100 %* for the 100 cm and 50 cm columns and *92 % percent* for the 15 cm column in the beginning, while it decreased to *88, 82* and *60 %* for the 100, 50 and 15 cm columns respectively at the end of the 11 weeks of the wastewater application. The removal was *highest* at 5 cm/week loading rate and decreased as the rate of loading increased for the columns of the same length.

CHAPTER 3

MATERIALS AND METHODS

3.1 DESCRIPTION OF LABORATORY COLUMN STUDIES

Laboratory column studies include construction of soil columns containing i.e., SCL, LS and SL; application of primary and secondary wastewater; assessment of hydraulic behaviour and pollutant removal efficiencies during SAT application.

3.1.1 THE SOILS

Soils having textures of SCL, LS and SL soils were used in the laboratory scale column study. SCL soil is obtained from an agricultural field in Ankara. Soils with SL and LS textures could not be obtained from natural on-site sources. Therefore, LS and SL soils were obtained by mixing the necessary amounts of natural SCL soil with fine sand passing 0.053 sieves.

The natural soil obtained from Gölbaşı, Ankara is analysed for texture, physical and chemical parameters in the laboratory of the Genel Directorate of Rural Affairs. The texture of the soil is SCL according to USDA classification and contains *56.72 %* sand, *23.28 %* clay and *20.00 %* silt. Preparation of LS and SL soils from the mixture of natural SCL soil and fine sand is described in detail in Appendix F.

Soils were packed into the acrylic columns with 13.5 inner diameter and 100 cm height using a packing device and 3 cm thick soil lifts. Each lift was packed by taking equal number of strokes from the packing device. Packing of lifts continued until the thickness of soil in the column reached 88 cm. Prior to packing a fine metal screen was placed at the bottom to prevent clogging of the column outlet.

Total mass of soils in the columns and corresponding bulk densities of the packed soils are tabulated in Table 3.1:

Table 3.1: Values of Soil Mass, Total Soil Volume, Bulk Density and Total Pore Volume for Columns

Column	Soil Mass (g)	Total Soil Volume (cm^3)	Packed Density (g/cm^3)	Porosity	Total Pore Volume (cm^3)
SL	18,210	12,500	1.46	0.45	5,625
LS	22,280	12,500	1.78	0.33	4,125
SCL	16,100	12,500	1.29	0.51	6,375

Total soil volume of the columns were calculated excluding the volumes of tensiometers and ceramic samplers from the total bulk soil volume (volume occupied by a 88 cm height soil). Packed densities of the column soils were calculated using total soil volume and soil mass values. Porosity values were calculated from:

$$\phi = 1 - \frac{\rho_b}{\rho_s} \qquad (3.1)$$

3.1.2 EXPERIMENTAL SETUP

Three acrylic columns having dimensions of *100 cm* height and outer diameter of *15 cm* (Inner Diameter= 13.5 cm) were constructed. Silicone was used to insulate the joints of the columns for a probable water leakage. The columns were tested to verify the insulation.

Copper and tygon tubing and rubber stoppers were used for preparation of porous sampling cups. The cross-section of sampling cups installed in the columns is shown in Figure 3.1.

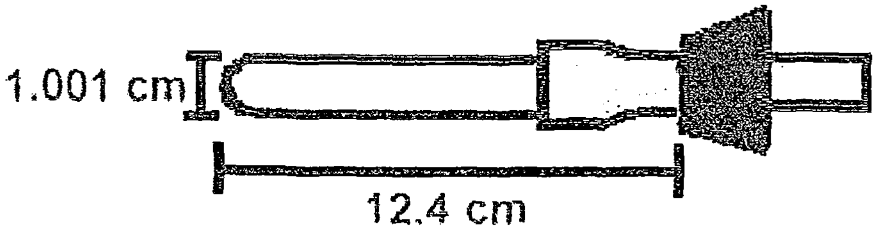

Figure 3.1: Cross-sectional view of porous, ceramic sampling cup

The ceramic sampling cups and ceramic tensiometers were obtained from Soilmoisture Equipment Corporation (USA). Round bottom ceramic cups of Soilmoisture Equipment Corporation (Code Number: 0652X04-B01M3) were used as *sampling cups.* The physical properties of the cups are given below:

Air Entry Value: 1 Bar, High Flow
Outer Diameter: 1.001 cm
Length: 10.000 cm
Thickness: 0.160 cm

Copper and tygon tubings and plastic stoppers were used for the preparation of *tensiometers.* The manufactured cylinderic porous ceramic cups are longer than the inner diameter of the columns, so they were cut to have appropriate lengths to fit the range. Cross-sectional view of the tensiometers installed into the columns is given in Figure 3.2 :

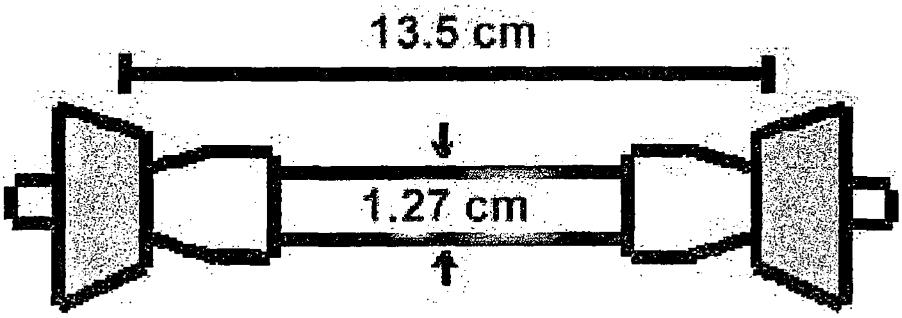

Figure 3.2 Cross-sectional view of tenisometer cups

The laboratory scale studies on SAT systems were examined to design experimental setup of the study (Quanrud *et al.,* 1996; Fox *et al.*, 1998). Three identical acrylic columns were constructed. Each column has:

a. Eight ports for tensiometers (Two ports facing each other for a single tensiometer),
b. Four ports for ceramic soil water samplers,
c. One column outlet at the bottom,
d. Four constant head overflow ports (Two overflow ports facing each other at equal height)

Overflow port locations, used to maintain the desired constant head at the top of the soil, were located at depths *7 cm* and *9.5* cm from the top of the columns. Sampling ports were installed at depths *21, 39, 54.5 ve 75 cm* from the top of the columns. Tensiometer ports were installed at depths *15, 30.5,* *45.5* ve *65.5 cm* from the top of the columns. A schematic view of the column with full instrumentation is shown in Figure 3.3.

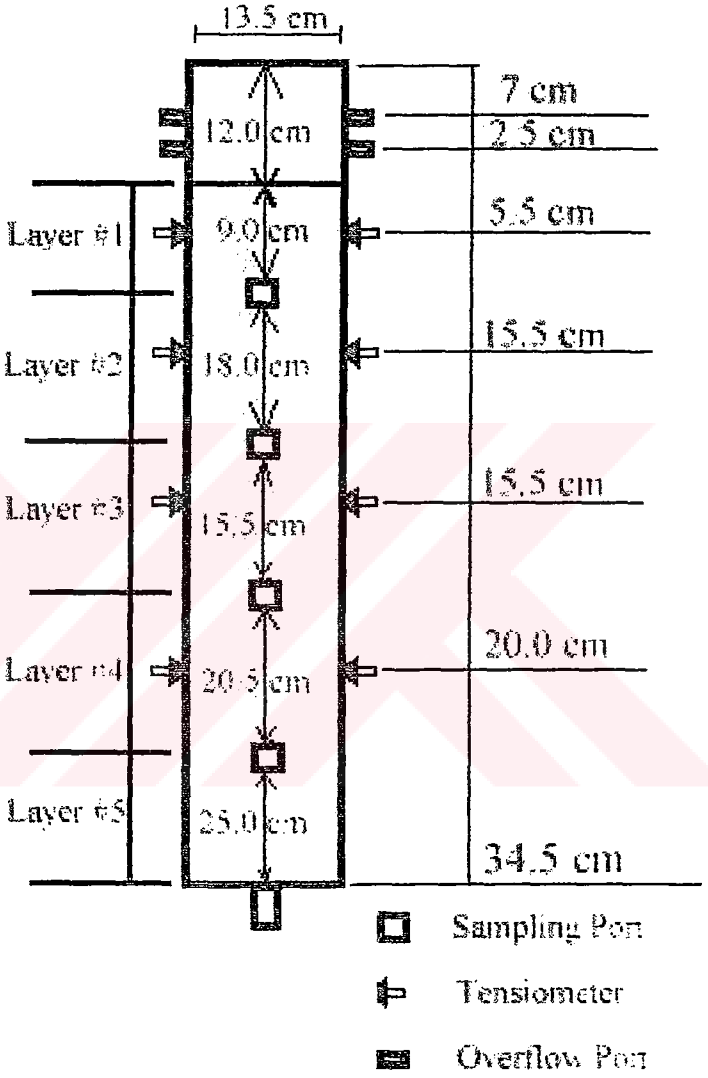

Figure 3.3: A schematic view of the soil column and its instruments

The tensiometers and sampling ports were coded for the sake of easy reference. The installation depths of the tensiometers and the sampling cups and their code names are shown in Table 3.2:

Table 3.2: Depths and Code Names of Sampling Ports and Tensiometers

Column Name	Code Name		Installation depth (cm)[a]	
	Sampling Port	Tensiometer	Sampling Port	Tensiometer
SCL	SCL-S4	SCL-T4	9	3
	SCL-S3	SCL-T3	27	18.5
	SCL-S2	SCL-T2	42.5	34
	SCL-S1	SCL-T1	63	54
LS	LS-S4	LS-T4	9	3
	LS-S3	LS-T3	27	18.5
	LS-S2	LS-T2	42.5	34
	LS-S1	LS-T1	63	54
SL	SL-S4	SL-T4	9	3
	SL-S3	SL-T3	27	18.5
	SL-S2	SL-T2	42.5	34
	SL-S1	SL-T1	63	54

[a]: Beginning from Soil Surface

The overall configuration and components of the SAT are shown in Figure 3.4:

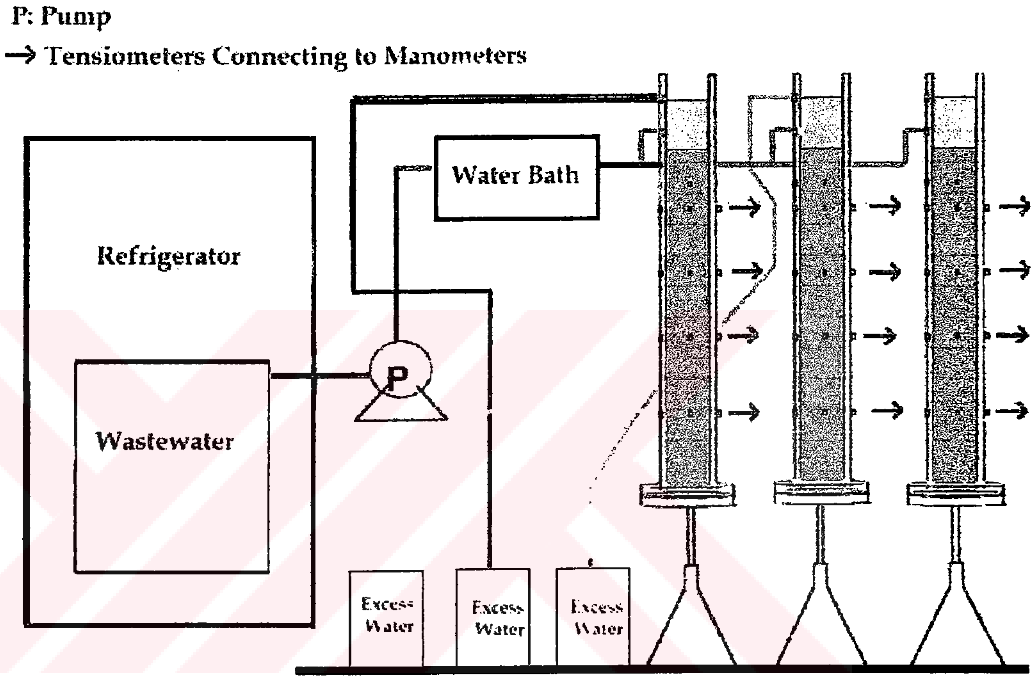

Figure 3.4: The overall configuration and components of SAT experimental setup

Components of the experimental setup and apparatus are listed as follows:

a. Refrigerator,
b. Water Bath,
c. Excess Water Tank,

d. Influent Tank,
e. Peristaltic Pump,
f. Soil Columns,
g. Manometers,
h. Air Pumps,
i. Handheld Vacuum Pumps.
j. Manometers

The manometers are not shown in Figure 3.4 in order to have a comprehensive figure. The figure of manometers is shown in Figure 3.5.

Manometer and tensiometer system must not include *any air pockets that may interfere with soil water pressure readings.* Hence, the manometer/tensiometer system must be prepared and operated such that it will not include these air pockets. Tensiometer/manometer system is activated using the following steps:

a. Tubing connections are made. The joints that are amenable to air entry are also sealed with glue,
b. A short rubber tubing is tightly installed on the free port of tensiometer (the one which is not connected to manometer with transparent rubber tubing),
c. Hot water (de-aired) is pumped using a peristaltic pump from the top of the manometer tubing to the manometer/tensiometer system,
d. Air pockets are thrown out the system as pressurised water enters,
e. Water is pumped into the system for sufficient time interval and system is visually checked to see that there is no air pockets remaining in the tubings,

f. The pump is turned off and instantaneously the short tubing connected to the port of tensiometer is clipped,
g. The end of clipped tubing is also glued.

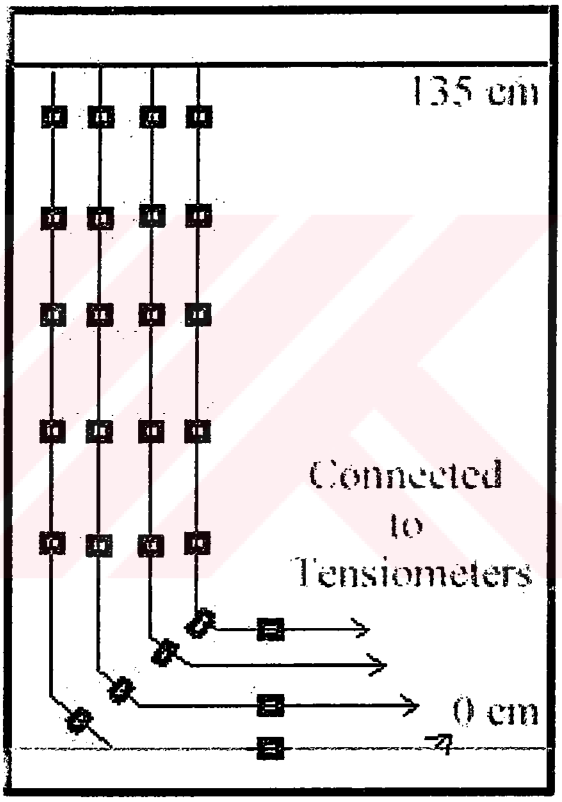

Figure 3.5: Manometer of the SAT project

a. Refrigerator: The refrigerator was used to keep the wastewater samples from ACWTP around *+4 °C* in order to minimise the effects of chemical and/or biochemical reactions in the wastewater (Eaton *et al.*, 1995).

b. Water Bath: Water bath *was used* in order to increase temperature of the wastewater resting in refrigerator to the average waastewater temperature before application. ACWTP wastewater temperatures were assessed in order to choose the average application temperature for the wastewater (Ankara Merkezi Atıksu Arıtma Tesisi Kalite Kontrol Şube Müdürlüğü, 1999). Minimum and maximum average wastewater temperature of ACWTP are *11.3* and *19.8 °C* respectively.

Average application temperature for wastewater was chosen as *20 °C*. This average value is appropriate as SAT systems are frequently implemented in arid or semi-arid climates producing wastewater temperatures around average maximum temperature of ACWTP.

c. Excess Water Tank: It is necessary to maintain constant ponding depth over the soil columns during ripening phase and rapid infiltration schedule. Excess water must be discharged from the column to prevent uncontrolled water rise in the ponding. Excess water discharged through overflow ports were conveyed to the excess water tanks and this excess water was recycled to the influent tank placed in refrigerator.

d. Influent Tank: 20 l plastic tank was placed in the refrigerator to store wastewater of ACWTP.

e. Peristaltic Pump: Pumping is necessary to convey wastewater from the refrigerator to the tops of the columns. Peristaltic pump of Masterflex Corporation was used. The pump can operate between 10 and 600 rpm; supply the following wastewater flowrate ranges with the selected tubings (LS 13 and LS 14) respectively: *0.6-36 ml/min* and *2.1-130 ml/min.*

f. Soil Columns: Three acrylic columns having height of *100 cm* and inner diameter of *13.5 cm* were constructed. Outer surfaces of columns were wrapped with aluminum foils in order to prevent algal growth through the soil depth during operation.

g. Manometer: Manometers were connected to tensiometer ports for measurement of soil water potential and indirectly, volumetric water content distribution through the columns. Each column had a distinct manometer. Four tensiometer ports were connected to 4 manometer tubings. Manometer supports have millimetric papers to quantify the soil water potential in the tensiometers. Manometers are able to measure soil water potentials within the range of *0-135 cm.* A sketch of the manometers is given in Figure 3.5.

h. Air Pumps: Rambo model air pumps were used to aerate the ponded wastewater during ripening and rapid infiltration schedules.

i. Handheld Vacuum Pump: Handheld vacuum pumps were used to take wastewater samples from different depths of the columns; the wastewater samples were stored in teflon bottles. The handheld vacuum pumps were supplied from Millipore Company (Catalogue Number: XKEM00107).

j. Oxygenmeter: Oxygenmeter was used to measure DO content of the samples taken from the sampling ports of the columns.

3.2 DESCRIPTION OF WASTEWATER

The wastewater utilised in this study is obtained from ACWTP. Wastewater treatment train in ACWTP is a *conventional biological treatment system* consisting of 2 ½ activated sludge routes running parallel to each other. Each route contains 4 aeration tanks, making a total of 10 aeration tanks together in operation. Influent wastewater is admitted to the plant through screening units, followed by the conventional preliminary treatment units (bar racks, fine screens, aerated grit chambers and primary sedimentation). Primary treated wastewater then goes through 10 parallel-operated activated sludge tanks that are aerated with surface aerators. The mixed liquor passes from the aeration tanks to the secondary (final) sedimentation tanks by gravity flow. Each aeration tank is connected to two circular sedimentation tanks where biomass is settled and recycled. The treated wastewater (supernatant of secondary sedimentation tanks) is discharged to the Ankara Creek (Sin, 2000).

Primary wastewater (effluent of primary sedimentation tanks of ACWTP) was used in the columns during ripening phase and secondary wastewater was used in rapid infiltration schedules (7 d wetting/ 7 d drying, 3 d wetting/ 4 d drying) and slow rate infiltration schedule.

As DOC concentration and infiltration rate can be used to indicate growth of microbial activity in the soil columns, DOC content of primary wastewater is important. Thus, primary wastewater is only analysed for DOC concentration (Westerhoff and Pinney, 2000); other pollutant parameters of this study are not considered primary wastewater. Wastewater type and influent quality during SAT application is given in Table 3.3:

Table 3.3: Wastewater Types, Influent Quality During SAT Application

Operational Phase	Wastewater	DOC (ppm)	COD (ppm)	NO_2-N (ppm)	NO_3-N (ppm)	NH_3-N (ppb)	TKN (ppm)	TP (ppm)
Ripening	Primary	55.6 ± 24.4	-	-	-	-	-	-
	Synthetic (*)	-	1000	-	-	-	-	-
7 d wetting/ 7 d drying	Secondary	-	-	1.066 ± 0.308	10.8 ± 2.60	17.7 ± 1.21	-	2.69 ± 0.09
3 d wetting/ 4 d drying	Secondary	23.7 ± 4.1	45 ± 4.6	0.821 ± 0.386	9.2 ± 0.22	21.1 ± 0.54	24.6	5.42 ± 0.12
Slow Rate Infiltration	Secondary	-	41 ± 5.1	0.738 ± 1.223	5.37 ± 0.31	-	30.7 ± 5.45	3.62 ± 0.07
(*): Stoichiometric Value of COD exerted by peptone								

Wastewater was stored in 20-l plastic containers after sampling. ACWTP is more than 40 km away from the METU Environmental Engineering Department where the experimental setup is constructed. Hence, wastewater was taken with reasonable intervals. At each shift, 100 ± 20 l of fresh wastewater was brought to the department.

Primary wastewater was filtered using coarse paper filter in order to decrease SS content; hence, the risk of severe infiltration rate decrement due to probable clogging was prevented. Secondary wastewater was not subjected to pre-treatment pumping into the soil columns.

Wastewater was stored in refrigerators prior to application. For longer period of storage, wastewater was sometimes frozen too. Frozen wastewater was thawed prior to application. No additive or preservative was used for preserving wastewater quality.

3.3 SOIL ANALYSES

Soil analyses of this study were conducted by the Ankara Research Institute Soil Laboratory of Rural Works General Directorate. Standardized methods of the ministry are used during analyses. The following parameters were measured in the samples:

a. Water Saturation,

b. Saturated Soil pH,
c. Organic Matter,
d. CEC
e. Texture (Sand, Silt and Clay Contents).

Soil textures are given in Table 3.4.

Table 3.4: Texture of Soils Used in Soil Columns

Sample	Sand (%)	Silt (%)	Clay (%)	USDA Classification
SCL	53.28	24.00	22.72	***SCL***
LS	78.28	10.64	11.08	***SL***[a]
SL	70.28	14.64	15.08	***SL***

[a]: Textural classification in the border of SL and LS

One of the artificially prepared soil samples was intended to have LS texture; however, preparation yielded a texture at the border of SL and LS classification. Hence, preference was given to LS and used in the following sections and chapters of this thesis.

Physical and chemical properties of soils used in the columns are tabulated in Table 3.5.

Table 3.5: Physical and Chemical Properties of the Soils

Sample	Water Saturation (%)	PH (saturation paste)	Organic Matter (%)	CEC[a] (Me/100 g)
SCL	47.5	8.02	2.25	16.80
LS	30.5	8.27	0.78	9.40
SL	35.0	8.20	1.43	13.80
[a]: CEC: Cation Exchange Capacity				

Topsoil of the columns were analysed in order to quantify adsorbed amount of carbon and attached biofilm as a cumulative parameter called as *total organic content.* Mixed Liquor Volatile Suspended Solids (MLVSS) analysis determine quantity of suspended mixed cultures in biological treatment systems; total organic content analysis has a similar procedure with MLVSS analysis (Alsmadi and Fox, 2000). The following procedure was used for Total Organic Content analysis, with reference of volatile solids to the organics bound to the soil particles in this analysis:

a. 3 – 5 g of topsoil is taken from the column provided that the topsoil is not heavily disturbed during sampling,

b. **Method 2540 D.** is used to determine Total Solids in the sample (Eaton *et al.*, 1995),

c. **Method 2540 E.** is used to determine Volatile Solids (Organics) in the sample (Eaton *et al.*, 1995), Total Organic Content is expressed by mass of organics per mass of soil particles.

3.4 WASTEWATER ANALYSES

Wastewater was analysed to measure the following water quality parameters: DOC, COD, NH_3, NO_2^-, $NO_3^=$, TKN, TP and DO. These parameters are used to determine composition of influent wastewater and quality of the wastewater through SAT treatment process.

a. DOC analysis was done using *5310-B Combustion-Infrared Method* (Eaton *et al.*, 1995). 0.45-μm filters were used to filtrate the samples prior to analysis. HCl was used to store samples with pH<2.
b. COD analysis was done using *5220-D Closed-Reflux Colorimetric Method* (Clesceri *et al.,* 1998). Low Range COD measurements bring a change to the method and instead of *10.216 g, 1.0216 g* $K_2Cr_2O_7$ was added to digestion solution. EPA approved premeasured kits (HACH) can also be used to measure Low Range COD.
c. NH_3 was analysed using *4500-C Nesslerization Method.* Wastewater samples must have NH_3-N concentrations exceeding 20 μg/l for accurate NH_3-N analysis[1] (Clesceri *et al.,* 1989)
d. NO_2^- analysis is done using EPA approved HACH premeasured kits (Catalogue Number: NitriVer3 14065-99)

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[1] Average NH_3-N concentrations of this study are lower than 20 μg/l. Hence, NH_3-N measurements are not very precise and accurate.

e. $NO_3^=$ analysis was done using EPA approved HACH premeasured kits (Catalogue Number: Nitraver5 14034-99)

f. TKN analysis was done using *4500-B Macro-Kjeldahl Method* (Eaton *et al.,* 1995).

g. TP analysis was done using *4500-P B.5. Persulfate Digestion Method* prior to *4500-P E. Ascorbic Acid Method* (Eaton *et al.,* 1995).

h. DO was measured using *4500-O G. Membrane Electrode Method* (Eaton *et al.,* 1995). The oxygen-sensitive membrane electrode was calibrated by wastewater temperature and METU Environmental Engineering Department elevation, which is around 3000 ft.

3.4.1 SAMPLE HANDLING AND STORAGE

Teflon containers of 75 ml volume were used during the study. Samples are acidified after nitrite and nitrate analysis if it is necessary to store them for further analyses. Sulfuric acid was used for preservation. However, DOC samples are never acidified with sulfuric acid because the acid interferes with DOC measurement method. For longer storage requirements, the samples were frozen and thawed prior to analysis.

3.5 OPERATION OF THE SOIL COLUMNS

The operational schedule for this study can be given in three main phases:

a. Ripening Studies, involving primary and synthetic wastewater application,
b. Rapid Infiltration, involving 7 day wetting/ 7 day drying and 3 day wetting/ 4 d drying cycles,
c. Slow Rate (Continuous) Infiltration.

Total operational history of the SAT columns is given in Appendix G.
Biofilm in the topsoil of SAT soil columns is critical for the biological removal performance of pollutants (organic and nitrogen removal). The soils, which have not received wastewater, are not biologically activated. Ripening and acclimation periods are the time intervals required for biofilm development in the soils. Following these former phases, maturation phase starts. During ripening phase, infiltration rates are to decrease sharply and DOC removal varies *between 25 %- 39 %*. During acclimation phase, DOC concentrations exiting the columns remain constant but infiltration rates go on declining. Finally, low concentrations of DOC are observed and infiltration rates are constant throughout maturation period. Westerhoff and Pinney (2000) states that ripening, acclimation and maturation phases last *10 weeks, 25 weeks* and *35 weeks*. The soils used in this thesis were not biologically activated either; hence, *a ripening phase was also required prior to regular rapid and slow rate infiltration schedules.* Initially, primary wastewater was applied to the columns under ponded, rapid infiltration conditions. Afterwards, synthetic wastewater

prepared by using peptone was also applied. However, ripening phase only lasted *35 days* for LS column and *30 days* for SCL and SL columns. Ripening phase period of this study is quite short with respect to the laboratory soil column study of Westerhoff and Pinney (2000).

Inherent organics in the soils have a desorbable fraction. This desorbable fraction of the soils may leach and contribute to exit DOC concentration. This phenomenon was observed by Quanrud, *et al.* (1996) and Fox, *et al.* (1998). Quanrud *et al.* (1998) flushed 30 pore volumes of reagent-grade water (containing 0.01 M $CaSO_4$) at a rate of 8 cm/day under saturated flow conditions for *the purpose of removing desorbable organics prior to effluent application.* The soils of this study had high organic content (Table 3.5); effluent DOC concentration of SL column was continuously *higher than influent DOC concentration* showing that desorbable organics were leaching from the column. Hence, 0.01 M $CaSO_4$ was used to flush the desorbable organics from the columns.

Following the operation of desorbable organic leaching, 1000 mg/l COD equivalent peptone solution (synthetic) was used to continue ripening period. The aim of this application was to speed up biological ripening of the columns by supplying concentrated substrate for the biofilm. However, this operation was not conducted more than 11 days for LS and 6 days for SCL and SL columns.

Ripening and rapid infiltration phases were realised under ponded conditions in order to maximize infiltration rate, cumulative amount of wastewater passed through the columns. Pumping rate was kept relatively higher to maintain ponded conditions; and it was decreased to have unsaturated flow conditions. Pondings on the columns were continuously aerated using air pumps during rapid infiltration. Aeration of SL column ponding was stopped starting from the synthetic wastewater application phase and the same column was not aerated in the following phase (rapid infiltration). Loading cycles are selected to maximize either the infiltration rate, nitrogen removal, or nitrification. To maximize infiltration rates, the engineer should include drying periods that are long enough for soil reaeration and for drying and oxidation of filtered solids. The following loading cycles for achieving the three main objectives stated above are tabulated in Table 3.6 (US EPA *et al.,* 1981).

Table 3.6: Suggested Loading Cycles for Rapid Infiltration

Loading Cycle Objective	Applied Wastewater	Season	Application Period[a] (days)	Drying Period (days)
Maximize Infiltration Rates	Primary	Summer	1-2	5-7
		Winter	1-2	7-12
	Secondary	**Summer**	**1-3**	**4-5**
		Winter	**1-3**	**5-10**
Maximize Nitrogen Removal	Primary	Summer	1-2	10-14
		Winter	1-2	12-16
	Secondary	**Summer**	**7-9**	**10-15**
		Winter	**9-12**	**12-16**
Maximize Nitrification	Primary	Summer	1-2	5-7
		Winter	1-2	7-12
	Secondary	**Summer**	**1-3**	**4-5**
		Winter	**1-3**	**5-10**

[a]: Regardless of season or cycle objective, application periods for primary effluent should be limited to 1-2 days to prevent excessive soil clogging

7 d wetting/ 7 d drying cycles provide satisfactory wetting time for facilitating denitrification. 7 d drying period enables regeneration of infiltration capacity of the soil and re-aeration of the column. This aeration assists nitrification process.

3 d wetting/ 4 d drying cycles have higher infiltration rates with respect to 7 d wetting/ 7 d drying cycles (Table 3.6). Therefore, more volume of wastewater is treated in unit time with 3 d wetting/ 4 d drying cycles. On the other hand, 4 d drying period favors nitrification process but does not complete denitrification.

Selection of 7 d wetting/ 7 d drying and 3 d wetting/ 4 d drying cycles makes it possible to compare high infiltration rate/nitrification and lower infiltration rate/denitrification alternatives. Moreover, the alternative rapid infiltration cycles are also compared by using their organic and phosphorus removal efficiencies too.

Slow rate infiltration effectively removes the pollutants having slow reaction rates in the soil. For example, denitrification is a slow rate process and its efficiency is inversely related with infiltration rate. Although unsaturated conditions prevail in the soils during slow rate infiltration and the soil profile is mostly aerobic, denitrification performance has been enhanced comparing with rapid infiltration (US EPA *et al.*, 1981). On the other hand, infiltration rate is obviously lower than that of rapid infiltration schedules in slow rate infiltration. Application of slow infiltration in the context of this thesis made it possible to compare especially denitrification capacity of slow rate infiltration with the two rapid infiltration schedules.

Influent wastewater temperature was measured to check the necessity to heat wastewater supplied by the influent to maintain *20°C* influent temperature. Influent tank had an average wastewater temperature of *9.4 ± 1.2 °C* during ripening phase. Ponding temperatures of *SCL, LS* and *SL* were *23 ± 1.7 °C, 23 ± 1.2 °C* and *23 ± 1.2 °C,* respectively. These reasonably high values of temperature are result of summer weather conditions. Influent average wastewater temperatures were *17 ± 1.7 °C, 17 ± 1.2 °C* for SCL, LS and SL columns during 3 d wetting/ 4 d drying cycles, respectively. Influent tank had an average wastewater temperature of *7.5 ± 3.5 °C* during slow rate infiltration. Average wastewater temperature through the columns ranged between *19 and 20 °C* slow rate infiltration. Average influent wastewater temperatures were higher than *20 °C* during summer period and *slightly lower* than the same target value during fall period of SAT operations.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 OPERATIONAL (HYDRAULIC) CHARACTERISTICS OF SOIL COLUMNS

Hydraulic characteristics of the SAT columns, which may have considerable impact on chemical removal rates, are examined using *hydraulic loading rate, infiltration rate* and *volumetric water content distribution (soil water pressure, suction pressure).* Columns are assumed to operate with *100 % water saturation* during rapid infiltration phase; suction pressures are used to calculate time-variant volumetric water contents of the columns during slow rate infiltration. Hydraulic detention times of the columns are also calculated. Total pore volumes of the columns are divided by infiltrating wastewater flowrate to find average detention times. Moreover, detention times of the layers (each bounded by sampling ports; e. g. first layer is the layer between topsoil and SL-S4, first sampling port) are also found using the same approach. This approach has a basic assumption that the columns have *uniform* porosity and infiltration rate does not vary with depth. There are five layers; identification codes of these layers are given in Table 4.1.

Table 4.1: Description of the Identification Codes of the Layers in the Soil Columns[1]

Identification Code of Layer	Location of Layer
Layer #1	Topsoil- Sampling Port 4 (Soil Depth: 0- 9 cm)
Layer #2	Sampling Port 4- Sampling Port 3 (Soil Depth: 9 cm- 27 cm)
Layer #3	Sampling Port 3- Sampling Port 2 (Soil Depth: 27 cm- 42.5 cm)
Layer #4	Sampling Port 2- Sampling Port 1 (Soil Depth: 42.5 cm- 63 cm)
Layer #5[2]	Sampling Port 1- Effluent Port (Soil Depth: 63 cm- 88 cm)

Hydraulic loading rate, infiltration rate and volumetric water content parameters are directly affected by the operational mode of SAT such as rapid or slow rate infiltration. Hydraulic loading and infiltration rates, volumetric water contents and pore volumes of water passed through the columns during SAT operation are presented in Table 4.2. Average detention times of the columns during SAT operation are shown in Table 4.3.

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[1] The layers are assumed to have equal hydraulic conductivities during operation

[2] Layer #5 could have been united with Layer #4. However, some DO measurements were realized at Sampling Port 1 of the columns. Hence, Layer #5 term is used.

Table 4.2: Hydraulic Parameters of the Columns during SAT Application

Phases	SCL[1]			LS[1]			SL[1]		
	IR (cm/d)	Θ	# of PV	IR (cm/d)	Θ	# of PV	IR (cm/d)	Θ	# of PV
Ripening: Primary WW Synthetic WW	9.5	0.51[a]	3.7	22	0.33[a]	12.4	4	0.45[a]	1.8
$CaSO_4$	12	0.51[a]	3	38	0.33[a]	11	6	0.45[a]	2
Rapid Infiltration: 7 d wetting/ 7 d drying	7	0.51[a]	3.4	21	0.33[a]	15.6	4.6	0.45[a]	2.5
3 d wetting/ 4 d drying	8.3	0.51[a]	3.3	33	0.33[a]	20.4	4.5	0.45[a]	2
Slow Rate Infiltration	2.8	0.47	3	5.2	0.32	8.3	2.5	0.44	3.2

[1] HLR of SCL, LS and SL were 30, 41 and 30 cm/d during ripening phase and 3.5, 5.4 and 3.4 cm/d during slow rate infiltration, respectively

[a] All columns are assumed to be 100 % water saturated under ponded conditions. Hence, porosities are taken as saturated water contents.

PV: Pore Volume

Table 4.3: Hydraulic Detention Times of the Columns

Rapid Infiltration Schedules	**SCL** Detention Time (day)*	**LS** Detention Time (day)*	**SL** Detention Time (day)*
7 d wetting/ 7 d drying			
Cycle #1	9	3	8.3
Cycle #2	6	1	8
Cycle #3	6	1.4	9
3 d wetting/ 4 d drying			
Cycle #1	6	0.6	8.4
Cycle #2	6	1	9.4
Cycle #3	5.2	1.1	8.7
Cycle #4	5,6	1.4	10.1
Cycle #5	5.7	1.2	8.3
Cycle #6	4.8	0.8	8.9

*: All layers are assumed to have same infiltration rate and porosity.

4.1.1 RIPENING PHASE HYDRAULIC CHARACTERISTICS

Ripening phase was started with using primary wastewater as influent of SAT. Mode of operation was selected as rapid infiltration; hence, all of the columns are operated under ponded conditions. Pond depth was *2.5 cm.* Ponds were aerated using air pumps; therefore, DO concentration of influent wastewater is increased to enhance microbial activity in the system. Hydraulic loading rate, infiltration rate and DOC parameters were continuously measured during this period. Total application period was *24* *days*; application ceased for about 5 days because of mechanical problems occurred in peristaltic pump.

$CaSO_4$ solution with 0.01 M concentration was prepared using reagent grade water and $CaSO_4$.. The process efficiency was controlled by measuring effluent COD of the columns. Before application of $CaSO_4$ solution, the columns were drained. Hence, primary wastewater was removed from the columns to the highest extent (field capacity). $CaSO_4$ solution was then applied to SCL and SL columns for 13 days, while the same application was done to LS column only for 8 days. The data for DOC effluent concentration (Ripening Phase) show that LS soil does not have significant desorbable organic content, while SL has significant organic desorption from the column and SCL has a tendency for organic desorption as well. Hydraulic loading rates for SCL, LS and SL columns are shown in Figure 4.1

Synthetic wastewater was prepared using peptone and reagent grade water; peptone was added to the water with the stoichiometric proportion to have a *1000 mg/l COD* synthetic wastewater. Total application period of synthetic wastewater was *12 days* for LS column while the application period was *6 days* for SCL and SL columns. Hydraulic loading rates for SCL, LS and SL columns are presented in Figure 4.2.

4.1.2 RAPID INFILTRATION HYDRAULIC CHARACTERISTICS

Rapid infiltration period has two different mode of operation: a. 7 d wetting/ 7 d drying cycles b. 3 d wetting/ 4 d drying cycles. Columns were operated under saturated conditions. SCL and LS ponds were aerated and SL pond was not aerated. LS and SL soils have very similar textural characteristics; SL column was not aerated so as to observe the effect of DO concentration on the process performance of columns with very similar soil texture. Infiltration rates of the columns are continuously recorded.

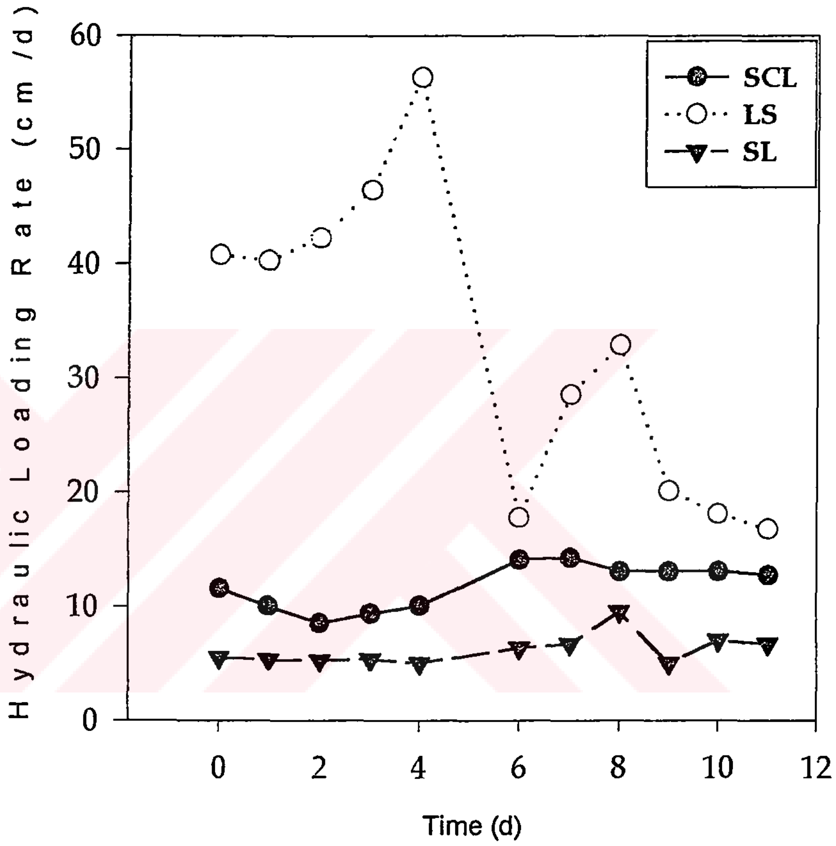

Figure 4.1: Hydraulic loading rates of the columns during $CaSO_4$ application

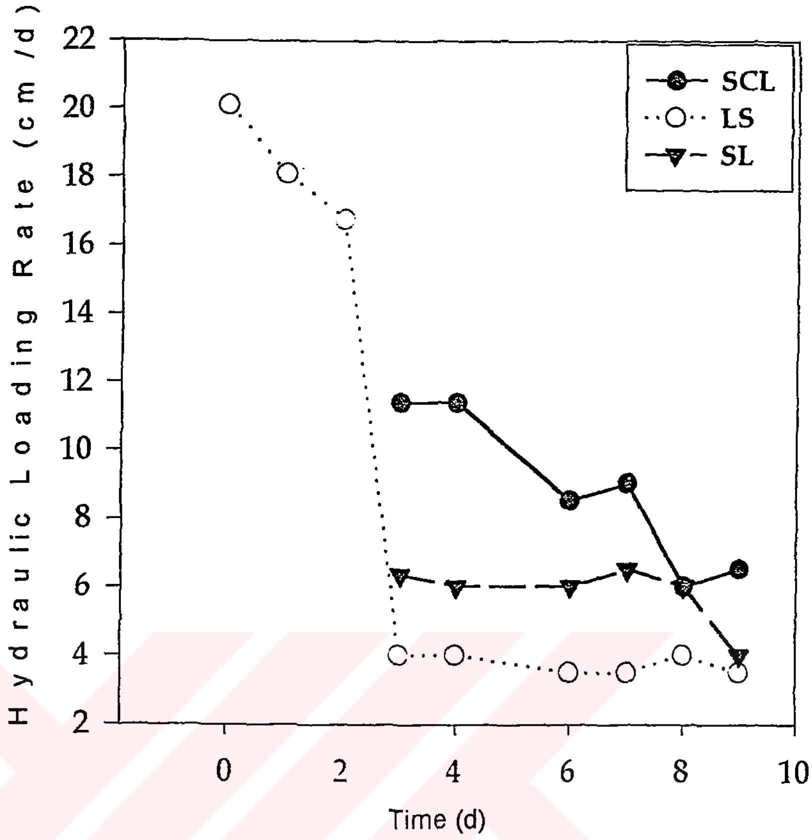

Figure 4.2: Hydraulic loading rates of the columns during synthetic wastewater application

Liquid samples are taken from three ports of the columns (SCL4, SCL3, SCL2, LS4, LS3, LS2, SL4, SL3, SL2). Three 7 d wetting/ 7 d drying cycles and six 3 d wetting/ 4 d drying cycles are implemented. Total operation time is given in Appendix G.

All the columns are operated with the same rapid infiltration schedules simultaneously. Liquid sampling is generally conducted once on the same day from each column; however, sometimes two samples are also taken during the same wetting period (7 d wetting/ 7 d drying cycles: Cycle 1, Cycle 2; 3 d wetting/ 4 d drying cycles: Cycle 2, Cycle 3).

a. 7 d Wetting/ 7 d Drying Cycles

Average infiltration rates of SCL, LS and SL columns during 7 d wetting/ 7 d drying cycles are *7 cm/d, 21 cm/d and 4.6 cm/d.* Average hydraulic detention times of SCL, LS and SL are *7, 1.8* and *8.6 days.* The number of pore volumes passed through SCL, LS and SL columns were *3.4, 15.6* and *2.5* respectively. LS has the highest infiltration rate amongst the columns in this period. Average infiltration rate of SCL increases slightly; on the other hand, infiltration rates of LS and SL decrease reasonably. Decrement of LS infiltration rate is more obvious than that of SL. As more wastewater passes through LS column per unit time with respect to the other two columns, clogging through the topsoil of columns occurs due to accumulation of non-degradable SS, causing decrease in infiltration rate with time.

7 d wetting/ 7 d drying cycles were applied only three times because of time limitations; two cycles take one month.

b. 3 d Wetting/ 4 d Drying Cycles:

Average infiltration rates of SCL, LS and SL columns during 3 d wetting/ 4 d drying cycles are *8.3, 33 and 4.5 cm/d.* Average column hydraulic detention times during the cycles are *5.6, 1* and *9 days* for SCL, LS and SL columns, respectively. The number of pore volumes passed through SCL, LS and SL columns are *3.3, 20.4* and *2* respectively.

In general, infiltration rates of the columns *have not decreased* during 3 d wetting/ 4 d drying cycles following 7 d wetting/7 d drying cycles. Average infiltration rate of SCL and SL columns are nearly the same for both cycles whereas average infiltration range of LS column during 3 d wetting/ 4 d drying cycles is *higher than* that of 7 d wetting/7 d drying. Compared to 7 d wetting/ 7 d drying cycles, average detention times of SCL, LS columns have decreased *25 % and 44 %* respectively. While, average hydraulic detention time of SL column has increased *5 %.*

4.1.3 SLOW RATE INFILTRATION HYDRAULIC CHARACTERISTICS

Slow rate infiltration was implemented by using lower hydraulic loading rates to maintain unsaturated flow conditions in the columns. Hydraulic loading rate, infiltration rate and soil water potential values were continuously measured to observe hydraulic behaviors of the columns during slow rate infiltration. Average hydraulic loading rates of SCL, LS and SL columns are *3.5, 5.4* and *3.4 cm/d* respectively; average infiltration rates of the columns are *2.8, 5.2* and *2.5 cm/d* (Figure 4.3). Total operation period is *50 days;* other operational details are given in Appendix G.

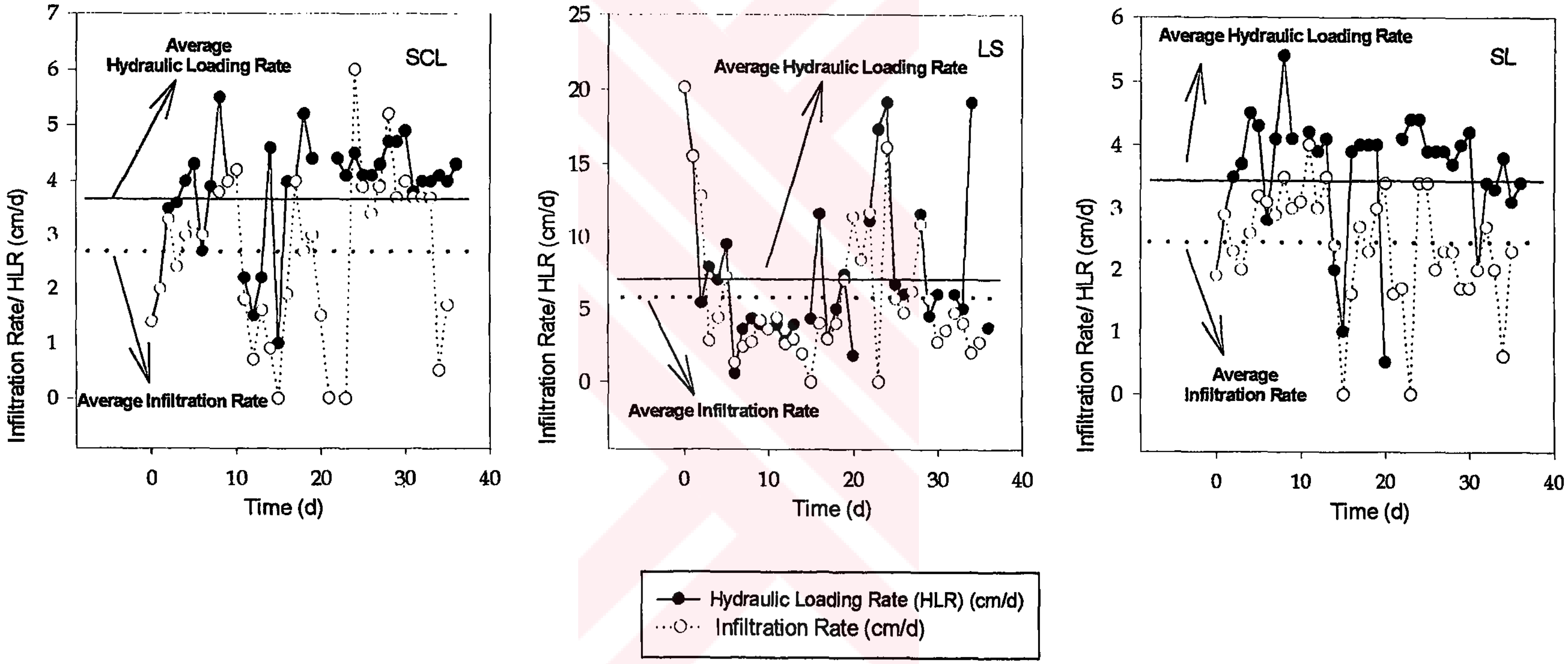

Figure 4.3: Hydraulic loading and infiltration rates of the columns during slow rate infiltration

Total pore volumes of wastewater passed through SCL, LS and SL columns during the application are *3.0, 8.3* and *3.2.*

Pumping rates are continuously altered to prevent ponded, saturated hydraulic conditions on the columns. Therefore, hydraulic loading rates of the columns have some significant fluctuations. Transient behavior of hydraulic loading rate has directly effected infiltration rate and hydraulic detention times of the columns. Figure 4.3 shows these changes in hydraulic loading rate and its effects on infiltration rate clearly. In SCL column, ponded condition occurred during Day 20; and pumping is stopped on Day 20 and Day 21. Hence, infiltration rates from the column decreased during these days. Moreover, infiltration rate decreased reasonably while hydraulic loading rate to SCL is almost steady. This *may be* a result of clogging at the topsoil. In LS column, initial hydraulic loading rate is around 20 cm/d, this higher hydraulic loading is implemented to reach a water content *near* saturation conditions. However, hydraulic loading rate is decreased to 5 cm/d in order to prevent ponded operation conditions. Infiltration rate decreased to 0 cm/d on Day 15 and 23 as a result of operational failure. Hydraulic loading and infiltration rates have very close values and they follow the same trend; this indicates that clogging phenomenon is not effective in LS column during slow rate infiltration. In SL column, infiltration rate decreased to 0 cm/d on Day 15 and Day 23 as a result of operational failure as it happened for LS column. Hydraulic loading and infiltration rates have close values throughout the operation period. SL column does not have a significant clogging either.

Soil water potentials are measured using tensiometer/manometer apparatus. Average volumetric water content of the SCL, LS and SL columns are *0.47 ± 0.01, 0.32 ± 0.004* and *0.44 ± 0.01,* respectively.

Corresponding porosities of the columns are *0.51, 0.33* and *0.45 for* SCL, LS and SL respectively. Average volumetric water content values show that the degree of water saturation for the columns is in the range of *90.2-94.0 %, 95.8-98.2 %* and *95.6-97.8 %.* Therefore, LS and SL columns are more saturated with water than SCL column. Time varying volumetric water contents of SCL, LS and SL columns measured at different depths are given in Figure 4.4, Figure 4.5 and Figure 4.6.

Daily infiltration rate measurements are used for calculation of detention times of the columns. Infiltration rate is inversely proportional with detention times of the columns. During slow rate infiltration, there is a fluctuation of infiltration rate (Figure 4.3) through the columns. Hence, overall column hydraulic detention times also fluctuate. Detention times of SCL, LS and SL columns are *20 ± 16 days, 8 ± 4.8 days* and *19 ± 9.5 days.*

4.2 REMOVAL OF POLLUTANTS

4.2.1 REMOVAL OF ORGANICS (DOC & COD)

DOC measurements were done continuously during ripening phase (primary wastewater application). Also, DOC snapshot measurements were conducted in the rapid and slow infiltration phases instead of continuous measurement.

DOC parameter gives the quantity of dissolved organics present in wastewater; dissolved organics are rapidly degraded by biofilm while particulate organics are rather filtered and adsorbed by soil particles. Total COD has both dissolved and particulate COD constituents. Therefore, DOC

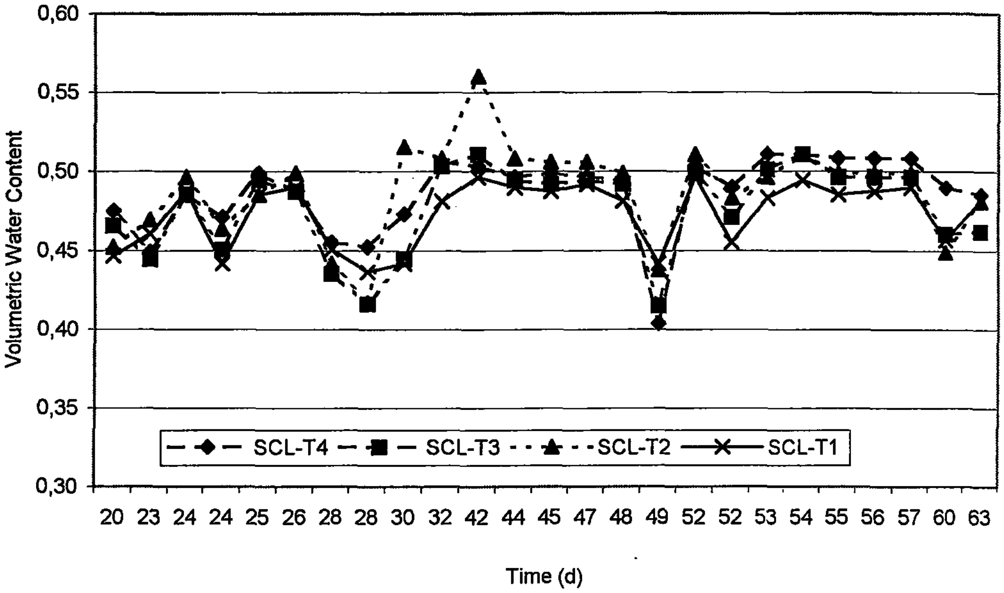

Figure 4.4: Volumetric water content through SCL column during slow rate infiltration

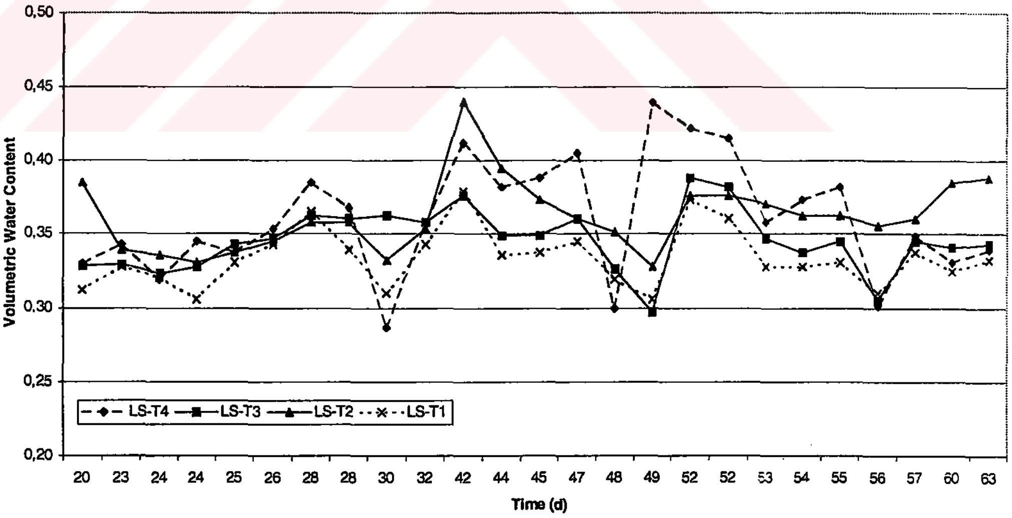

Figure 4.5: Volumetric water content through LS column during slow rate infiltration

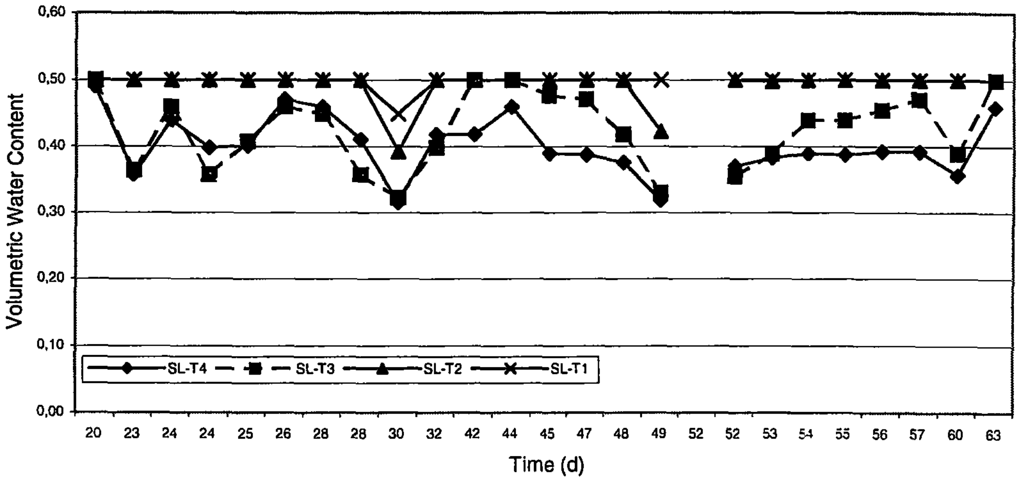

Figure 4.6: Volumetric water content of SL column during slow rate infiltration

concentration changes during SAT operation mainly show bacterial activity in the columns. This experimental work on SAT system investigation has a shorter operation period compared to the previous soil column studies given in the literature. It is hard to reach matured soil columns with a total operation period of *199 days*. DOC concentration trends of the soil columns during primary wastewater application period also confirmed that *24 days of operation* is unsatisfactory to have the soil columns ripened. COD concentration changes through the soil columns are due to not only biotic but abiotic organic removal mechanisms in the columns as well. Therefore COD parameter is continuously measured to observe *overall organics* *removal performance of the columns during synthetic wastewater application, 3 d wetting/ 4 d drying cycles and slow infiltration;* DOC snap measurements are also conducted to observe instantaneous distribution of dissolved organics through the columns.

a. Ripening Phase

DOC concentrations of influent and effluent wastewater are continuously measured to monitor organic removal efficiency of the columns. Influent and effluent concentrations through the columns are shown in Figure 4.7. Influent DOC has an average concentration of *56 ± 24.4 mg/l.* This high standard deviation is due to higher DOC concentrations present in few samples. LS column effluent usually has the same DOC concentrations with the column influent showing that effect of microbial activity is negligible throughout the column. SCL has a DOC effluent trend similar to LS. However, DOC concentrations in SCL effluent begin to increase starting from Day 14 despite a steady decline in influent DOC concentration since Day 11. This situation can be explained by this fact that desorbable organics present in the soil leaches out SCL column. SCL has an organic content of *2.25 %*, which is fairly high (Table 3.5). Certain amount of organics present in SCL soil may contribute to influent wastewater DOC. DOC behavior of SL column different from LS and SCL columns. DOC concentrations in SL effluent are *always higher* than that of the influent. SL soil has an organic content of *1.43 %* (Table 3.5). This organic content value is lower than that of SCL, which is the highest amongst the other soil samples. However, effluent DOC concentrations of SL column is the highest. Desorbable organic fraction in the total organic content of SL is thought to be *higher.*

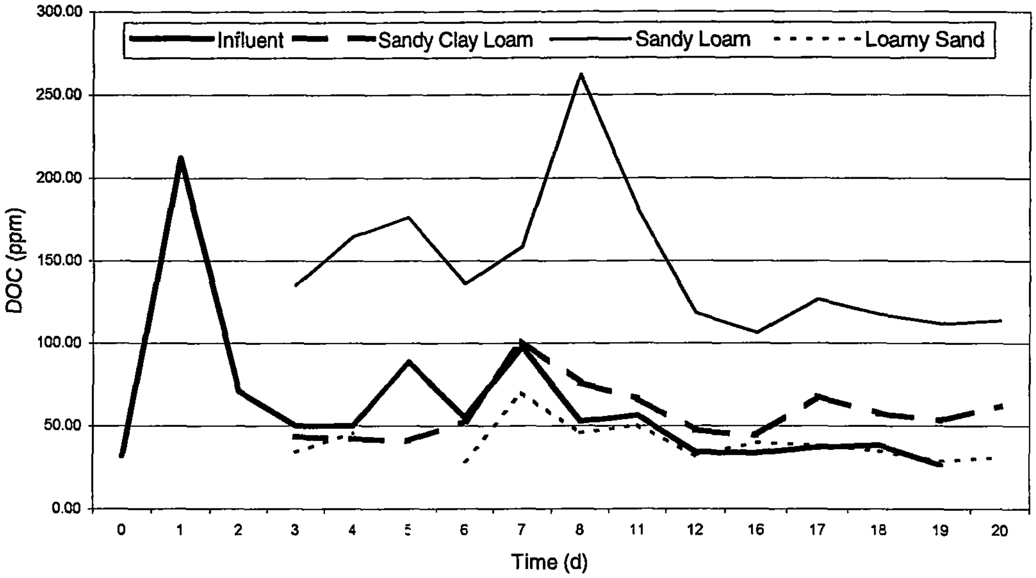

Figure 4.7: DOC concentrations through the columns during primary wastewater application

It is not possible to make reliable comments on development of microbial activity in the soil columns if there is an important contribution of inherent desorbable organics to DOC concentration of infiltrating wastewater. Therefore, it is decided to stop wastewater application and leach desorbable organic contents of the columns with *0.01 M* $CaSO_4$ solution before continuation of SAT application.

COD concentrations of the SL and SCL column effluents are given in Figure 4.8. LS column produced 0 mg/l COD concentration steadily from the very beginning of the operation. SCL column produced a peak COD concentration at day 2, and the concentration decreased to 0 mg/l at day 6. Also, SL column effluent had a COD peak at day 2, and effluent COD concentration dropped to 0 mg/l at day 6. When all of the columns have steady 0 mg/l COD concentration, desorbable organics were flushed and the application was over. Steady 0 mg/l COD concentration indicates that COD concentration had the same 0 mg/l value in the consecutive samples.

During synthetic wastewater application, influent and effluent COD concentrations were continuously measured. Effluent to influent COD ratios were plotted against time in Figure 4.9. Synthetic wastewater application was implemented for a relatively short period due to intensive agenda of study and time limitations. Initially applied $CaSO_4$ was drained from the column by the incoming synthetic wastewater plume. Hence, initial effluent to influent COD ratio was measured to be around 0.5. SCL column has only three available data points and they do not show a reasonable trend of decrement in effluent to influent COD ratio. Effluent to influent COD ratio for LS column decreases from around 0.85 to 0.7. SL column gives a peak effluent to influent COD ratio at day 3; however, the ratio decreases in the following days. Fox *et al.* (1998) reported that abiotic organic removal can

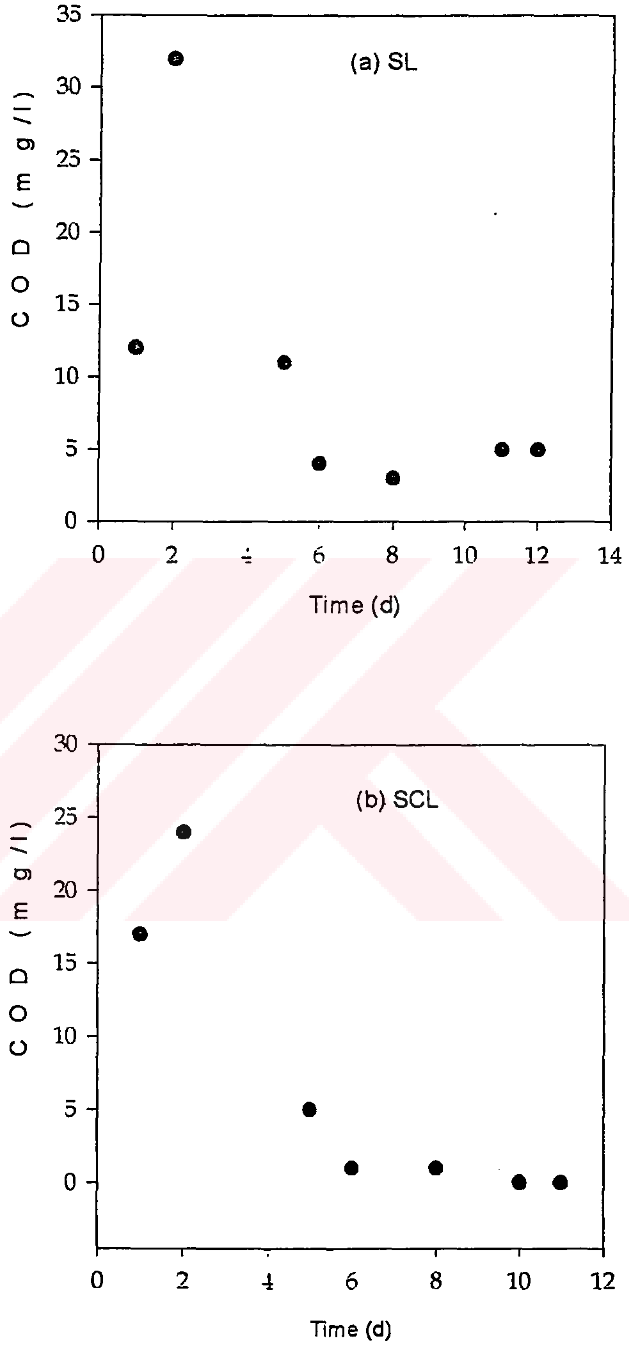

Figure 4.8: COD effluent concentrations for (a) SL column and (b) SCL column during $CaSO_4$ application

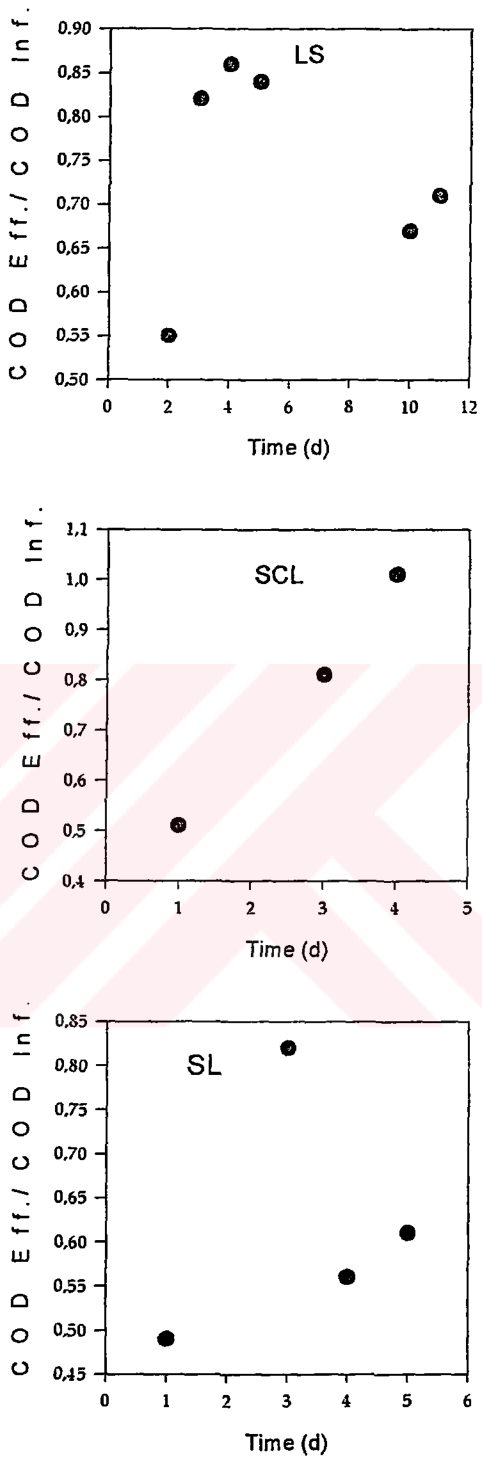

Figure 4.9: Effluent to influent COD ratios of the columns during synthetic wastewater application

be *up to 20 %* in SAT systems; hence, available data of LS and SL columns *may imply beginning of a biological activity.* Organic content analysis of the column topsoils indicated that organic matter content of the soils (SCL, LS and SL) reached their maxima during synthetic wastewater application. Figure 4.10 shows that organic matter content of SCL, LS and SL during synthetic wastewater application were as high as *8, 12.7* and *9.3 %* (w/w), respectively[3]. These values are also indicators of microbial activity on the topsoil of the columns.

b. Rapid Infiltration

i. *7 d Wetting/ 7 d Drying Cycles*

DOC concentrations of the soil columns are measured during Cycle 2 and Cycle 3. DOC concentrations of SCL, LS and SL columns are given in Figure 4.11.

SCL column has influent DOC concentrations of *13.2 mg/l* and *12 mg/l* in Cycle 2 and Cycle 3, respectively. However, effluent concentrations of the same column are *17.9* and *21.4 mg/l* . Effluent concentrations are *26.2 %* and *78 %* higher than influent concentrations. Moreover, there are peaks having higher concentrations than both influent and effluent DOC concentrations during Cycle 2 and Cycle 3. Figure 4.10 shows that organic content of SCL topsoil has increased to *7.95 %* during synthetic wastewater application. During the transition phase between synthetic wastewater application and 7 d wetting/ 7 d drying cycles, columns are dried for one

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[3] "Baseline Organic Content" term refers to the organic content of the soils prior to SAT application (Total organic contents of air-dried SCL, LS and SL samples)

day and then secondary wastewater application with 7 d wetting/ 7 d drying cycles was started. During the drying days, organic content decreased to *3.86 %* from peak value of *7.95 %* showing that some portion of the organics sorbed by the soil particles have mobilized during gravity drainage and started to travel through the soil. SCL has a low saturated hydraulic conductivity and detention time is higher than LS under the same hydraulic loading conditions. Therefore, mobilized organics entering SCL column have a high detention time (Average hydraulic detention time of 7 days). Desorbed organics (remaining from synthetic wastewater application) have contributed to DOC concentrations during 7 d wetting/ 7 d drying cycles.

LS topsoil organic content increases to *12.7 %* during synthetic wastewater application and the organic content has decreased to *3 %* during 7 d wetting/ 7 d drying cycles initiation (see Figure 4.10). Significant portion of topsoil sorbed organics have been mobilized during drainage and percolation. LS has the highest hydraulic conductivity amongst the other columns; therefore, organics leached after synthetic wastewater leaves LS column in a shorter time (Average hydraulic detention time of LS column is 1.8 days). Cycle 2 DOC concentrations of LS show that there is a decreasing trend from sampling port LS-S4 to Effluent Port, excluding LS-S2. Relatively high DOC concentration at LS-S2 *may be* resulting from desorbing organics. During Cycle 3, LS-S4 and LS Effluent DOC concentrations have higher values than the influent. LS4 DOC concentration can be resulting from dissolution of desiccated algae during drying period and leaching through the soil. Peak DOC concentration in LS effluent *may be due to* from desorbing organics.

SL organic matter content has reached to *9.27 %* during synthetic wastewater application*;* this parameter decreases to *2.9 %* when 7 d wetting/ 7 d drying cycles begin (see Figure 4.10). Significant amount of time of 8.6 days). Hence, desorbed organics plume has not leached from the column throughly. Especially SL-S3 and SL-S2 sampling ports show presence of high DOC concentrations at the bottom of the column. SL-S4 port has low DOC concentration in Cycle 2 but this condition changes in Cycle 3. High DOC concentration during Cycle 3 at sampling port SL-S4 *may be resulting* from desiccated algae contribution to percolation wastewater.

The total number of pore volumes passed through the columns are *2.0, 10.0* and *1.3* for SCL, LS and SL, respectively. Effect of dissolved organics remaining from synthetic wastewater application is expected to be minimal for LS column as dilution effect of secondary wastewater on LS is the highest. DOC peaks seen in Figure 4.11 also imply that DOC contribution from antecedent (displaced) wastewater to infiltrating (displacing) wastewater is highest in SL, lower in SCL and lowest in LS. It is not possible to discuss on DOC removal efficiencies and microbial growth in the columns as the column effluents usually have very high DOC concentrations exceeding the influent DOC concentrations. It is necessary to pass more secondary wastewater through the columns in order to wash out remaing DOC from synthetic wastewater application period.

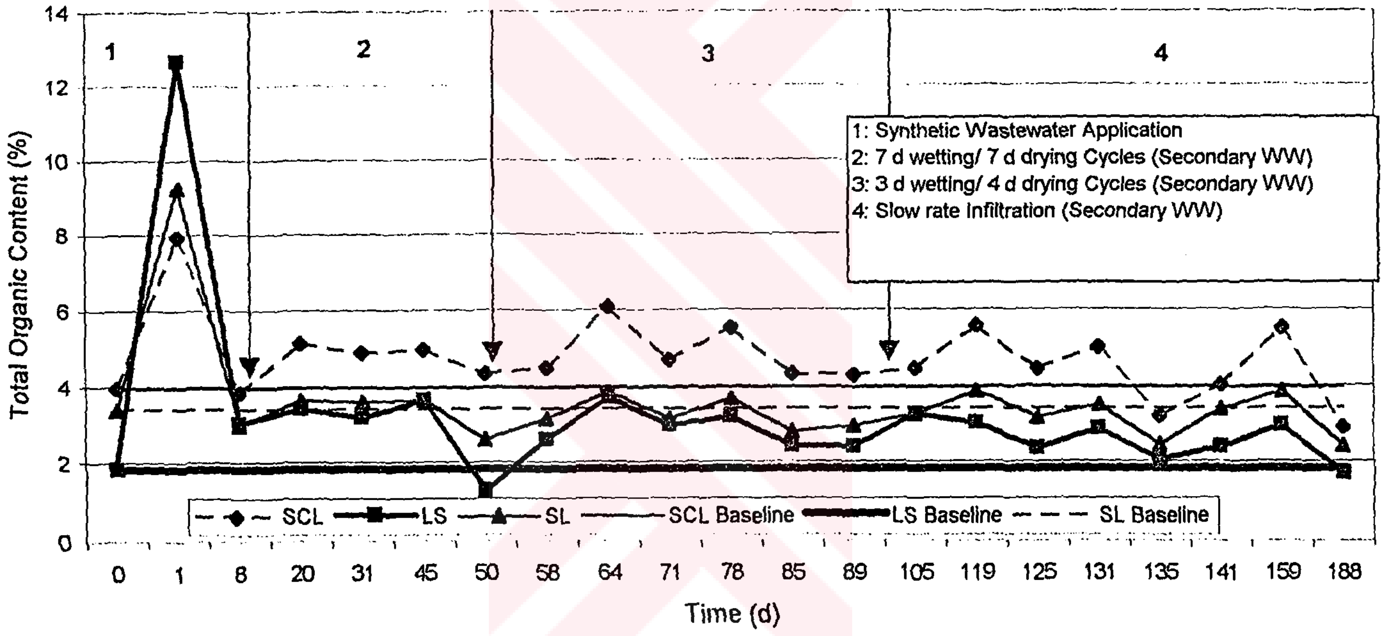

Figure 4.10: Total organic content of column topsoils during different phases of SAT operation

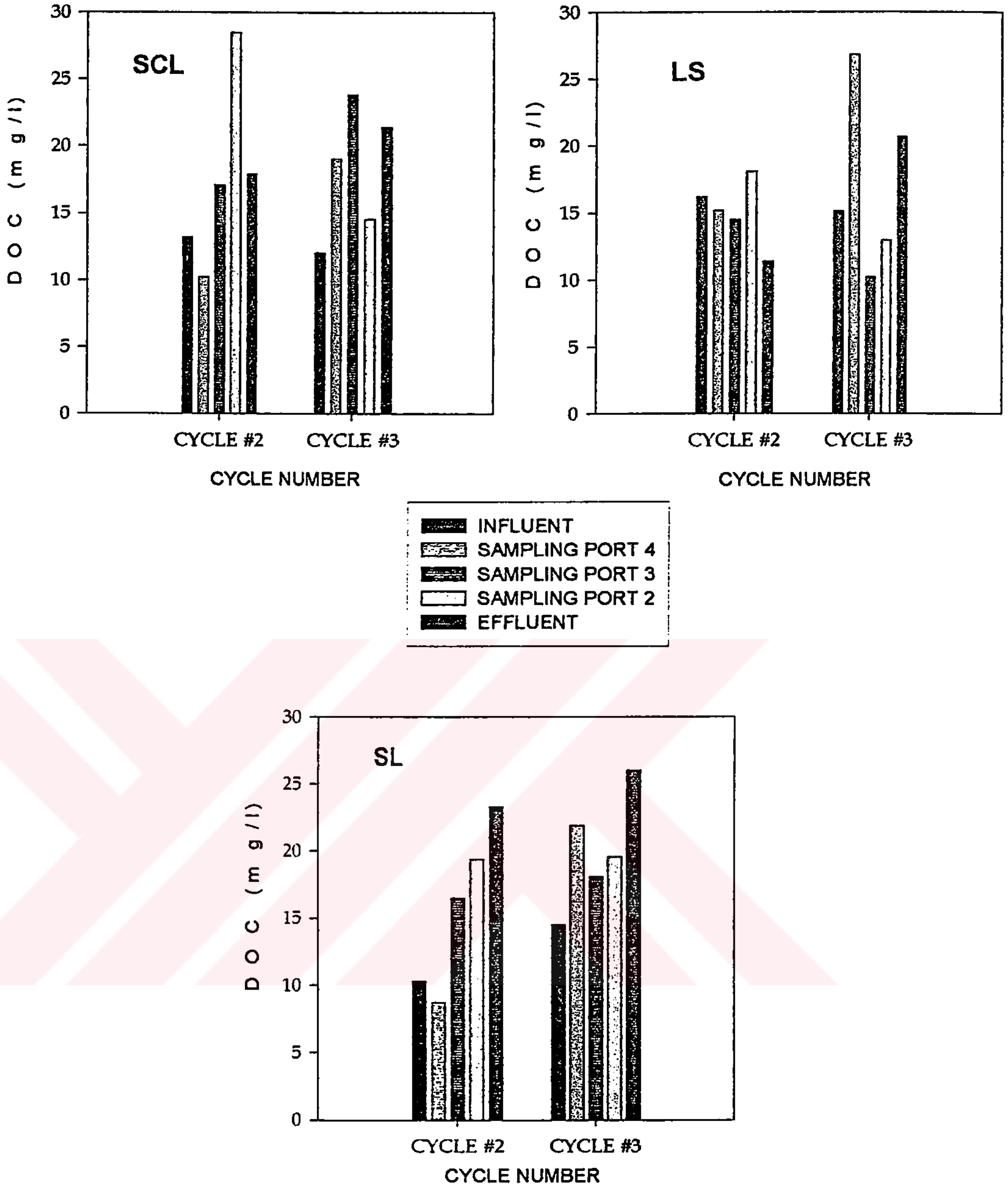

Figure 4.11: DOC concentrations through the columns during 7 d wetting/ 7 d drying cycles

ii. *3 d Wetting/ 4 d Drying Cycles*

COD concentrations are measured during 3 d wetting/ 4 drying cycles; moreover, a snap measurement of DOC is realised during 6th. wetting period. Time variant COD concentrations through the columns wereanalysed in detail and the concentration trends in the sampling ports of the columns were examined and discussed.

SCL ponding was continuously aerated during 3 d wetting/ 4 drying cycles. DO concentration through SCL column is shown in Figure 4.12. Average influent DO concentration is *5 mg/l.* Average effluent DO concentration is *2.6 mg/l.* DO decreases from *5 mg/l* to *1.5 mg/l* passing through the first 9 cm of topsoil. DO profile in SCL column depicts that aerobic conditions prevail.

LS ponding was continuously aerated during the cycles. DO concentration through LS column is shown in Figure 4.12. Average influent DO concentration is *5.5 mg/l.* Average effluent DO concentration is *2.8 mg/l.* DO decreases from *5.5 mg/l* to *1.5 mg/l* passing through the first 9 cm of topsoil. DO profile of LS column shows that aerobic conditions are present.

SL ponding was *not* aerated during the cycles. DO concentration through SL column is shown in Figure 4.12. Average influent DO concentration is *2.3 mg/l.* Average effluent DO concentration is *3.2 mg/l.* Influent DO is lower than effluent DO. On the other hand, DO concentration trend through the column is a declining trend. SL column has the lowest infiltration rate and highest detention time; infiltrating wastewater *is re-aerated* in Layer #5

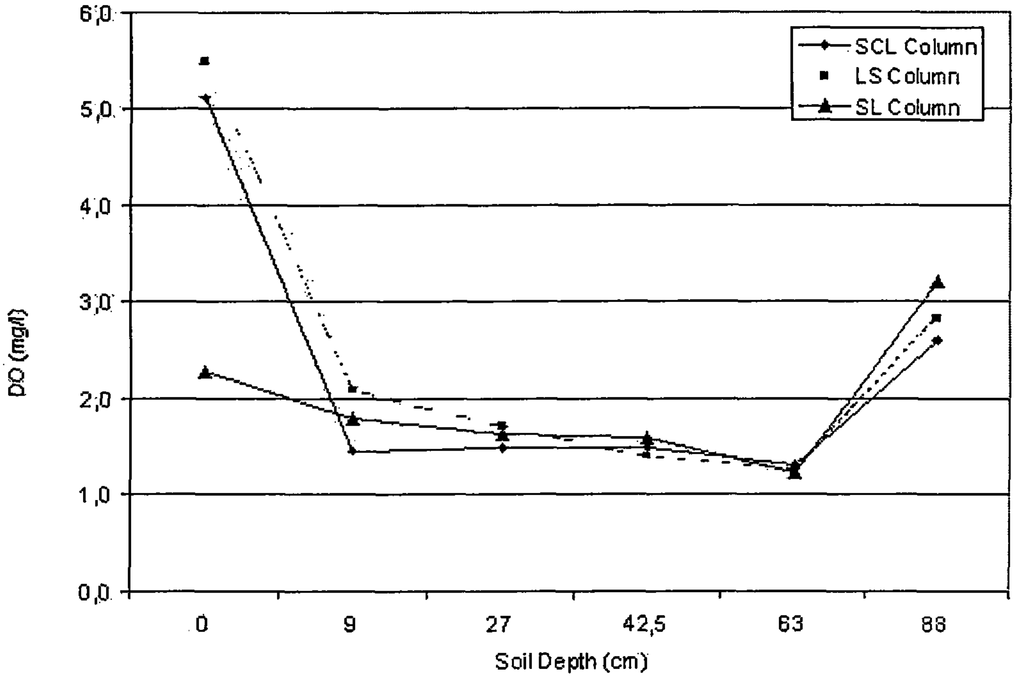

Figure 4.12: Dissolved oxygen concentrations through the columns during 3 d wetting/ 4 d drying cycles

with oxygen entering the system through the effluent port into partially unsaturated parts of Layer #5. Detention time of Layer #5 in SL column ranges between *50-60 hrs;* this time is satisfactory for dissolution of molecular oxygen present in unsaturated parts of the Layer #5 to liquid phase. Hence, effluent DO concentration is higher than that of influent. Average DO concentration decreases from *2.3 mg/l* to *1.8 mg/l* through the first 9 cm of topsoil. DO profile of SL shows higher DO concentrations at the same sampling ports compared to SCL and LS columns. Aerobic conditions are also present in the SL column.

SCL, LS and SL have average DO removals of *70, 73* and *22 %* respectively. SCL and LS have capacity to utilize around 3-4 mg/l dissolved oxygen during oxidation of organics. Biofilm developed in the top 9 cm of SL soil does not remove significant amount of dissolved oxygen. SL ponding was not aerated; hence, influent DO concentration of SL column is lower compared to SCL and LS columns. Aerobic microbial activity in topsoil of SL could be lower than those of SCL and LS columns. Consequently, DO removal in SL was significantly less than SCL and LS columns.

Topsoils of the columns are also analysed during 3 d wetting/ 4 d drying cycles (see Figure 4.10). SCL total organic content ranges between *4-6 %*; while baseline SCL total organic content is *4 %.* LS total organic content increases from *1.26 %* to *2.60 %* with the initiation 3 d wetting/ 4 drying cycles. During 3 d wetting/ 4 d drying cycles, LS total organic content ranges between *2.40-2.60 %;* while LS baseline total organic content is *1.82 %.* SL total organic content ranges between *2.60-2.95 %;* while the baseline organic content is *3.40 %.*

DO and total organic content data were assessed together. SL topsoil had the lowest organic content and lowest DO removal. SL average organic content was lower than the baseline organic content of the same column soil. SCL and LS topsoils had higher total organic contents than the baseline values and they have reasonable DO reductions.

Average influent COD concentration of the columns is *44 mg/l* while average effluent COD concentration of the columns are *30 mg/l, 19 mg/l* and *28 mg/l* for SCL, LS and SL columns, respectively. COD concentrations through SCL column during 3 d wetting/ 4 d drying cycles are shown in Figure 4.13. COD is removed through the topsoil (0-9 cm) with a range of *50-70 %* during the initial four cycles. During Cycle 1 and Cycle 5, COD concentrations have an increasing trend through the column after the 9th. cm of soil profile. During Cycle 5 and Cycle 6, COD removal is *not effective* in Layer #1. Layer #3 had a significant COD removal from Cycle 2 to Cycle 4. COD concentration was same at SCL-Effluent from Cycle 1 to Cycle 4. Overall COD removal for SCL column is *33 %.*

COD concentrations through LS column during 3 d wetting/ 4 d drying cycles are shown in Figure 4.14. COD removal through Layer #1 ranges between *19-66 %*. Lowest removal occurs during the lowest influent COD application in Cycle 5. There is no reasonable increase in COD profile through LS column during the operation except the COD spike in Layer #2 at Cycle 6. COD concentrations show steady behavior in Layer #5 although LS influent COD concentrations fluctuate from cycle to cycle. Overall COD removal efficiency of LS column drops from *50-60 %* to *22 %* during Cycle 5, which has the lowest influent COD concentration. Average overall COD removal removal efficiency is *54 %.*

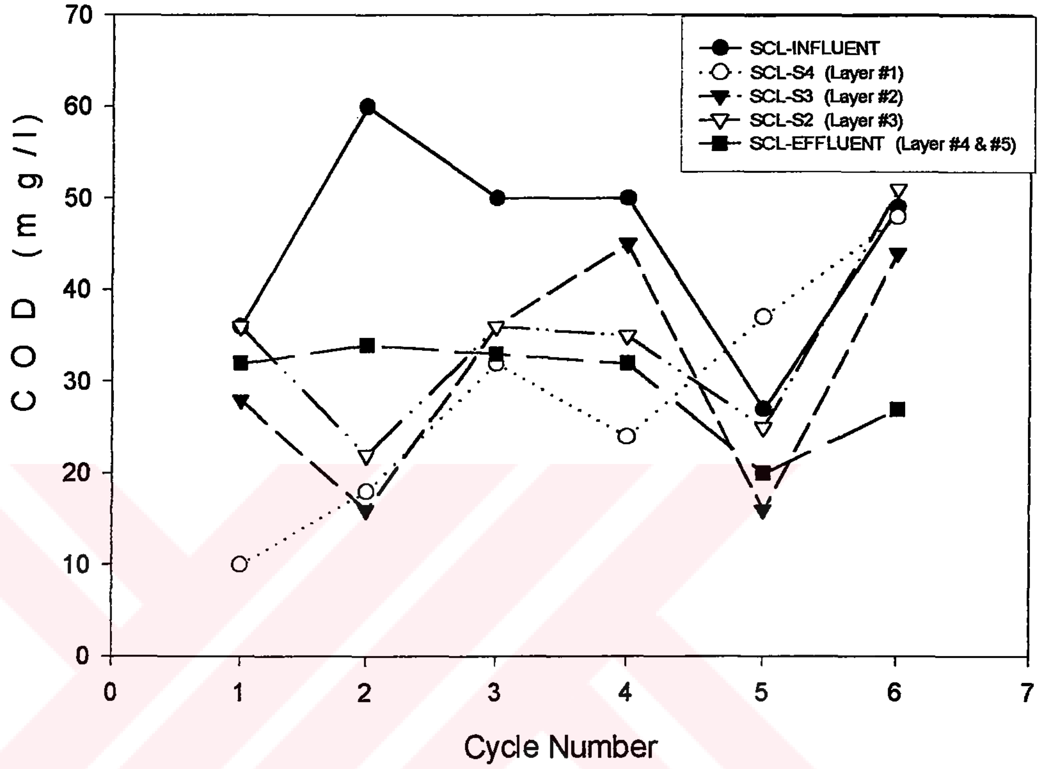

Figure 4.13: COD Concentrations through SCL column during 3 d wetting/ 4 d drying cycles

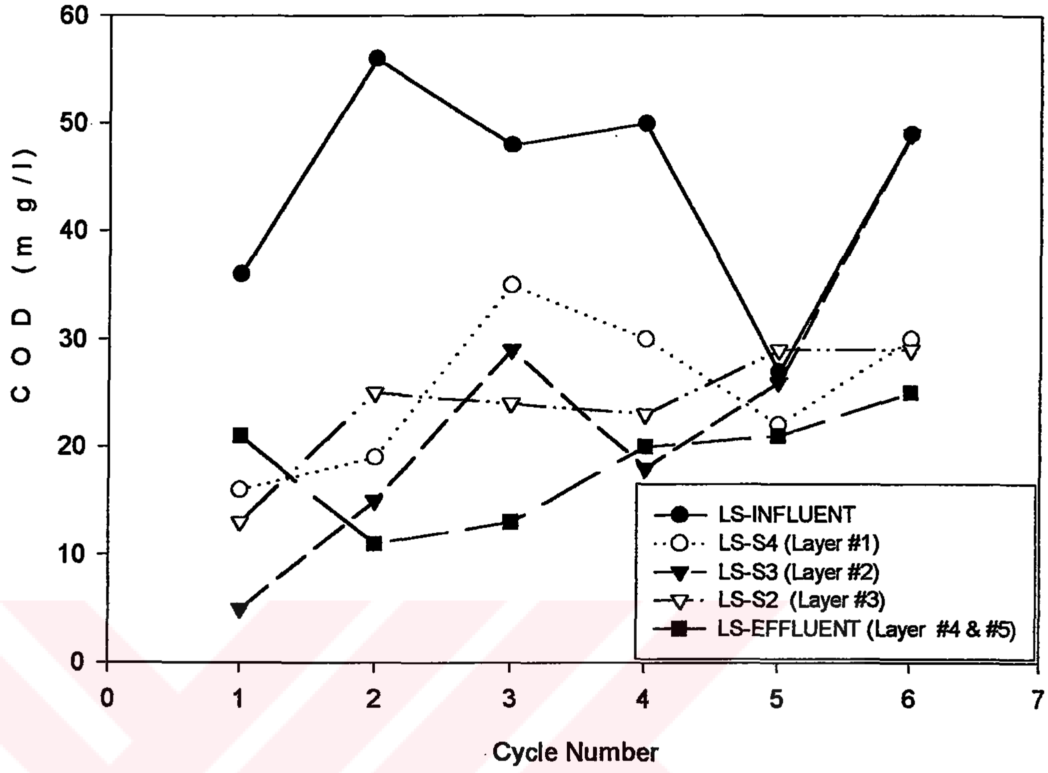

Figure 4.14: COD concentrations through LS column during 3 d wetting/ 4 d drying cycles

COD concentration profile of SL is shown in Figure 4.15. COD removal through Layer #1 is very low and SL4 COD concentration exceeds influent COD concentration. There is reasonable COD removal in Layer #1 of SL only during Cycle 2 and Cycle 4. Layer #2 and Layer #3 have lower COD concentrations than those of Layer #1. *COD removal mechanisms are more effective in Layer #2 and Layer #3.* Overall column COD removal is significant during Cycles 1, 2 and 4. During Cycle 3, a COD spike having an equal value with the corresponding influent COD quantity is observed. Overall SL COD removal efficiency is almost 0 % in Cycle 3 and Cycle 5. Excluding these two cycles, average overall COD removal efficiency is *49 %*; when all available COD influent and COD effluent data are used, overall average COD reduction efficiency becomes *30 %.*

SCL and LS consume high amount of DO oxygen (reduction of 70 and 73 %) in Layer #1 during the cycles and both of the columns have higher total organic content in Layer #1 than the baseline total organic content. Higher total organic content in topsoil implies higher microbial activity, hence it is expected that COD removal efficiencies of SCL and LS *should be greater* than that of SL column. Experimental data show that LS has the highest average COD removal; however, there is not a significant difference between removal efficiencies of *72, 70, 36* and *52 %* through Layer #1, respectively*.* SCL and SL. SCL has removal efficiencies in the first four cycles through Layer #1: SL has the following removal efficiencies through Layer #1 during the same cycles: *18, 81, 15* and *54 %.* Therefore, SCL has usually better COD removal efficiency than SL in Layer #1. . However, SCL Layer #2 has contributed to COD concentrations in Cycle1 and Cycle 4 while only SL Layer #5 has contributed to COD only in Cycle 3.

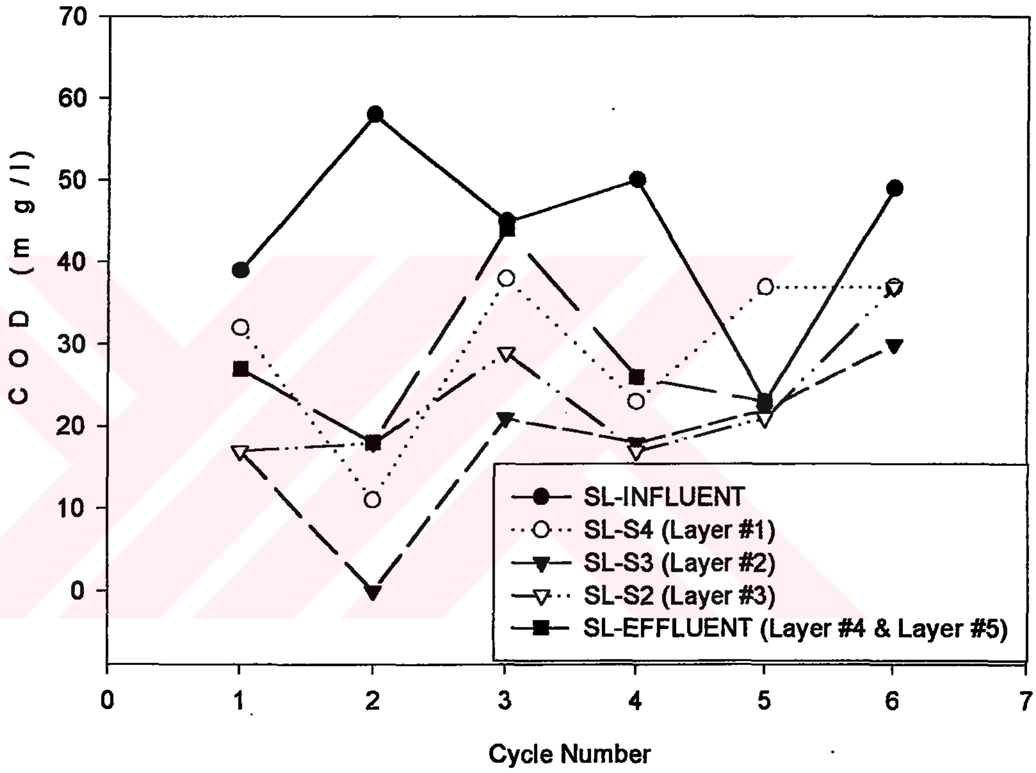

Figure 4.15: COD concentrations through SL column during 3 d wetting/ 4 d drying cycles

Baseline total organic content of SCL is higher than SL. SCL might have a higher affinity to sorb and desorb organic matter, which may ultimately effect effluent water quality of SCL column.

LS has highest average COD removal efficiency although it has the lowest hydraulic detention time. This finding coincides with the statement of Fox *et al.* (1998) saying that organic removal efficiency is *independent of infiltration rate.*

DOC of the columns are measured during Cycle 6. Liquid samples are taken from the upper sampling ports (e.g. SL-S4, SCL-S3), influent and effluent wastewater. DOC concentrations of the columns are given in Figure 4.16. DOC concentrations do not change considerably in SCL and LS columns; there is a DOC spike observed in SL-S4. This may be due to organics leaching from dessicated algae and/or desorbing organics. SCL, LS and SL *do not* remove DOC in Layer #1 and effluent DOC concentrations of the columns are not lower than influent DOC concentrations either. Cycle 6 of 3 d wetting/ 4 d drying cycles is not effective in removal DOC.

c. Slow Rate Infiltration

COD concentrations were continuously measured for the slow rate operation period. Wastewater was not aerated during this phase of SAT operation. Total organic content of the topsoils were also measured. DO profile of the columns were also determined.

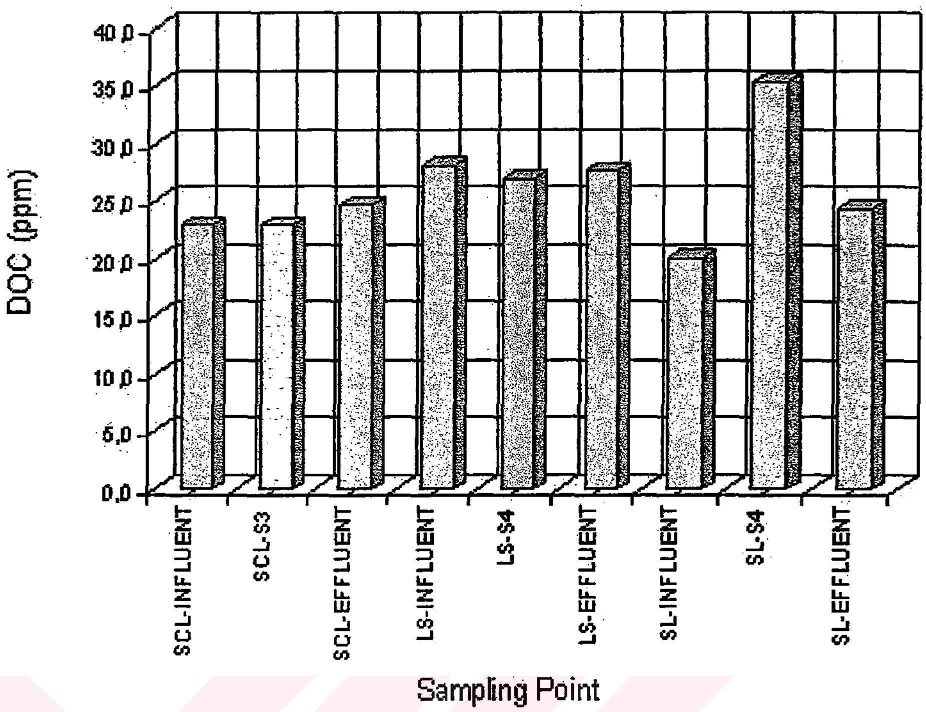

Figure 4.16: DOC concentrations of the columns during cycle 6 of 3 d wetting/ 4 d drying cycles

Total organic contents of SCL, LS and SL columns during slow rate infiltration are given in Figure 4.10. Initial total organic content of SCL was *4.46 %* and the final total organic content was *2.9 %.* The organic content was *usually* over the baseline value during operation. Initial organic content of LS topsoil is *3.2 %* and final organic of the same topsoil is *1.82 %.* The total organic content is *always* higher than the baseline value during slow rate application. SL topsoil initial organic content is *3.26 %* and final value of this parameter is *2.41 %.* Total organic content of SL topsoil is *slightly lower* than the SL baseline value for total organic content.

DO profiles of SCL, LS and SL columns are given in Figure 4.17. Average influent DO concentration (Influent Tank) is *1.9 mg/l* (this value is same for the other two columns as the columns use the same influent tank). Average SCL-S1, LS-S1 and SL-S1 DO concentrations are *1.2 mg/l, 1.3 mg/l* and *1.1 mg/l,* respectively.

Average influent COD concentration is *42 mg/l.* Average effluent COD concentrations for SCL, LS and SL columns are *36, 29* and *27 mg/l,* respectively. COD concentrations through SCL column during slow rate infiltration is given in Figure 4.18. Layer #1 reduces COD on Day 6, 17 and 56; the other sampling days influent and sampling port COD concentrations are almost same. Layer#1 do not significantly remove COD; Figure 4.17 indicates that DO utilisation through the SCL column is very low. Highest overall COD removal efficiency of SCL is observed on Day 56 as *64 %.* Overall average COD removal is negligible in this column.

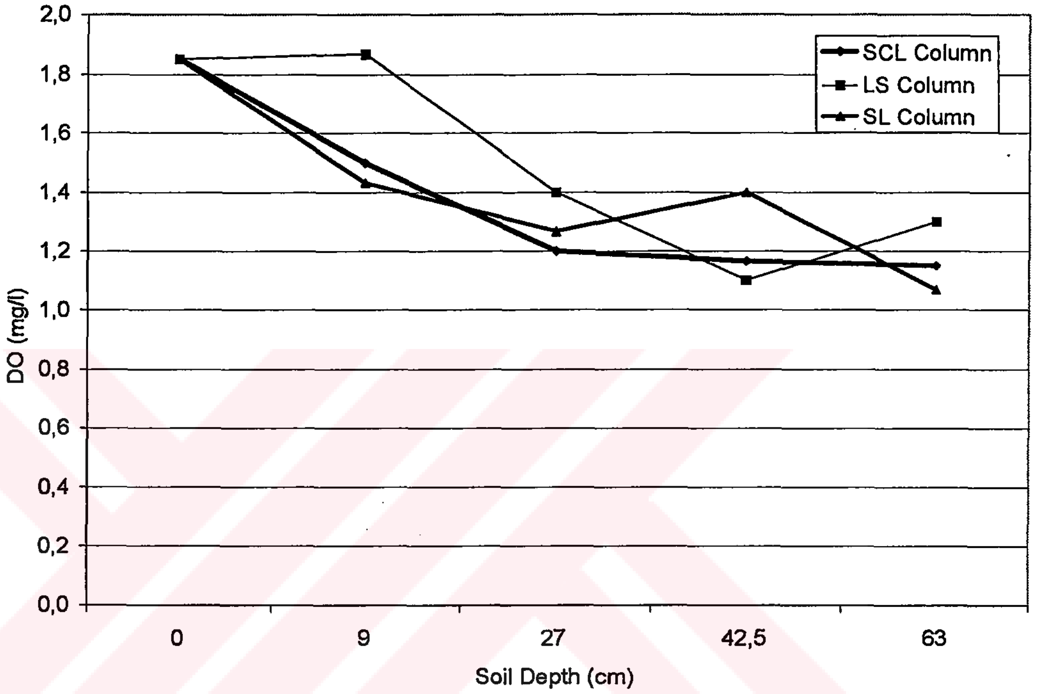

Figure 4.17: Dissolved oxygen concentrations through the columns during slow rate infiltration

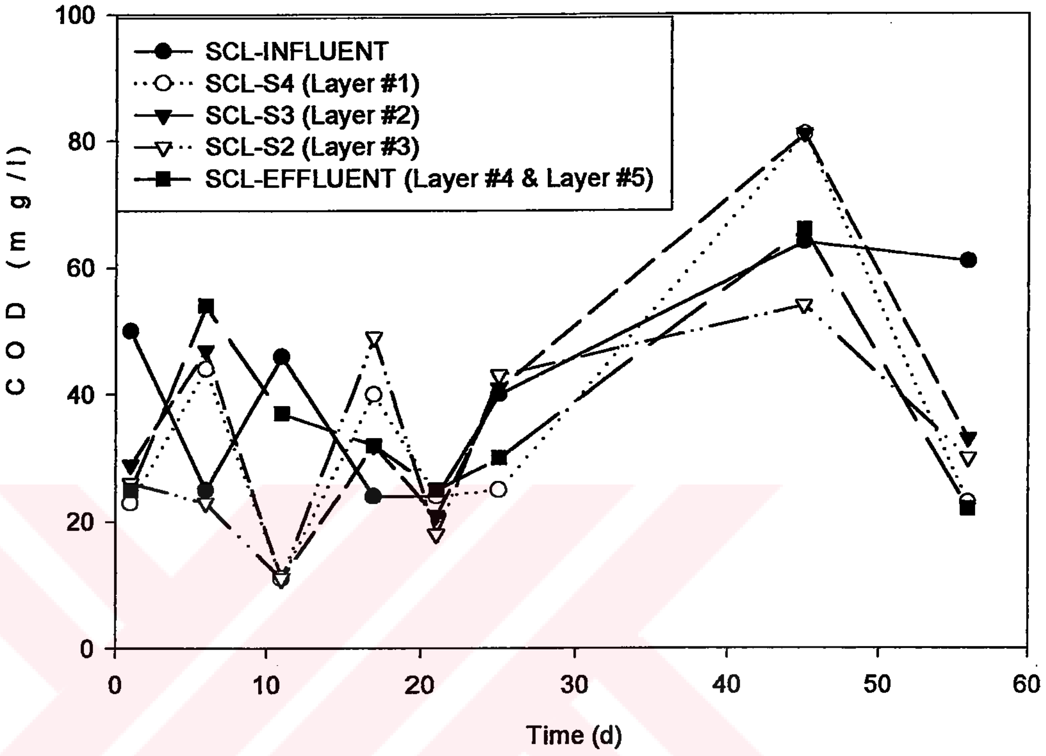

Figure 4.18: COD concentrations through SCL column during slow rate infiltration

COD concentrations through LS column are given in Figure 4.19. LS Layer #1 COD removal trend is different than SCL column. COD is removed through Layer #1 on all of the sampling days except Day 6 when influent COD concentration is *25 mg/l*. DO concentration of influent wastewater does not decrease through Layer #1 as show in Figure 4.17. It is clearly seen that COD removal efficiencies increase considerably when influent COD concentrations are on the rise after 25 days from the initiation of slow rate infiltration period. Highest COD removal observed is *54 %.* Average COD removal is *41 %.*

COD profile of SL column is given in Figure 4.20. Layer #1 has COD removal on Day 1 and during the period beginning from Day 25 lasting until Day 56. DO concentration of influent tank and COD influent concentrations during the period between Day 1 and Day 25, generally decrease (see Figure 4.17). Effluent COD concentrations are almost equal to influent COD concentrations. However, Day 11 sampling show that a significant COD removal is realised especially in Layer #2 and Layer #3. Highest overall removal efficiency of Day is *76 %* on Day 11. Overall average COD removal is *37 %.*

DO profile of the columns show that DO of influent wastewater was used slightly by Layer #1 of SCL and SL columns. Layer #1 LS column did not consume any DO through slow rate infiltration. Therefore, aerobic biofilm of SCL and SL were slightly active while LS aerobic biofilm activity was negligible. Hence, LS column removed COD by abiotic and anerobic mechanisms during slow rate infiltration.

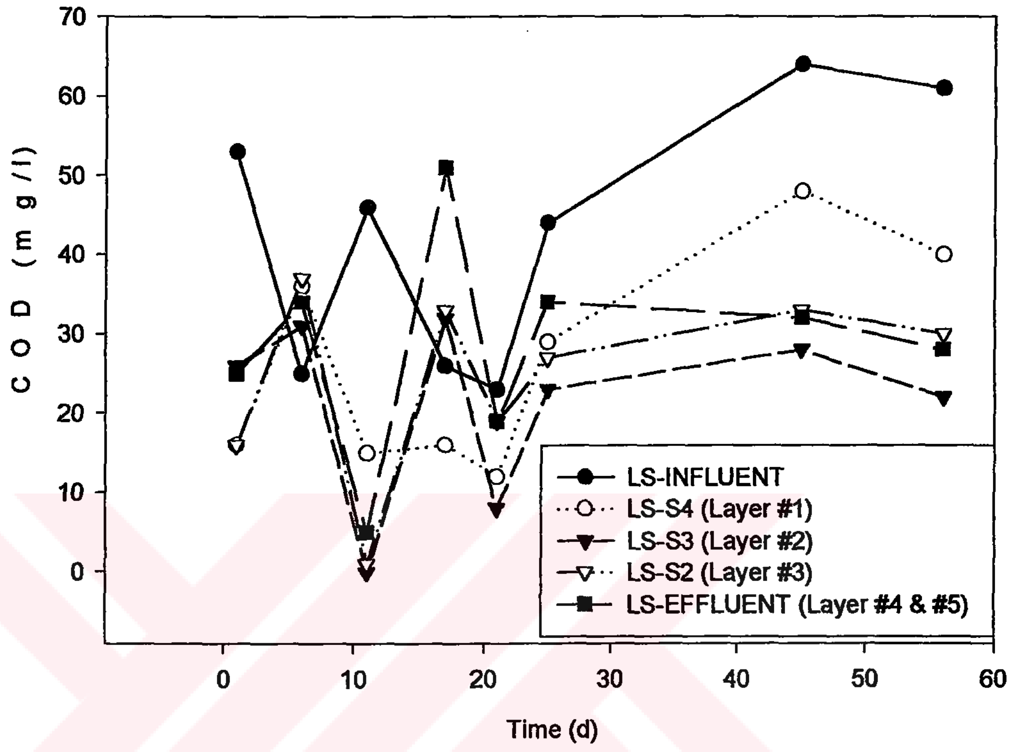

Figure 4.19: COD concentrations through LS column during slow rate infiltration

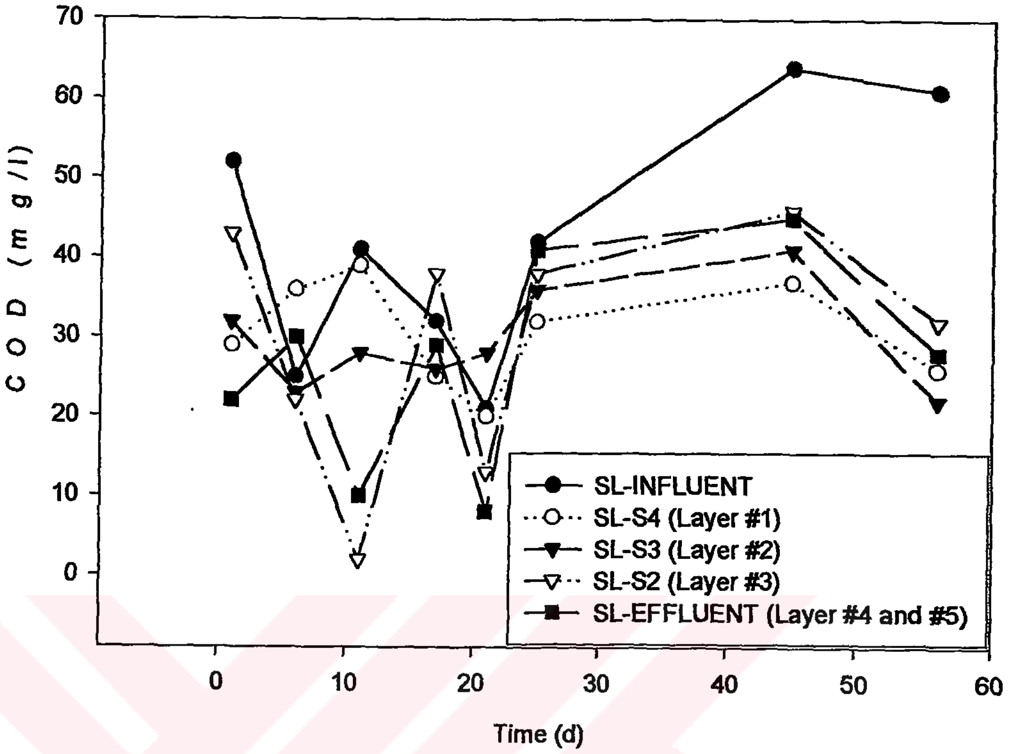

Figure 4.20: COD concentrations through SL column during slow rate infiltration

COD removal performance of the columns decrease when influent COD concentration is under *25 mg/l.* The influence of influent COD concentration on biochemical organic removal can be seen by examining the COD removal behavior in Layer #1 of the columns (Layer #1 is the most biologically active part of the soil columns). Layer #1 of SCL and SL columns did not remove influent wastewater having 25 mg/l COD (see Figure 4.18 and Figure 4.20). COD removal efficiency of Layer #1 in LS column also decreased upon receiving 25 mg/l or less COD concentration; however, the layer removed influent COD slightly when influent COD was around 25 mg/l (see Day 10-20 interval in Figure 4.19). Therefore, LS topsoil was more efficient in removal of low concentration COD compared to SCL and SL columns.

4.2.2 REMOVAL OF NITROGEN SPECIES

The nitrogen species continuously measured during SAT application are: NH_3 (rapid infiltration), NO_2^- and $NO_3^=$. TKN measurements are conducted as snap shot measurements during rapid and slow rate infiltration phases.

Nitrogen species dynamically may tranform each other during the process. In this SAT application, presence of molecular oxygen (nitrification) and organic matter (denitrification) are important. Therefore, COD: NO_3-N ratios are calculated to see favorability of denitrification process through the columns. Moreover, double sampling were conducted during some of the cycles of rapid infiltration. This aims to observe any nitrate spike forming during flooding. Nitrate spikes were usually observed in the initial sample of a cycle. Therefore, initial sample data (two samples were taken in the same wetting period of a cycle) were excluded when the overall nitrate profiles were plotted. These initial samples were plotted exclusively together with final samples of the same wetting period in order to observe movement of $NO_3^=$ spikes through the soil profile.

a. Rapid Infiltration

i. 7 d Wetting/ 7 d Drying Period

Average influent NH_3-N concentration of SCL, LS and SL columns is around *17 μg/l.* This concentrations too low and showing that ACWTP wastewater samples were nitrified and ammonia had been converted to other nitrogen species such as NO_2^- and $NO_3^=$.

NH_3-N concentrations through SCL, LS and SL columns are shown in Figure 4.21. Effluent NH_3-N concentrations of the columns are around *1 μg/l.* Most of NH_3-N removal is realized in Layer #1 of the columns. Layer #1 removal efficiencies of SCL, LS and SL are *71 %, 73 %* and *64 %.* NH_3 concentrations are very low; hence, the sorbed NH_3 (during wetting period) may impose a risk of nitrate/nitrite spikes in the following cycles if they accumulate in the soil longer time (with respect to the other SAT studies receiving high NH_3-N bearing wastewater) without being nitrified.

Average influent NO_2-N concentration of SCL, LS and SL columns *are around 1 mg/l.* NO_2-N distribution through SCL, LS and SL columns are given in Figure 4.22. In all three columns, there is a drastic decline in NO_2^- concentration in Layer #1 and there after concentration does not change significantly with depth.

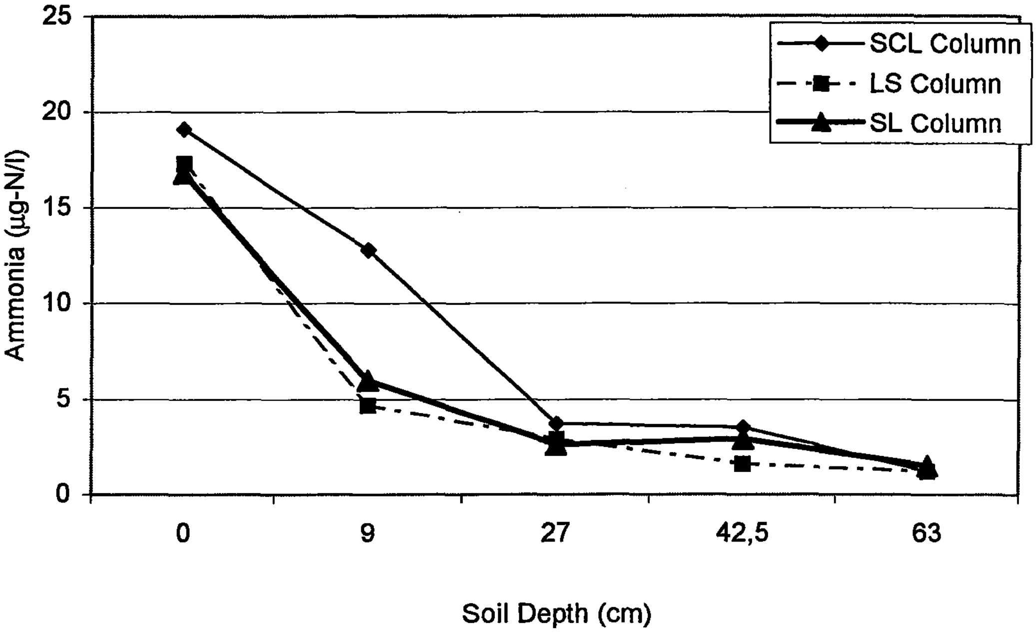

Figure 4.21: Ammonia concentrations through the columns during 7 d wetting/ 7 d drying cycles

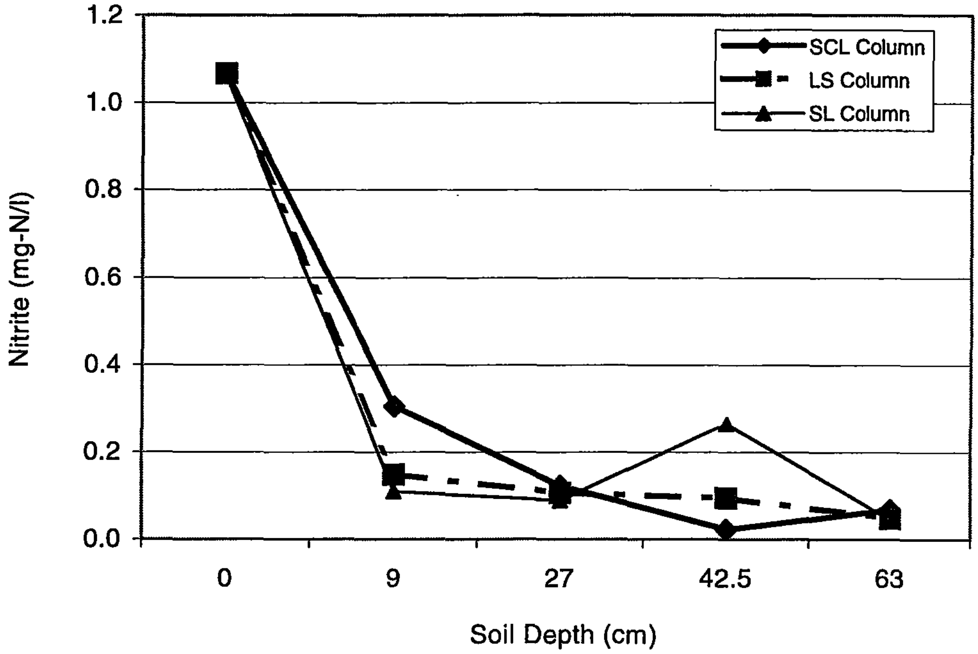

Figure 4.22: Nitrite concentrations through the columns during 7 d wetting/ 7 d drying cycles

NO_2^- concentration changes within the same wetting period of a cycle have also been observed. SCL and LS have *two* spikes of nitrite during initial flooding and SL has also one spike of nitrite during Cycle 2 (Figure 4.23, Figure 4.25, Figure 4.27). Formation of nitrite spikes are also observed during Cycle 3; none of the columns have nitrite spikes at the beginning or end of the wetting period (Figure 4.24, Figure 4.26, Figure 4.28). This finding shows that nitrite spikes are not continuously repeated at each flooding initiation. Overall nitrite reductions of SCL, LS and SL columns are *94, 95* and *96 %,* respectively.

One sample data of NO_3-N was obtained from SCL column operating under 7 d wetting/ 7 d drying cycles (from Cycle #3). Nitrate profiles of the columns are shown in Figure 4.29. The measured influent, SCL-S4, SCL-S3, SCL-S2 and effluent NO_3-N for SCL column concentrations are: *12.3, 5.2, 7.2, 0* and *1.2 mg/l,* respecively. Highest reduction is occuring in Layer #1 during this cycle; denitrification *may be* effective in this layer during Cycle 3. Overall NO_3-N reduction efficiency is *90 %.* Liquid samples are taken from LS column on the same day (Cycle 3). Influent, LS-S4, LS-S3, LS-S2 and effluent NO_3-N concentrations of LS column are as follows: *12.3, 6.9, 8.4, 6.9* and *0.9 mg/l*, respectively. Overall NO_3-N reduction is *93 %.* Influent, SL-S4, SL-S3, SL-S2 and effluent for SL column NO_3-N concentrations: *12.3, 4.5, 3.6, 0* and *3.3 mg/l*, respectively. Layer #1 is the most effective layer in denitrification. Overall NO_3-N reduction efficiency is *73 %.*

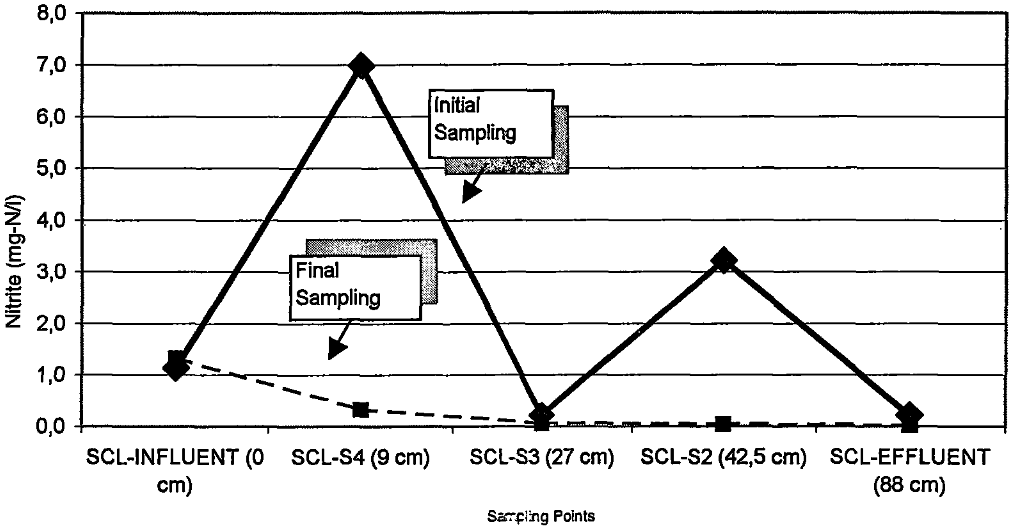

Figure 4.23: Nitrite distribution through SCL column during cycle 2 of 7 d wetting/ 7 d drying cycles

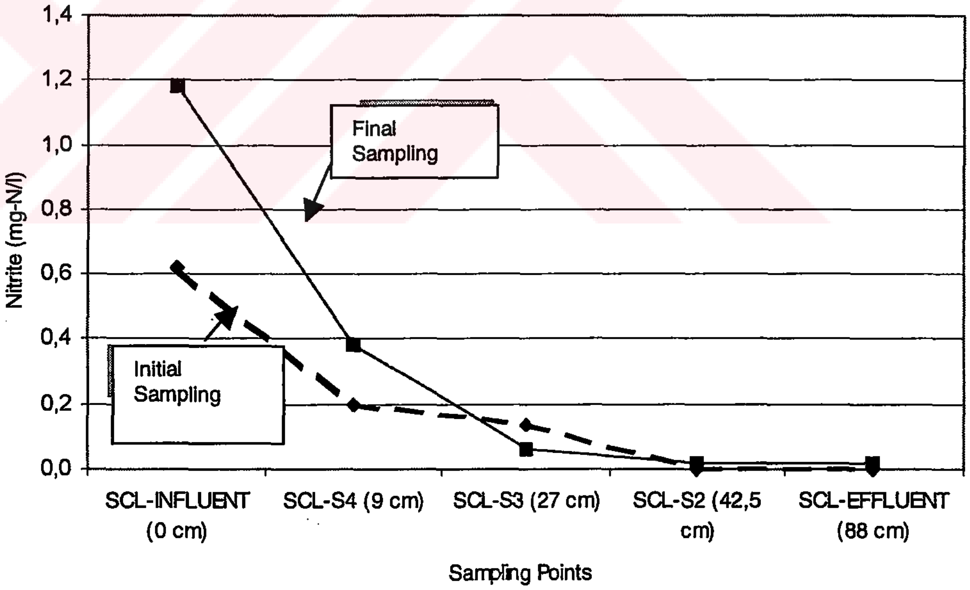

Figure 4.24: Nitrite distribution through SCL column during cycle 3 of 7 d wetting/ 7 d drying cycles

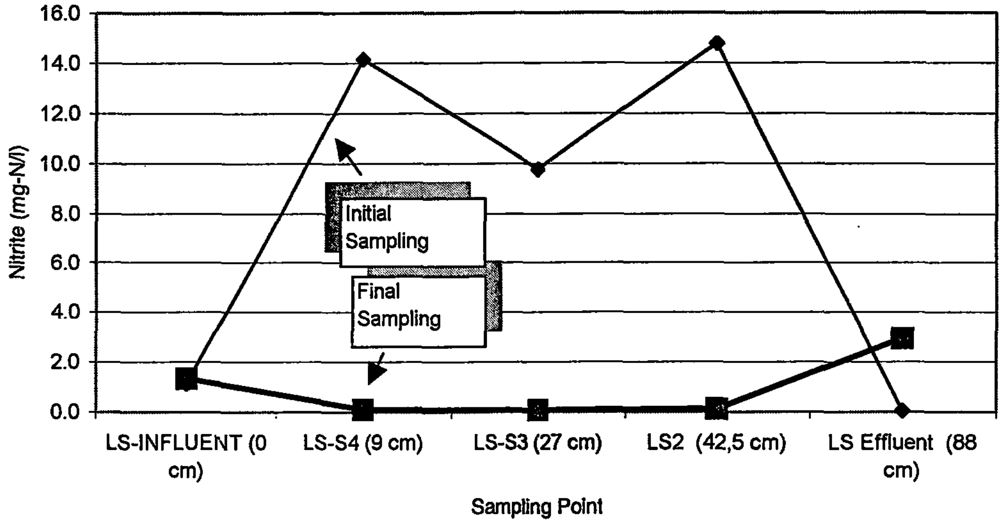

Figure 4.25: Nitrite distribution through LS column during cycle 2 of 7 d wetting/ 7 d drying cycles

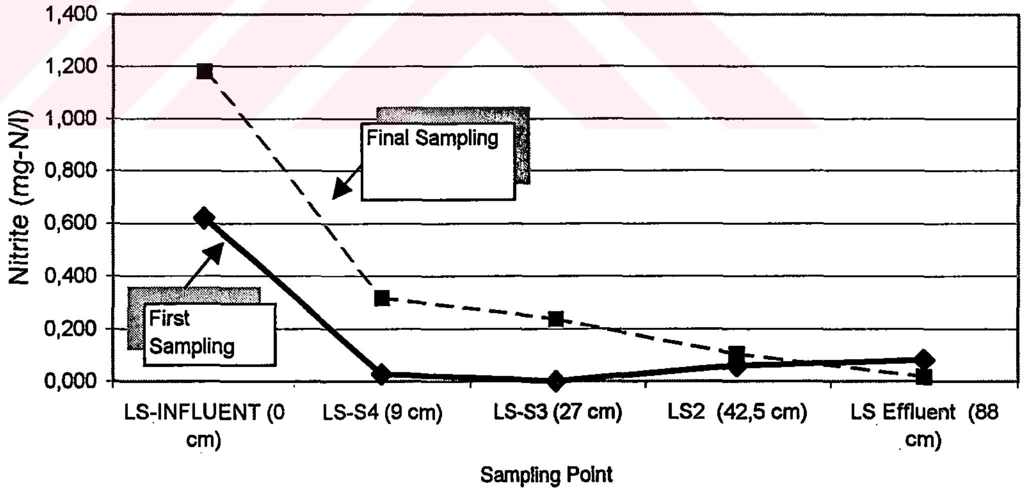

Figure 4.26: Nitrite distribution through LS column during cycle 3 of 7 d wetting/ 7 d drying cycles

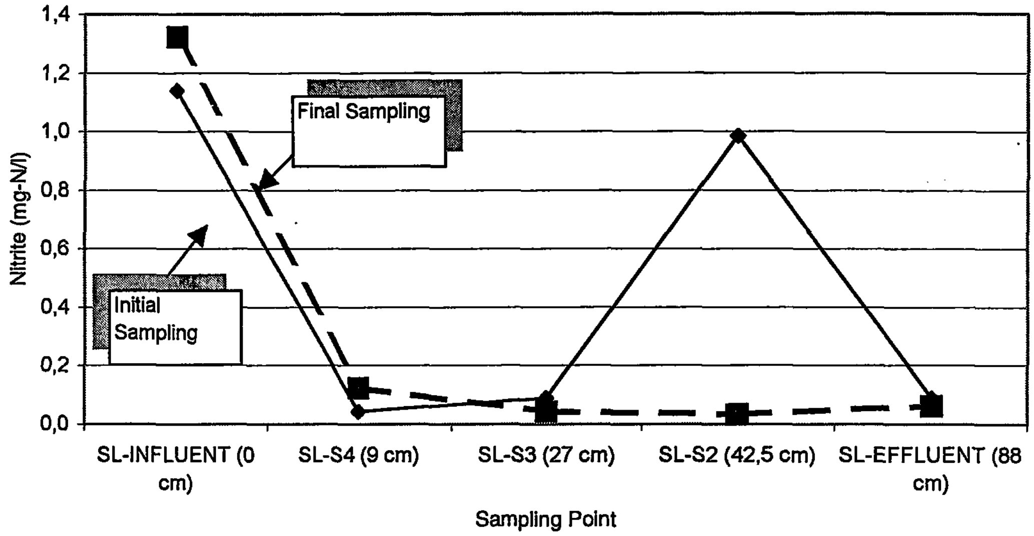

Figure 4.27: Nitrite distribution through SL column during cycle 2 of 7 d wetting/ 7 d drying cycles

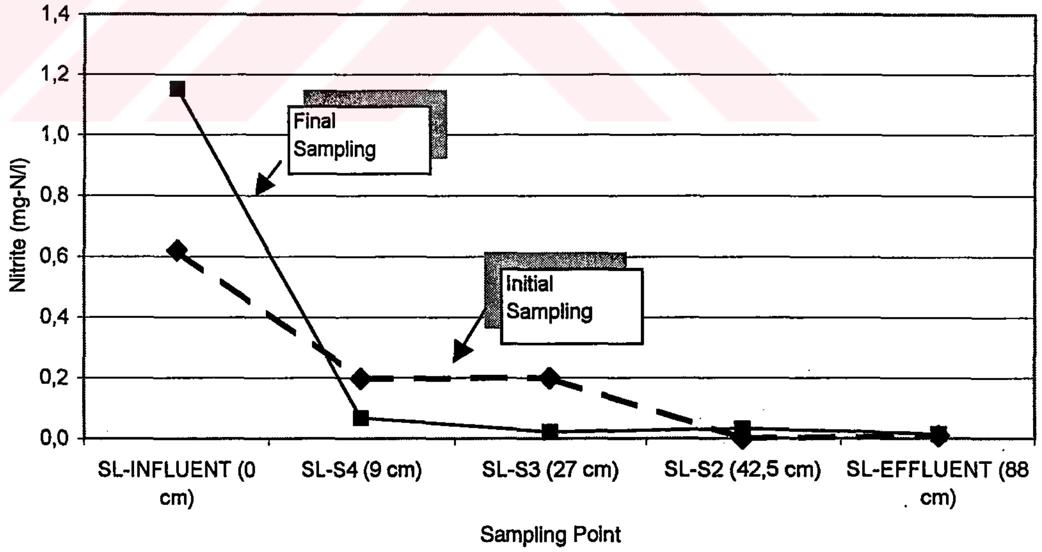

Figure 4.28: Nitrite distribution through SL column during cycle 3 of 7 d wetting/ 7 d drying cycles

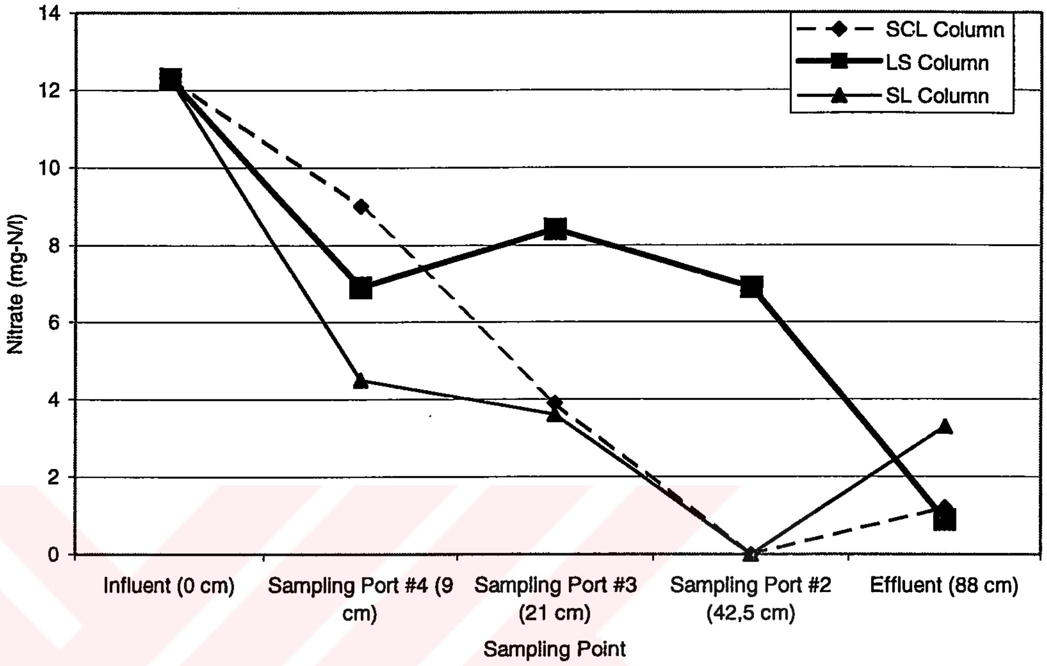

Figure 4.29: Nitrate distribution through the columns during cycle 3 of 7 d wetting/ 7 drying cycles

ii. 3 d Wetting/ 4 d Drying Period

Average influent NH_3-N concentration of SCL, LS and SL columns during 3 d wetting/ 4 drying cycles is around *20 μg/l.* NH_3-N concentrations through SCL, LS and SL columns are given in Figure 4.30. Average NH_3-N removal efficiencies of SCL, LS and SL columns in Layer #1 are *55, 60* and *60 %,* respectively. Soil columns showed similar sorption behavior in this operational schedule.

Average influent NO_2-N concentration for SCL, LS and SL columns is *0.8 mg/l.* NO_2^- distribution through the columns during 3 d wetting/ 4 d drying cycles are shown in Figure 4.31. In SCL, NO_2^- concentrations decline with increasing soil depth and highest NO_2^- removal occurs at the top of the column, i.e. in Layer #1. In LS, there is a decreasing trend of NO_2^- until Layer #5 (Effluent); effluent NO_2^- concentration exceeds the influent concentration. In SL, there is a decreasing trend of NO_2^-; however, SL-S2 sampling port near the bottom of the column has a NO_2^- spike (Layer #4). This part of the column Layer #4 has an average DO concentration of 1.5 mg/l; hence, the condition is micro-aerobic. This NO_2^- spike may be a result of partial denitrification and/or desorption of nitrogen in the form of NO_2^- during wetting period.

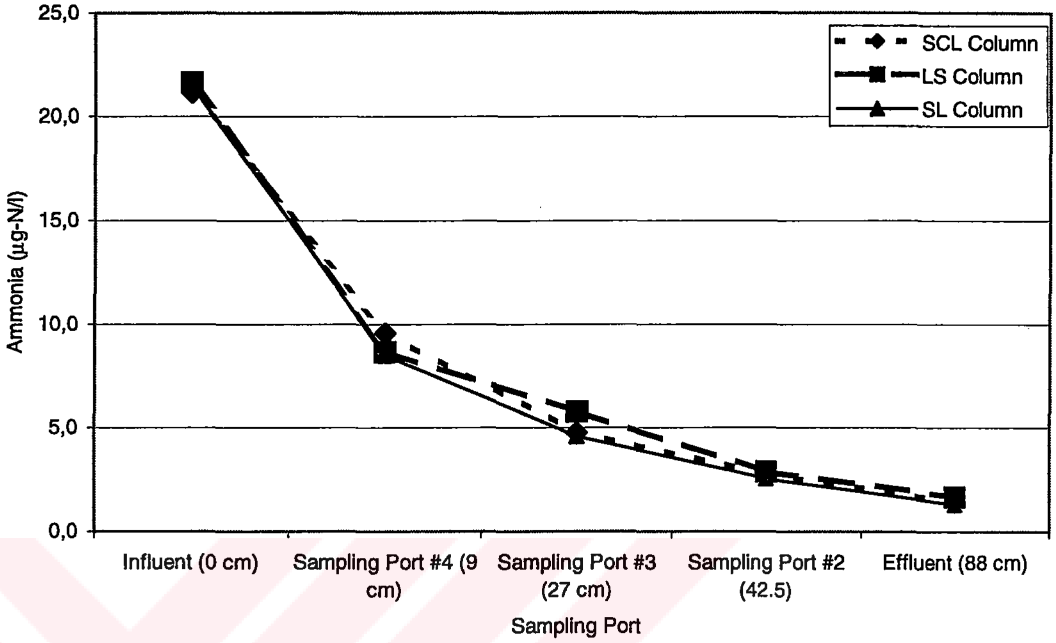

Figure 4.30: Ammonia concentrations through the columns during 3 d wetting/ 4 d drying cycles

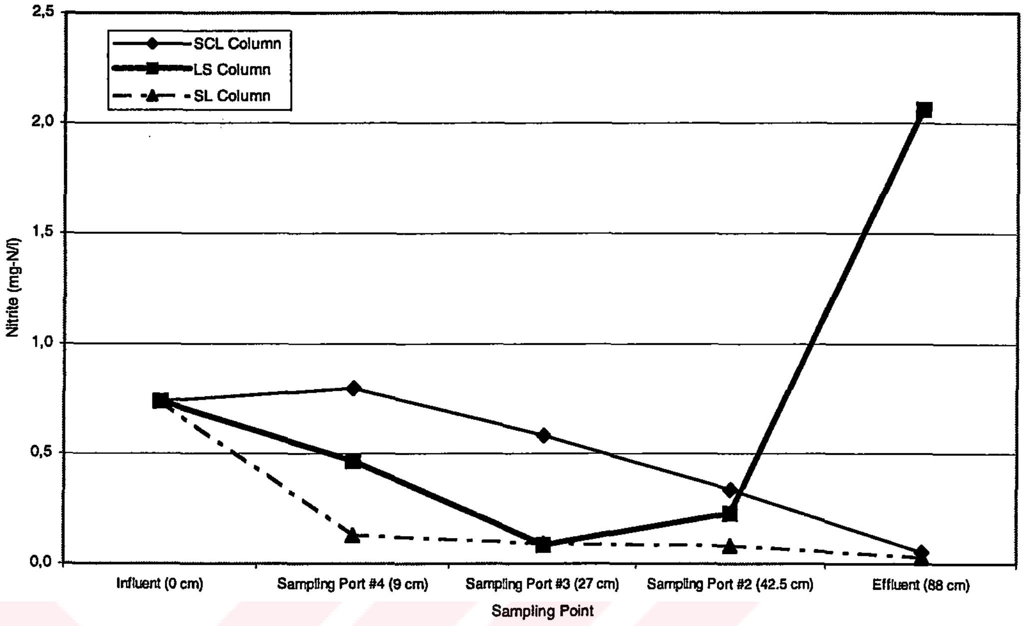

Figure 4.31: Nitrite concentrations through the columns during 3 d wetting/ 4 d drying cycles

In SCL column, average NO_3-N influent concentration is *10 mg/l.* Influent COD to influent NO_3-N ratios for SCL are tabulated in Table 4.4:

Table 4.4: Influent COD to Influent NO_3-N Ratios During 3 d Wetting/ 4 d Drying Cycles
(SCL COLUMN)

Cycle Number	1	2	3	4	5	6
COD To NO_3-N Ratio	4.9	7.5	7.2	9.4	1.8	2.6

Highest ratio occurs in Cycle 4 and lowest ratio in Cycle 5. Nitrate distribution through SCL column during 3 d wetting/ 4 d drying cycles is shown in Figure 4.32. Layers #4 and #5 *removes* a significant amount of NO_3 during all cycles except the removal during Cycle 2. During Cycle 2, COD removal efficiency is very high and DO depletion through Layers #4 and #5 i also high. Hence, anoxic conditions could prevail in this layer; COD/NO_3-N ratio is 7.5 for the same same cycle. Reasonable NO_3 reduction occurs *in the presence of this (mostly) anoxic conditions.* The cycles having higher COD: NO_3-N ratios are Cycle 4, 2 and 3. Nitrate removal efficiencies of these cycles are realized as: *100, 92* and *76 %.* Cycle 5 with the lowest COD: NO_3-N ratio bearing has *only 41 % removal.* Nitrate spikes are another concern during 3 d wetting/ 4 drying cycles (Figure 4.33, Figure 4.34). Figure 4.33 shows nitrate concentration distribution through SCL column during initial and final sampling of Cycle 2 in 3 d wetting/ 4 d drying schedule. Initial sampling is conducted at the end of first wetting day; and final sampling is realized at the end of third wetting day.

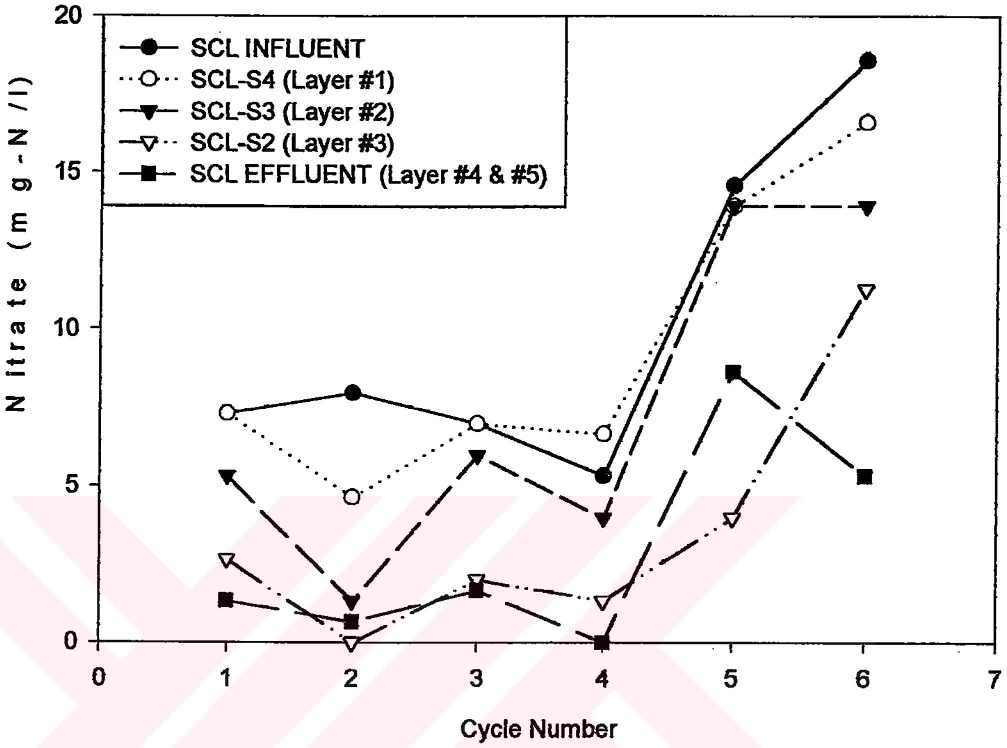

Figure 4.32: Nitrate distribution through SCL column during 3 d wetting/ 4 drying cycles

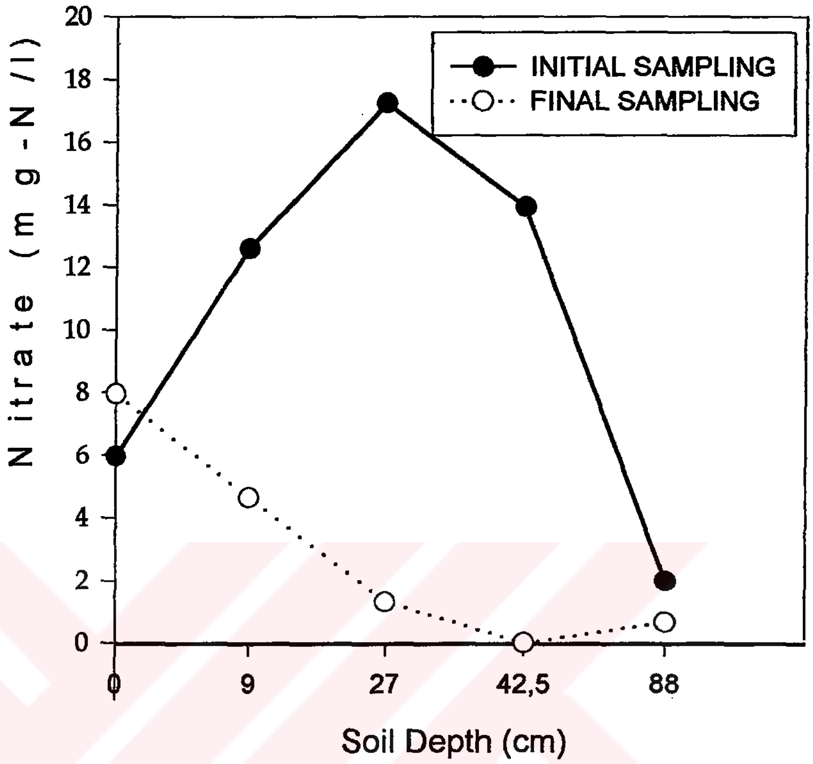

Figure 4.33: Nitrate concentrations through SCL column during cycle 2 of 3 d wetting/ 4 d drying cycles

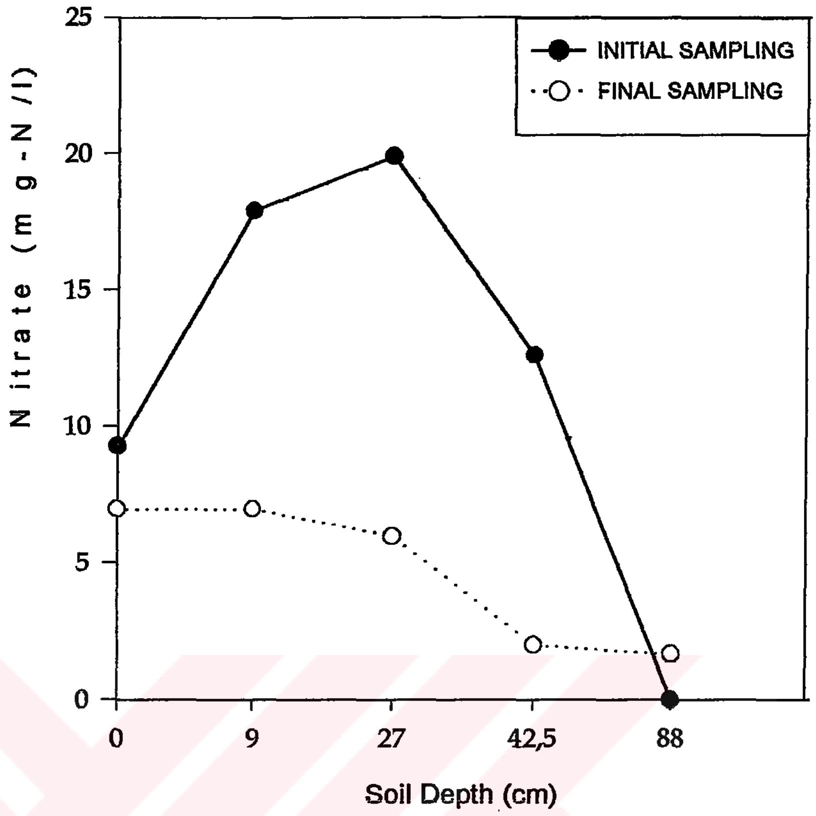

Figure 4.34: Nitrate concentrations through SCL column during cycle 3 of 3 d wetting/ 4 d drying cycles

1.5-2.0 days elapses between the initial and final sampling. Nitrate concentrations are *at least 100 % greater* than influent nitrate concentration at deeper depths of the column at sampling ports SCL-S4, SCL-S3 and SCL-S2 during the initial sampling. However, $NO_3^=$ concentrations at sampling ports, SCL-S4, SCL-S3 and SCL-S2 *drastically fall below* influent nitrate concentration during final sampling. Average hydraulic detention time is calculated as *20 d* for SCL column. This means that the nitrate spikes *can not leave the column within 1 day.* Thus, it is clear that nitrate is removed from aqueous phase either by physical or biochemical processes. Physical means adsorption to positively charged soil particles; biochemical means denitrification under anoxic conditions. Cycle 3 following Cycle 2 depicts similar nitrate behavior during initial flooding. From the comparison of these figures, it can be inferred that nitrate spike formation is *repeated each cycle.*

Overall nitrate removal efficiencies for SCL column from cycle to cycle ranges between *41 and 100 %;* average nitrate removal efficiency of SCL column is *64.*

In LS column, average NO_3-N influent concentration is *9.4 mg/l.* Influent COD to influent NO_3-N ratios for each cycle are given in Table 4.5:

Table 4.5: Influent COD to Influent NO_3-N Ratios During 3 d Wetting/ 4 d Drying Cycles (LS COLUMN)

Cycle Number	1	2	3	4	5	6
COD To NO_3-N Ratio	10.8	6.0	7.2	9.4	1.9	2.7

Levine *et al.* (1978) reported 90 % nitrogen removal in the full scale SAT application when C:N ratio was 6:1[1]. In this study, nitrate and organic nitrogen have higher concentrations compared to the other nitrogen species, nitrite and ammonia. Influent nitrate is prone to denitrification when organic source and anoxic conditions prevail. Therefore, influent COD: influent nitrate ratios are used to assess ability of the ratio to foretell denitrification through the SAT soil profiles. Highest ratio occurs for Cycle 1 and lowest ratio for Cycle 5. Nitrate distribution through LS column is given in Figure 4.35. Cycle 1 has the highest ratio of COD: NO_3-N; however, denitrification is not effective in Cycle 1 and effluent nitrate is higher than influent nitrate. Cycle 4 has the second highest COD: NO_3-N ratio; however, denitrification is not effective in this cycle either. There is a high spike of nitrate at Cycle 4; this is not due to nitrfication of nitrite since nitrite concentration at the top soil layer during Cycle 4 is very low. This spike *may be a result of* nitrate leaching from soil. Influent nitrate concentrations *do not vary* with time significantly.

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[1] C:N ratio of Levine *et al.* (1978) is not exactly the same with C:N ratio of this study. This study uses COD:NO_3-N mass balance as C:N ratio.

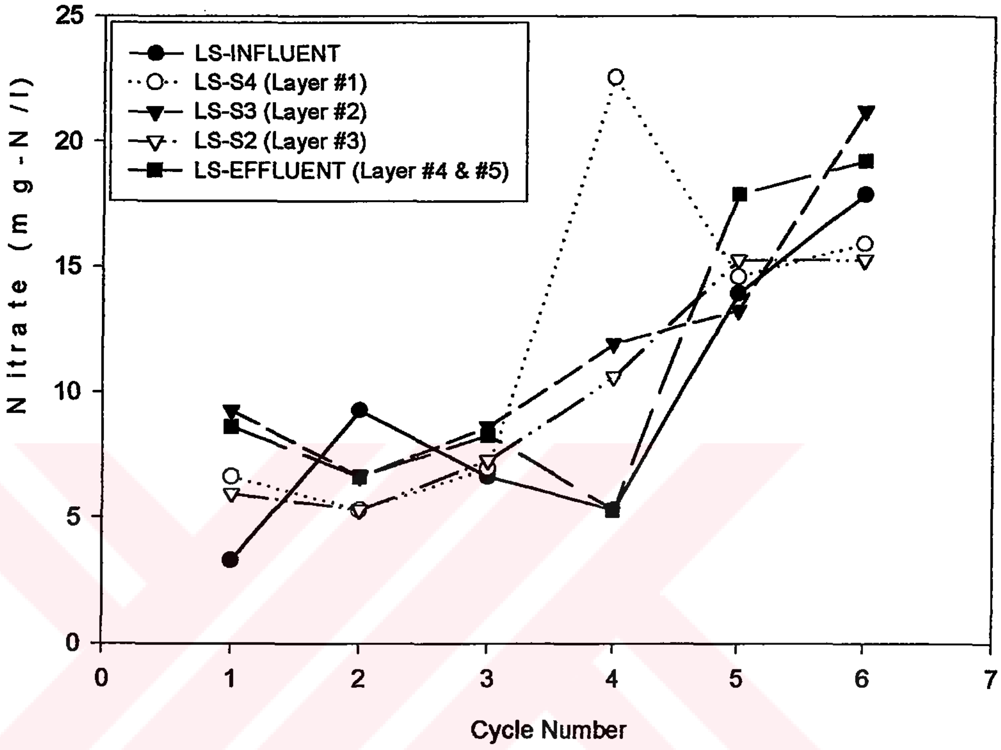

Figure 4.35: Nitrate distribution through LS column during 3 d wetting/ 4 drying cycles

Theoretical detention time of LS column is the lowest (6 days) among the other columns and denitrification/ nitrification processes do not have fast kinetics. Nitrate ions can be leaching without being metabolised. It is also seen that COD: NO_3-N ratio *is not by itself enough to induce denitrification in the soil. Column, infiltration rate also plays a critical role to triger denitrification.*

In SL column, average influent NO_3-N concentration is *9.2 mg/l* . Influent COD to influent NO_3-N ratios for each cycle are given in Table 4.6:

Table 4.6: Influent COD to Influent NO_3-N Ratios During 3 d Wetting/ 4 d Drying Cycles (SL COLUMN)

Cycle Number	1	2	3	4	5	6
COD To NO_3-N Ratio	8.4	7.3	9.7	9.4	1.7	2.5

Cycle 3 has the highest ratio while Cycle 5 has the lowest ratio. NO_3-N concentrations through SL column during 3 d wetting/ 4 d drying cycles are given in Figure 4.36. Nitrate concentrations show a cyclic behavior in Layer #1, #2 and #3. Cycles 1, 3 and 5 have *high nitrate concentrations.* Top of the column; i.e., Layers #1, #2, #3 have nitrifying characteristics while the bottom of the column; i.e. layers #4 and #5 have nitrate removing characteristics.

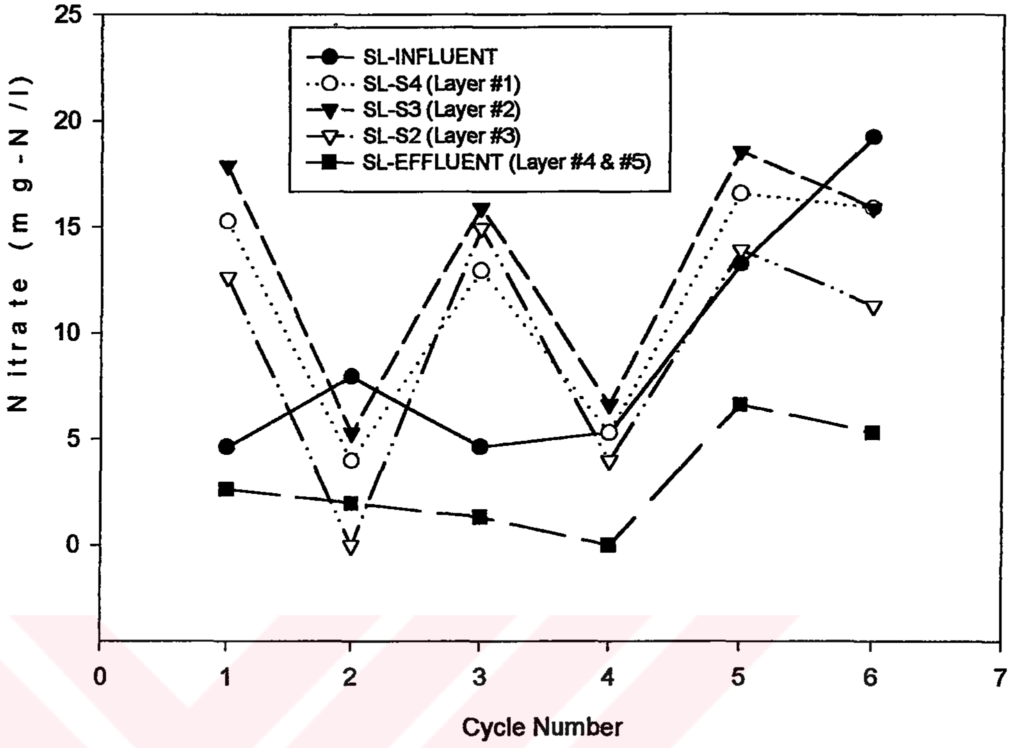

Figure 4.36: Nitrate distribution through SL column during 3 d wetting/ 4 drying cycles

In Layers #4 and #5, nitrate concentrations are *lower than* influent nitrate concentrations. Cycles 1, 3 and 4 have high COD: NO_3-N ratios and overall nitrate removal efficiencies of these cycles are *59, 55* and *59 %,* respectively. However, these removal efficiencies observed in these cycles are not the maximum removal efficiencies, Cycle 2 and Cycle 5 have higher removal efficiencies *78* and *74 %,* respectively.

TKN snap sampling at Cycle 6 gives the following data for the columns: Influent TKN of the columns is *24.6 mg/l.* SCL-S4, LS-S4 and SL-S4 have the values *24.6, 33.6* and *15.7* mg/l, respectively. TKN is the sum of ammonia nitrogen and organic nitrogen. It is seen that ammonia has a very low concentration in column influent wastewater; hence, TKN parameter can be accepted to give organic nitrogen content of the wastewater. SL topsoil *removes 36 % organic nitrogen.* Major organic nitrogen reduction happens in Layer #5: SCL, LS and SL columns have overall organic nitrogen reductions of *41, 56* and *68 %, respectively.*

b. Slow Rate Infiltration

During slow rate infiltration, nitrite and nitrate were continously measured. Ammonia concentrations were not measured as their concentration in applied wastewater was too low. TKN snap sampling is done to understand TKN distribution through the columns.

Average NO_2-N influent concentration of the columns is *0.74 mg/l.* Average NO_2-N concentrations through the soil profiles of SCL, LS and SL are given in Figure 4.37. The values plotted on the figure are *average values;* there were some *nitrite spikes* in the column effected the nitrite concentrations

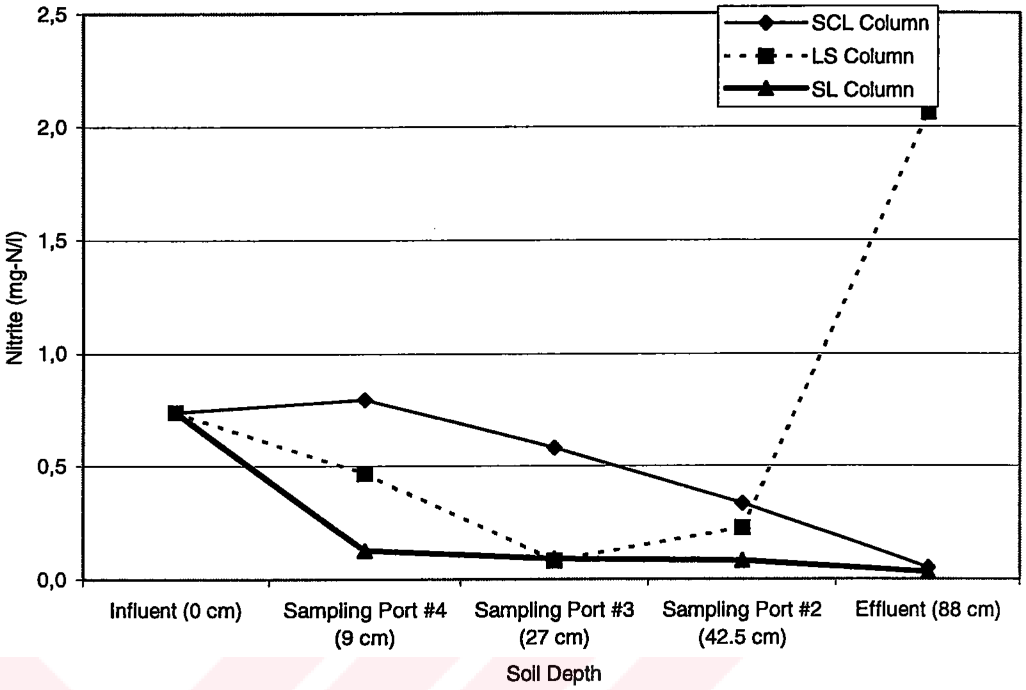

Figure 4.37: Nitrite concentrations through the columns during slow rate infiltration

through the column. However, these spikes are not seen in Figure 4.37 as the figure plots have average nitrite concentrations of the sampling ports. In SCL column, NO_2-N removal through the top 9 cm of soil is *usually* very high; NO_2-N is removed more than *95 %* through Layer #1. On 56th. day of operation (last day of operation), a NO_2 peak, which *is 173 % greater than corresponding influent NO_2-N*, is observed at SCL-S4 sampling port. There is another spike of NO_2^- at SCL-S3 at Day 25 in slow rate infiltration. Although SCL column operated with an average *water saturation degree of 92 % (air content of 0.03)*, DO in infiltrating water is between *1-1.5 mg/l.* NO_2^- spike observed at SCL-S3 at Day 25 may be a product of nitrifying bacteria near that sampling port. Overall average removal of NO_2^- through the column is *93 %* on average.

Average influent concentration of NO_3-N for SCL column is *5.3 mg/l.* Nitrate distribution through SCL column during slow rate infiltration period is given in Figure 4.38. In Layers #1, #2 and #3, there is an obvious nitrification actiivity. Only on Day 15, there is a significant removal of nitrate in the same layers; this may be due to decrease in influent DO concentration (anoxic conditions). Denitrification is effective in Layer#4 and #5. That is, nitrification is more effective at the top of soil profile while denitrification is more effective at the bottom of the column. This may be due to temporary clogging of the column, depletion of oxygen in the bottom of soil column increase of DO in bottom of the soil column. Hence, the processes (nitrification/ denitrification couple) may be effective in sequencing layers. Overall average nitrate removal efficiency of SCL is *57 %.*

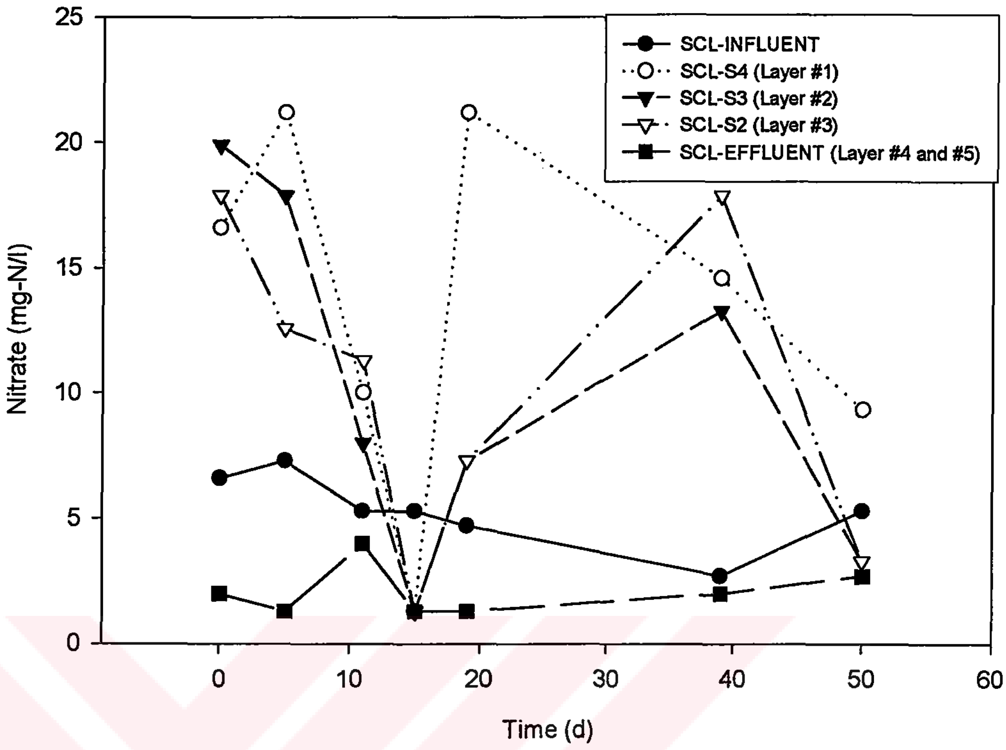

Figure 4.38: Nitrate distribution through SCL column during slow rate infiltration

In LS column, NO_2-N concentrations follow a declining trend and LS-S4, LS-S3 and LS-S2 have low NO_2^- content (see 4.37). NO_2^- concentrations at these ports *do not vary* significantly with time. LS effluent has *four NO_2^- spikes,* which are follow each other. Initial spikes are seen at Day 11 and Day 17; and final spikes are observed at Day 45 and Day 56. If these spikes are excluded, average effluent NO_2-N concentration for LS column is *0.38 mg/l.*

Average influent NO_3-N to LS column is *5 mg/l.* Time-variant NO_3-N distribution through LS column is shown in Figure 4.39. Nitrification is the dominant mechanism throughout this column. LS column effluent usually exceeds *10 mg/l* NO_3-N concentration, being the maximum concentration level for drinking water. it is highly nitrifying. LS has high infiltration rate and low detention time; hence, there may be insufficient time available to denitrify nitrogen species of nitrification phase.

In SL column, NO_2-N concentration has a sharp decline in Layer #1 and the low NO_2^- concentrations do not change significantly through the soil profile of the column (see Figure 4.37). There may be two reasons for this steady trend of NO_2^- through SL column: First, COD reduction is low in SL column and there is a DO input of *1.9 mg/l* to the soil column, this oxygen may be used by nitrifiers to oxidize NO_2^- to $NO_3^=$, and second, infiltration rate of SL is the lowest amongst the columns; so, high detention time allows longer susception of NO_2^- to nitrification/denitrification process and removal from the soil environment. Average overall NO_2^- removal in the column is *96 %.*

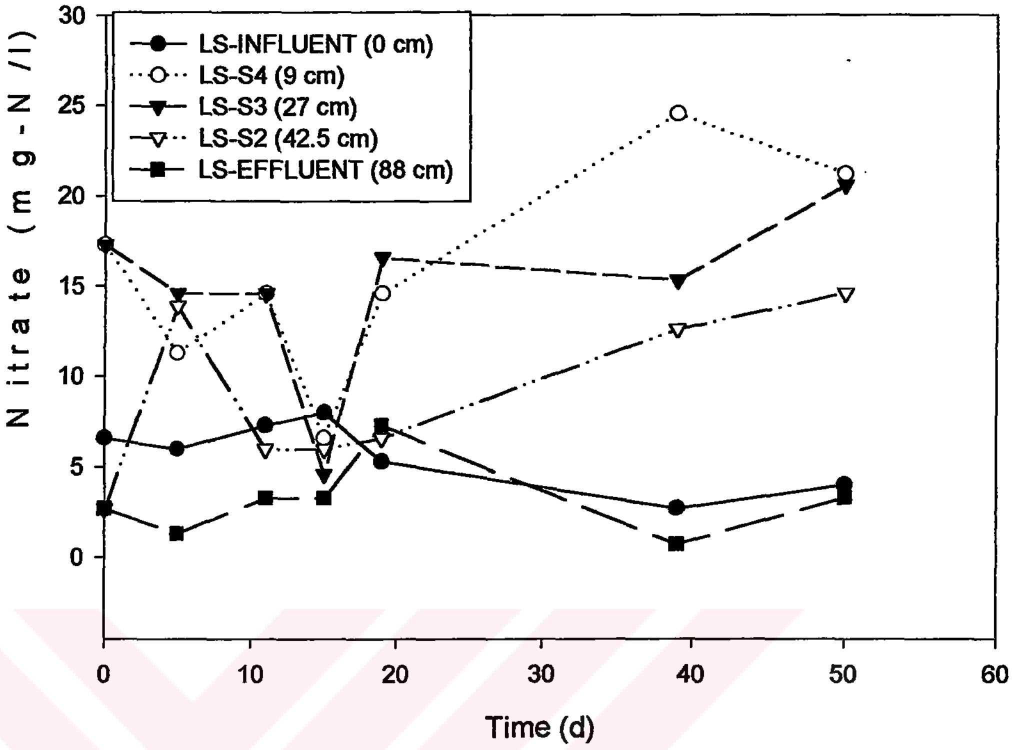

Figure 4.39: Nitrate distribution through LS column during slow rate infiltration

Average NO_3-N concentration for SL column is *5.7 mg/l.* Time variant NO_3-N concentrations through SL column is given in Figure 4.40. Layer #1 and #2 are highly nitrifying layers. Between Day 11-Day 19, Layer #3 denitrifies. However, long term denitrification process takes place in Layer #4 and #5. Nitrate spike in SL effluent on Day 19 may be the influent spike of Day 15. Although NO_3-N concentrations mostly exceed 10 mg/l through the soil profile, effluent NO_3-N is below 10 mg/l at all times. Overall average NO_3-N removal effiiciency of SL column is *44 %.*

The sample of Day 50 (final day of slow rate infiltration operation) is analysed for TKN content of the columns during slow rate infiltration. Influent TKN is *28 mg/l.* SCL soil removes *80 %* of influent TKN in Layer #1 whereas SL soil removes *100 %* of influent TKN in Layer #1. LS soil does not remove any TKN in Layer #1; this may be due to low detention time of LS Layer #1 compared to Layer #1 detention times of SCL and LS columns. LS removes TKN significantly through Layer #2. Overall TKN removal efficiencies of the columns (SCL, LS and SL) are *72, 65* and *80 %,* respectively.

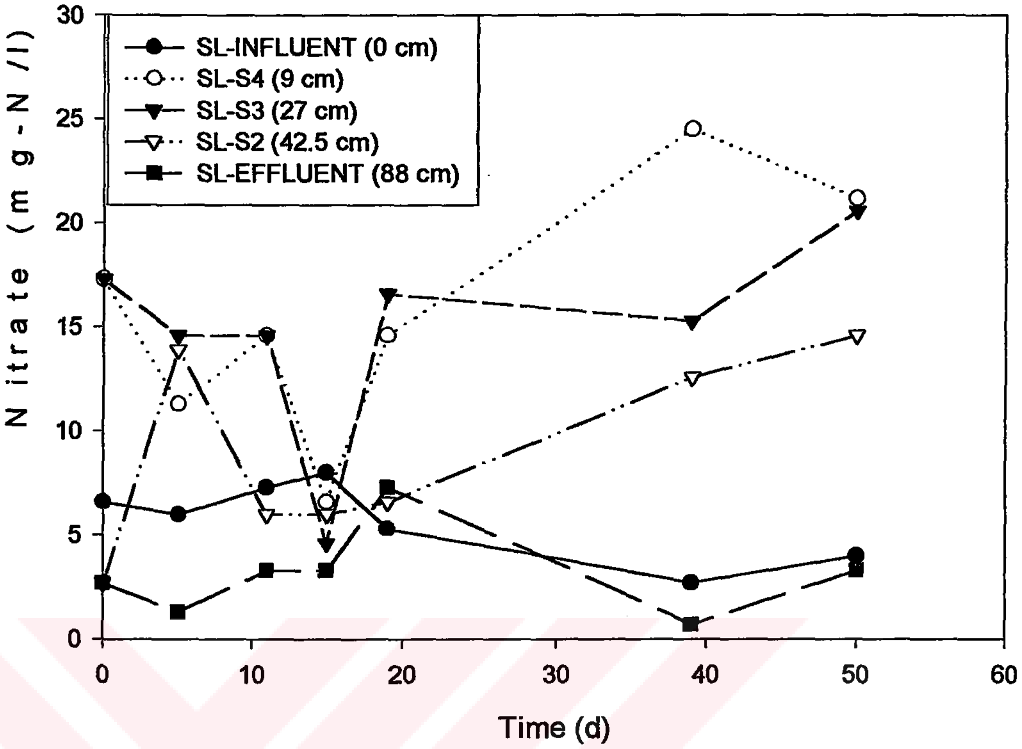

Figure 4.40: Nitrate distribution through SL column during slow rate infiltration

4.2.3 REMOVAL OF TOTAL PHOSPHORUS

a. Rapid Infiltration

i. 7 d Wetting/ 7 d Drying Period

Average influent TP concentrations of SCL, LS and SL columns are *2.8, 2.8* and *2.9 mg/l,* respectively. TP concentration distributions through the columns during 7 d wetting/7 d drying cycles are shown in Figure 4.41. Each sampling point is shown with its code and soil depth, layer number in parantheses. Initial sampling term refers to the sampling conducted at second day of the wetting period during Cycle 3 and final sampling was conducted at the last day of wetting period during Cycle 3.

In SCL column, Layer #2 is effective in TP removal and almost all of the removal is realised in this layer of the column. TP concentration does not change significantly from Layer #3 to Layer #5 during Cycle 2. Final sample of the same cycle shows that TP concentrations in the former layers decrease. Although influent TP concentration has not decreased, Layer #2-#5 TP concentrations decrease. This phenomenon can be explained with formation of phosphorus precipitates. Average TP removal efficiency of TP is *90 %.*

In LS column, significant TP removal starts through Layer #3 in Cycle 2. TP concentrations do not increase through Layer #1 and #2; however, Layer #3 is very effective in TP removal. Initial and final sampling data of LS column shows that major TP removal takes place in Layers #3, #4 and #5. Overall average TP removal of the column is *91 %.*

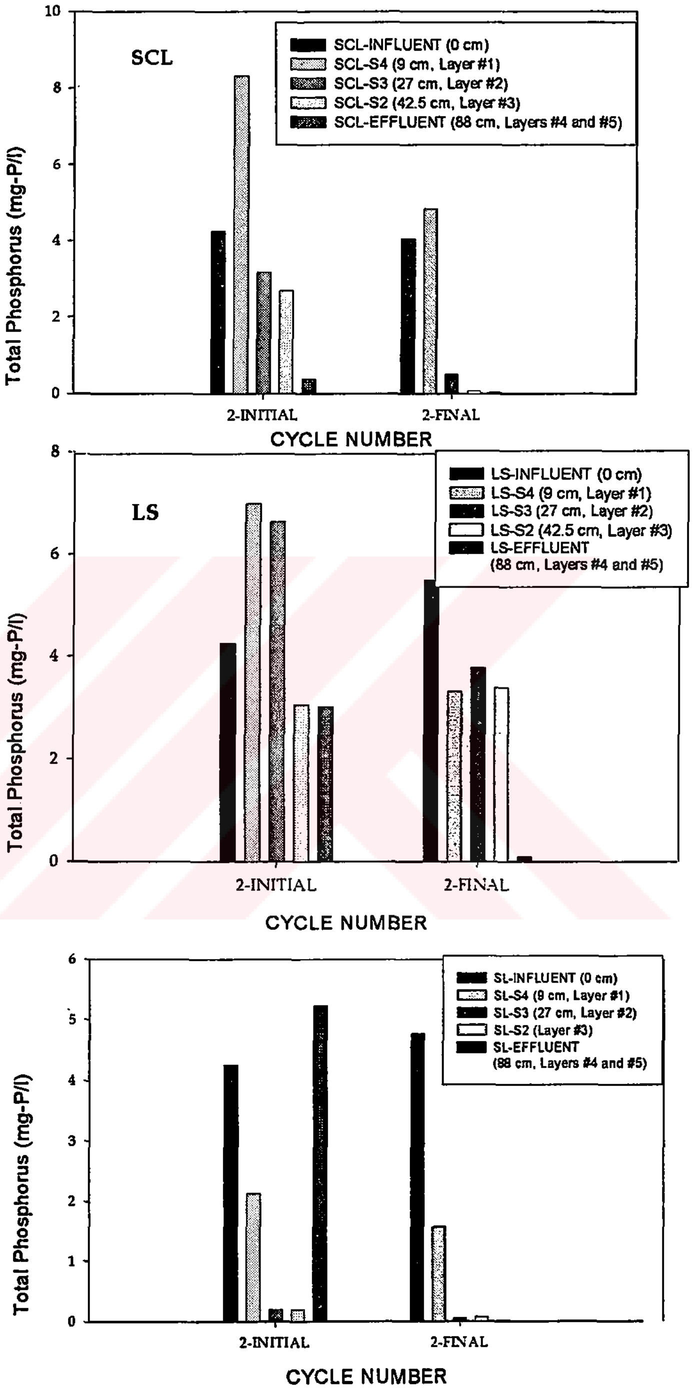

Figure 4.41: Total phosphorus concentrations through the columns during 7 d wetting/ 7 d drying cycles

In SL column, TP removal mainly occurs through Layer #2. There is no significant removal in the following layers. The increase in SL-S4, sampling port in the initial sampling phase of Cycle #3 (Figure 4.41) may be the effect of infiltrating TP plume. As it can be inferred from Figure 4.41, TP removal in SL column is not a very fast reaction and more or less 50-55 % of TP is removed until initial sampling and the remaining portion is removed until the final sampling, which is 5 days later than the initial sampling. Redessolution of phosphorus from precipitated state and spike production are not clearly observed. Average TP removal efficiency of the column is *91 %.*

ii. 3 d Wetting/ 4 d Drying Period

Average influent TP concentrations of SCL, LS and SL columns are *5.3, 5.4* and *5.5 mg/l,* respectively. There are six cycles of 3 d wetting/ 4 d drying period; hence, time-variant TP concentrations averaged over measurements pf sampling ports are plotted to show phosphorus removal trends in the colums. Moreover, furher comments are also possible using time-variant concentrations of TP measured at individual sampling ports.

In SCL column, TP removals are taking place mainly in Layer #1 and #2 as shown in Figure 4.42. Although Layers #1 and #2 are active in removal of TP, there is not a significant removal of TP from Layer #3 to effluent port. Maximum and minimum removal efficiencies of Layer #1 are *29 %* and *67 %* respectively. Layer #2 has a maximum and minimum removal efficiency of *43 %* and *91 %.* All effluent TP concentrations of SCL column is very close to 0 mg/l; however, TP concentration exceeds *2 mg/l* during Cycle 3.

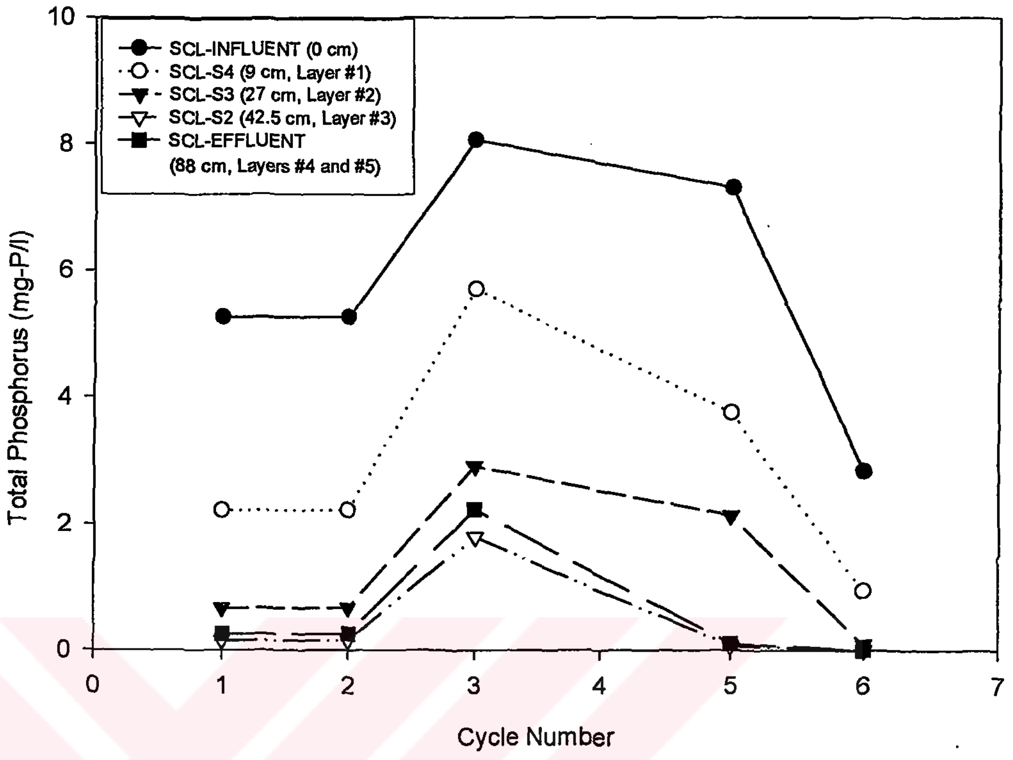

Figure 4.42: Total phosphorus concentrations through SCL column during 3 d wetting/ 4 d drying cycles

Influent concentration has the maximum TP concentration in Cycle 3 and influent TP concentration is *8 mg/l.* It can be stated that SCL column may have less than 100 % phosphorus removal when the influent concentration begins to exceed 8 mg/l. Overall TP removal efficiecies of the column is *83 %; however, if Cycle 3 data are excluded, TP removal efficiency increases to 100 %. When influent TP concentration is 8 mg/l in Cycle 3 (TP influent maxima among the influent concentrations of the cycles) can not be removed totally by the column and its removal efficiency is 75 %.*

In LS column, TP removal is gradually taking place from Layer #1 to Layer#2; TP concentrations almost remain unchanged through Layer #3 as illustrated in Figure 4.43. TP concentrations decrease to 0 mg/l through their travel down Layer #4 and #5. One TP spike is observed at LS3 during Cycle 1; this may be due to dissolution of phosphorus precipitates in Layer #1. This *can be expected* because Layer #1 receives the highest TP concentration during operation; high amount of phosphorus precipitates may accumulate in this layer and they can dissolve with changing environmental conditions. Highest influent TP concentration is around 8 mg/l (Cycle 3); this TP load of Cycle 3 *can not be removed totally by LS column and TP removal efficiency is 74 %.* TP removal efficiencies of the other cycles are *100 %.*

As shown in Figure 4.44, Layers #1 and #2 of SL column are very effective in removal of TP. Cycle 2 has an exceptional concentration of TP in Layer #1 (at SL-S4); influent TP concentration and SL4 TP concentration are almost equal. There is a phosphorus leaching problem, which may be due to re-dissolution of phosphorus precipitates in the topsoil. Beginning from

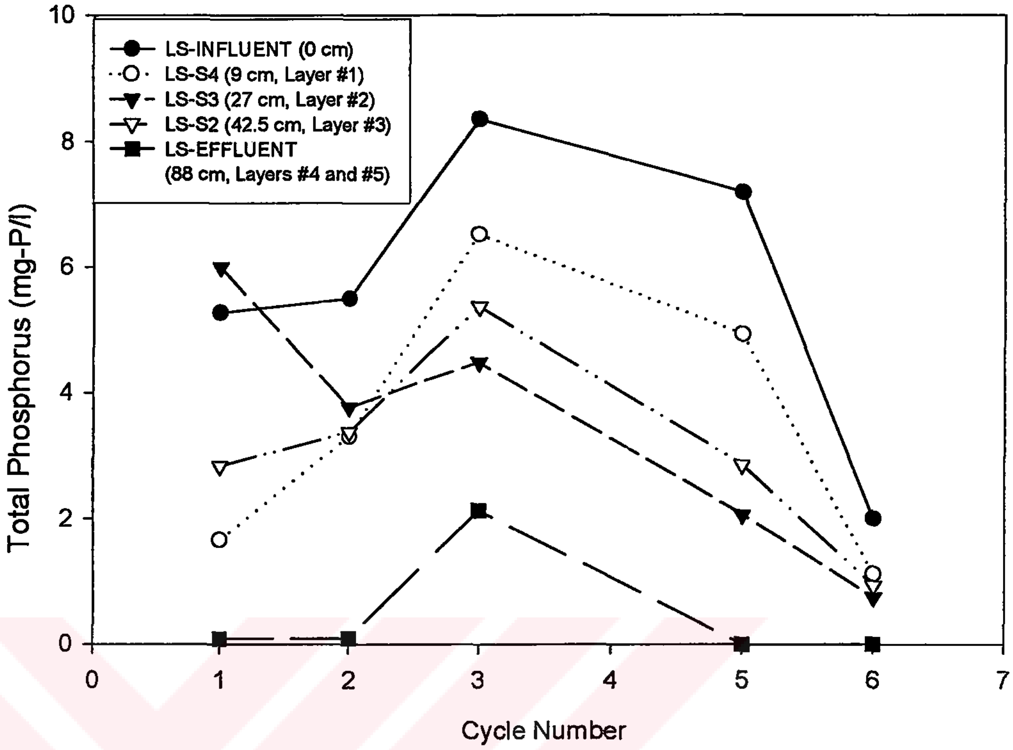

Figure 4.43: Total phosphorus concentrations through LS column during 3 d wetting/ 4 drying cycles

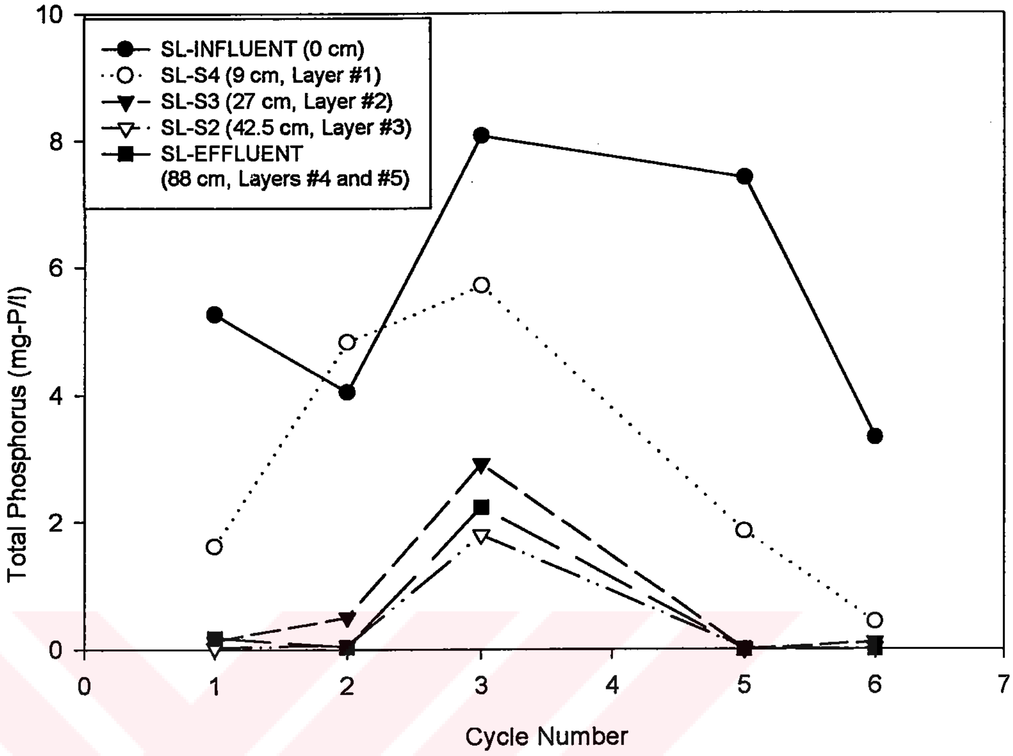

Figure 4.44: Total phosphorus concentrations through SL column during 3 d wetting/ 4 drying cycles

Layer #3 to effluent port, the soil profile *is not effective in TP removal.* SL column *could not* remove the highest TP loading occurred in Cycle 3. TP removal efficiencies are around 100 % for all of the cycles except Cycle 3, which has a TP removal of *72 %.*

Common point of all three columns during 3 d wetting/ 4 d drying cycles is that removal efficiencies are 100 % until TP concentrations increase to 8 mg/l. This critical concentration could not be removed 100 % by any of the columns. During 8 mg/l TP influent application, TP reduction is in range of 70- 75 % in the columns.

b. Slow Infiltration

Average influent TP concentrations of SCL, LS and SL are *3.5, 3.7* and *3.7 mg/l,* respectively. These average TP values are smaller than those of 3 d wetting/ 4 d drying cycles while they are slightly greater than average TP influent concentrations of 7 d wetting/ 7 d drying cycles.

In SCL column, Layer #1 removes TP around *80 %* until Day 5, removal rate slows down between Day 5-Day 10 (Figure 4.45). Layer # 1 *does not remove important amount of influent TP* between Day 10- Day 55. The effective cations binding with phosphates *could have been used in significant amount* during the rapid TP removal period of 5 days in Layer #1. Layer #2 is very effective in TP removal. Layer #3 does not remove TP significantly. Layer #4 and Layer #5 receives almost *0 mg/l* TP from Layer #3. However, there is a TP concentration around 1 mg/l at Day 5 in Layer #4 and Layer #5 meaning that a reasonable amount of precipitates dissolve again to exert TP. However, this phenomenon does not continue

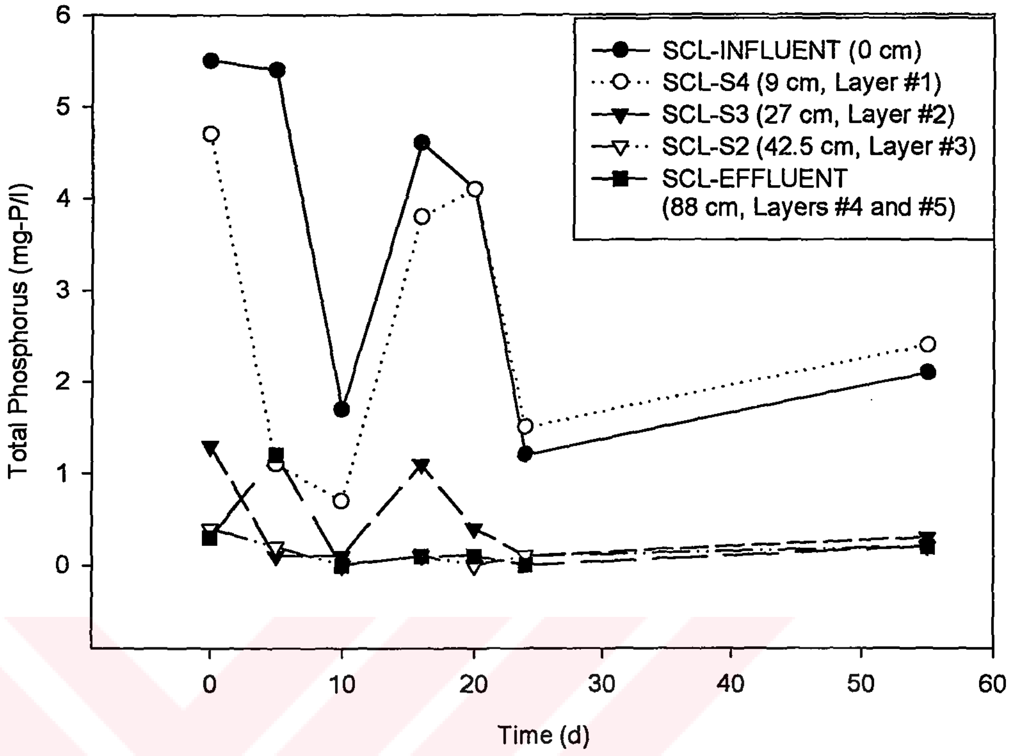

Figure 4.45: Total phosphorus concentrations through SCL column during slow rate infiltration

for a long time and beginning from Day 10 until the end of operation TP concentration in the column effluent is around *0 mg/l.* Overall column TP removal efficiencies are around *100 %*, but *78 %* on Day 5.

In LS column, Layer #1 removes TP until Day 10. From Day 10 to the end of operation, there is not a reasonable TP removal in the same layer (Figure 4.46). This may be due to the consumption of cations binding phosphates as for SCL column. Also, between days 10 and 20, some of the precipitated phosphates re-dissolves into the soil water. Layer #2 and Layer #3 are not effective in TP removal. Layer #4 and Layer #5 removes *all TP present in wastewater* . Significant TP spikes are not observed in the effluent indicating that precipitates of Layer #4 and Layer #5 are not re-dissolved to cause phosphorus spike. Overall TP removal efficiency of the column is about *100 %.*

In SL column, Layer #1 is removing significant amount of TP; remaining TP is stabilized in the following Layer #2 (Figure 4.47). The other layers do not receive TP because the first two layers remove all available TP. No increase in phosphorus is observed in the samples of bottom layers in the SL column. Overall TP removal efficiency is *100 %.*

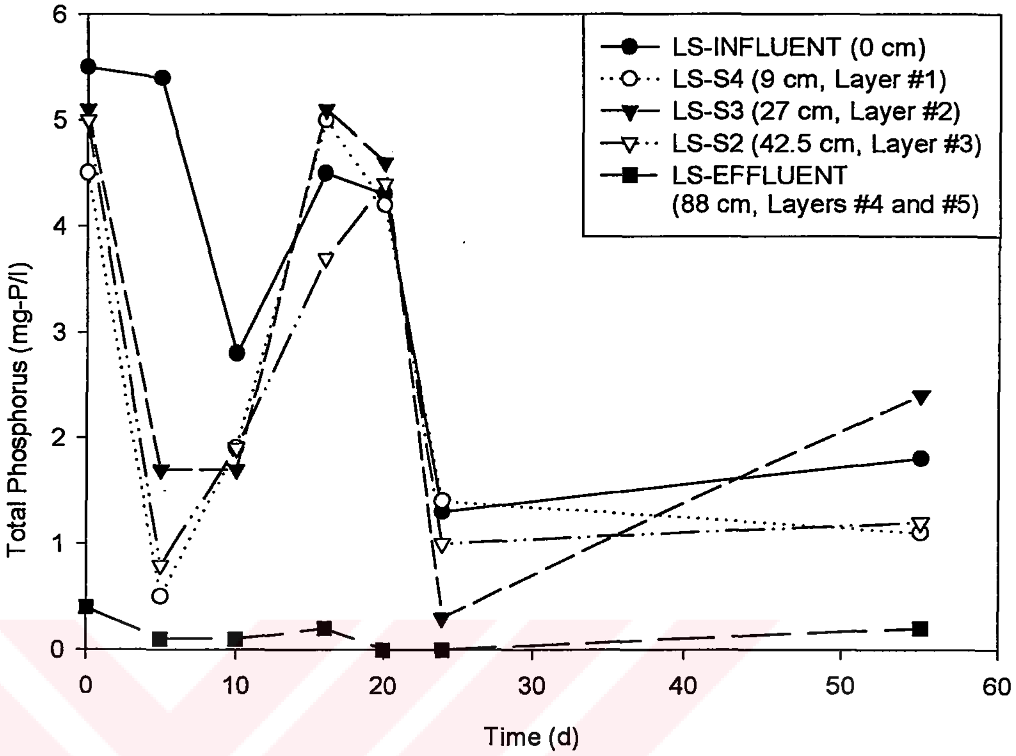

Figure 4.46: Total phosphorus concentrations through LS column during slow rate infiltration

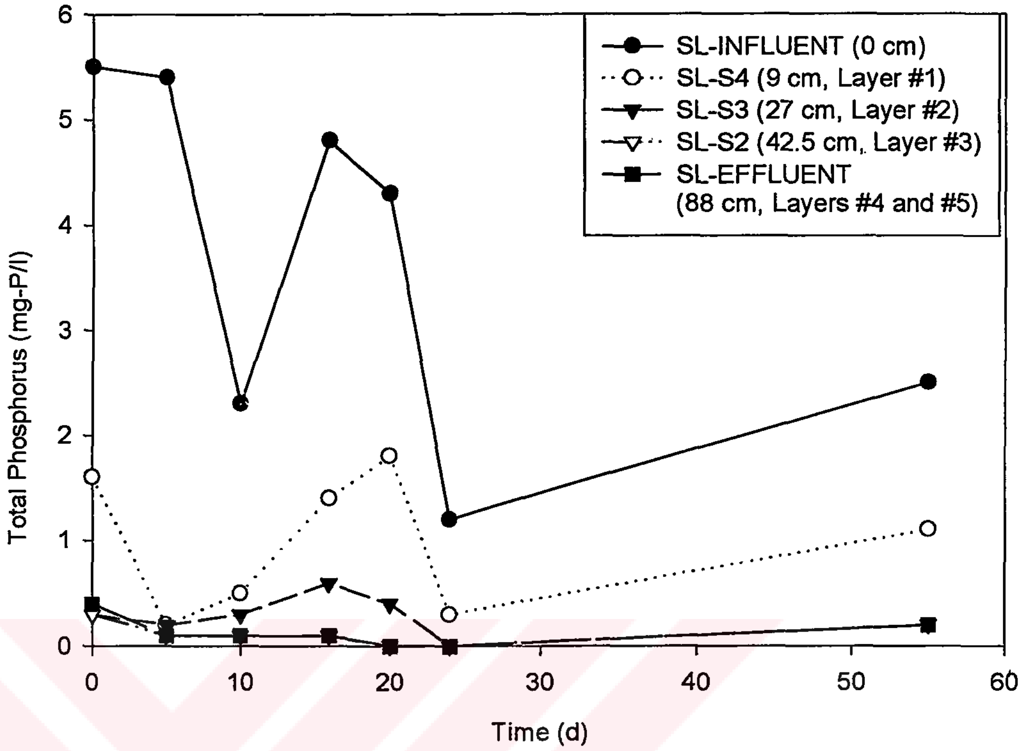

Figure 4.47: Total phosphorus concentrations through SL column during slow rate infiltration

4.2.4 COMPARISON OF POLLUTANT REMOVALS UNDER RAPID AND SLOW RATE INFILTRATION

Some pollution parameters are not measured continuously during the course of this study. For example, NH_3-N is measured during rapid infiltration. Concentration of ammonia in wastewater feeding the column is too low compared to nitrite or nitrate species. Hence, it is not measured in slow rate infiltration period as it is not a *critical* parameter. COD is not measured during 7 d wetting/ 7 d drying cycles; while the same parameter is continuously measured during 3 d wetting/ 4 d drying cycles and slow rate infiltration. Parameter measurement frequency and effects of different operation schedules on SAT pollutant removal performance are summarized in Table 4.7 for the purpose of comparison.

Table 4.7: Overall (Average) Percent Removal Rates of Contaminants for each SAT Column during Rapid and Slow Rate Infiltration

Contaminant	Rapid Infiltration						Slow Infiltration		
	7 d wetting/ 7 d drying cycles			3 d wetting/ 4 d drying cycles					
	SCL	LS	SL	SCL	LS	SL	SCL	LS	SL
COD	-	-	-	33	54	30	0	41	37
DOC	☹	**0**	☹	**0**	**0**	☹	-	-	-
NH_3-N	94	93	91	93	92	94	-	-	-
NO_2-N	94	95	96	93	☹	83	93	☹	96
NO_3-N	90	93	73	64	☹	45	57	☹	44
TKN	-	-	-	**41**	**56**	**68**	**72**	**65**	**80**
TP	90	91	91	83	100	100	100	100	100

-: Not Measured

☹: Effluent concentration exceeds influent concentration

Bold typed values show that the removal efficiencies are calculated basd on a single measurement

SCL and LS soils remove COD more efficiently in 3 d wetting/ 4 d drying cycles compared to slow rate infiltration. COD removal efficiency of SL soil slightly increases in slow rate infiltration compared to 3 d wetting/4 d drying cycles. Infiltration rates were lower and detention times were higher in the columns during slow rate infiltration than those of 3 d wetting/ 4 d drying cycles. Although detention times were increased, COD removal efficiencies did not improve in SCL and LS columns and the efficiency slightly increased in SL column. Therefore, infiltration rates do not have a significant impact over COD removal efficiencies of the soils. However, the change realized in operation conditions was not only infiltration rate decrease while the SAT columns were switched from 3 d wetting/ 4 d drying cycles to slow rate infiltration. LS and SL have sandy loam texture; ponding on LS column was aerated during 3 d wetting/4 d drying cycles while ponding on SL column was not aerated. Average COD removal efficiency of LS is 54 % and the same parameter is removed only 30 % by the SL column. Therefore, DO concentration of influent wastewater can be important in COD removal efficiencies of the similar textured soils.

Aeration of influent was stopped during slow rate infiltration; the DO concentrations of the influent decreased significantly. While DO concentration of influent wastewater was low in this period, the COD removal efficiencies of SCL and LS columns decreased significantly. COD removal efficiency of SL was not adversely effected with the decrease in DO concentration. Therefore, COD removal mechanisms in SCL and LS columns have aerobic biofilm development in topsoil to remove COD; while COD removal mechanism in SL column is more dependent on abiotic COD removal mechanism, i.e. sorption of organics.

COD removal performances of the columns were observed to decrease significantly when COD concentration of influent wastewater decreased to 25 mg/l or lower values.

DOC measurements of rapid infiltration period (see Table 4.5) show that DOC removal did not improve during the rapid infiltration phase. Therefore, DOC removal efficiencies of the soils during 7 d wetting/ 7 d drying and 3 d wetting/ 4 d drying cycles can not be compared.

All of the soils remove ammonia more than 90 % regardless of the rapid infiltration operation schedules. Influent ammonia concentrations were too low; hence, the pollutant load of ammonia was not significant. The high removal efficiencies observed in this study must be tested by the same rapid and slow infiltration schedules but influent wastewater must include higher concentration of ammonia. 7 d wetting/ 7 d drying and 3 d wetting/ 4 d drying cycles did not have significant impact on ammonia removal efficiencies of SCL, LS and SL soils.

7 d wetting/ 7 d drying cycles had higher nitrate removal efficiencies compared to 3 d wetting/ 4 d drying cycles. LS soil, which has the highest infiltration rate compared to the other soils nitrified nitrogen species but denitrification did not take place in this soil column during 3 d wetting/ 4 drying cycles. SCL had *high nitrate removal efficiency regardless of the operation schedule applied.* SL had the second best nitrate removal performance. Denitrification performance of the columns decreased significantly when rapid infiltration operation schedule was switched from 7 d wetting/ 7 d drying to 3 d wetting/ 4 drying cycles. *7 d wetting/ 7 d drying cycle is superior to 3 d wetting/ 4 d drying cycles if treatment objective is denitrification.* SCL, LS and SL nitrate removal behaviors did not

significantly change in slow rate infiltration compared to 3 d wetting/ 4 d drying cycles. Infiltration rates of the columns are important in deniftrifying wastewater through the columns; however, length of wetting period is also important. Although LS had high infiltration rates during the two schedules of rapid infiltration, nitrate removal through the column was very high in 7 d wetting/ 7 d drying cycles.

LS and SL had better TP removal efficiencies compared to SCL under all of the operation conditions during this study. All of the columns gave steady 0 mg-P/l concentration. However, when the influent wastewater concentration of TP increased to 8 mg/l, the effluent TP concentration of the columns increased reasonably and the TP removal efficiencies decreased.

Fox *et al.* (1998) worked with sandy loam columns for 13-20 cycles (Appendix E.6). Average DOC removal in that study was around *50 %.* However, this removal efficiencies could not be maintained in the columns because the inherent organics have leached from the columns especially in primary wastewater application in ripening phase (Fox *et al.* (1998) and Kopchynski *et al.* (1996)). Westerhoff and Pinney (1996) have operated soil columns for more than *30 weeks (210 days).* to acclimate the columns (*70 days for ripening and 140 days for acclimation).* Due to time limitations of this study, primary wastewater could only be fed to the columns for *4 weeks* (Appendix G). Four weeks of ripening phase and 1 week of synthetic wastewater application *are very short time intervals* for ripening phase. Hence, it should not be expected from the SCL, LS and SL columns to biodegrade the influent organics as efficient as the studies mentioned in Appendix E.6. COD removals reported by Billur (1981). In his study involving the METU Oxidation Pond Effluent's acceptability by SCL soil column, higher COD removals compared to this thesis study were reported (Billur, 1981). This can be explained by comparing influent COD concentrations of the two studies (Billur (1981) and Table 3.1). COD influent concentrations of this study is around 1/3 of Billur's influent COD concentrations. Substrate utilization rate of the microbial mass increases with substrate concentration and low COD loadings of this study caused lower COD removal efficiencies to occur.

The soils have *relatively higher CEC* compared with the data given in Appendix E.1. Therefore, high ammonia removals during this study are a result of adsorption of ammonia to the soil particles in SCL, LS and SL columns. Nitrite is removed under all operation schedules except 3 d wetting/ 4 d drying cycles of LS column, this indicates *incomplete nitrification* stated. 3 d wetting/ 4 d drying cycles and slow rate infiltration have the similar *nitrate removal (denitrification)* performances as of the soil columns of Fox *et al.* (1998). The 7 d wetting/ 7 d drying cycles seem to have better nitrate removal efficiencies than 3 d wetting/ 4 d drying cycles. However, additional 7 d wetting/ 7 d drying cycles data *are necessary to support this conclusion, further.*

Experimental findings of SCL column study agrees with the data given by Billur (1981). The 3 d wetting/ 4 d drying and 7 d wetting/ 7 d drying cycles (rapid infiltration) have high infiltration rates with respect to slow rate infiltration phase (4.1.4 and 4.1.5). However, this difference in infiltration rates have not effected TP removal efficiencies; this data contradicts with experimental findings stated by Billur (1981).

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The major conclusions drawn from the ripening phase[1] SAT operation of SCL, LS and SL soil columns are summarized as follows:

1. LS soil has better overall pollutant removal performance compared to SCL and SL during 7 d wetting/ 7 d drying cycles,
2. SCL soil has better overall pollutant removal performance compared to LS and SL during 3 d wetting/ 4 d drying cycles,
3. SL soil has better overall pollutant removal performance compared to SCL and LS during slow rate infiltration,
4. LS soil has denitrification capacity during 7 d wetting/ 7 d drying cycles while it nitrifies effluent during 3 d wetting/ 4 d drying cycles,
5. 7 d wetting/ 7 d drying cycles have better nitrogen removal compared to 3 d wetting/ 4 d drying cycles,
6. Although infiltration rates of slow rate infiltration are low, LS nitrifies secondary effluent during slow rate infiltration due unsaturated soil conditions and aeration,

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[1] As this study was conducted for a shorter time compared to the literature on SAT (i.e. Westerhoff and Pinney, 2000), all of the study is called as "ripening phase" SAT application

7. Although infiltration rates of 7 d wetting/ 7 d drying cycles are high compared to slow rate infiltration, LS denitrifies secondary effluent due to long wetting period lasting 7 days,
8. Infiltration rate and soil water saturation period are two important parameters effecting nitrogen removal efficiency of LS,
9. Slow rate infiltration is more effective than the rapid infiltration schedules in TP removal regardless of the soil type,
10. Slow rate infiltration does not improve the SAT performance significantly compared to the rapid infiltration schedules,
11. LS soil operated with 7 d wetting/ 7 d drying cycles has the best nitrogen removal performance,
12. LS soil can be operated with both 7 d wetting/ 7 d cycles and 3 d wetting/ 4 d drying cycles to meet denitrification/nitrification requirements of the SAT project. Hence, this soil is more flexible than SCL and SL soils.

5.2 RECOMMENDATIONS

The following recommendations are made for the future laboratory column works on SAT system:

1. Nitrification/ Denitrification processes can not be completed in most of the SAT laboratory studies. A lysimeter experimental setup can be constructed to monitor concentrations of nitrogen species through the lysimeter under different operational schedules. Soil samples can be taken on a routine basis from several depths of the soil profile and analysed for microbial content (microbial species) and NH_3 content of the soil. Therefore, time-variant changes in the SAT effluent can be explained more precisely. Identification of the microbiological species through the soil profile will be useful on

quantifying the abiotic and biotic removal mechanisms taking place *simultaneously* in the *same lysimeter.* Cyclic measurements of nitrite, nitrate and ammonia must be conducted on daily (if necessary, hourly) basis to determine rates of ammonia sorption/desorption, nitrite oxidation and nitrate reduction. These experimental analyses can be conducted for different soil types and different effluent pretreatments. Secondary derivative UV/VIS spectrophotometric method is recommended for prompt analysis of nitrogen species (NO_2, NO_3 (in liquid phase) and NH_3 (in solid phase)). This method requires very low sample volume and it is fast and precise. Hence, using second derivative UV/VIS spectrophotometric method will enable the researches to withdraw more samples from the soil and analyse them in short time.

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APPENDIX A

CATEGORIES OF MUNICIPAL WASTEWATER REUSE AND POTENTIAL CONSTRAINTS

Categories of Municipal Wastewater Reuse and Potential Constraints	
Wastewater Reuse Categories	Potential Constraints
Agricultural irrigation Crop irrigation Commercial Nurseries	Surface- and groundwater pollution if not properly managed Marketability of crops and public acceptance Effect of water quality, particularly salts, on soils and crops Public health concerns related to pathogens (bacteria, viruses, and parasites) Use area control including buffer zone. May result in high user costs.
Landscape irrigation Park School yard Freeway median Golf course Cemetery Greenbelt Residential	
Industrial recycling and reuse Cooling Boiler feed Process water Heavy construction	Constituents in reclaimed wastewater related to scaling, corrosion, biological growth, and fouling Public health concerns, particularly aerosol transmission of pathogens in cooling water
Groundwater recharge **Groundwater replenishment** **Salt water intrusion control** **Subsidence control**	Organic chemicals in reclaimed wastewater and their toxicological effects. Total dissolved solids, nitrates and pathogens in reclaimed wastewater
Recreational/environmental uses Lakes and ponds Marsh enhancement Streamflow augmentation Fisheries Snowmaking	Health concerns of bacteria and viruses Eutrophication due to N and P in receiving water Toxicity to aquatic life
Nonpotable urban uses Fire protection Air conditioning Toilet flushing	Public health concerns on pathogens transmitted by aerosols Effects of water quality on scaling, corrosion, biological growth, and fouling Cross-connection
Potable reuse Blending in water supply reservoir Pipe to pipe water supply	Constituents in reclaimed wastewater, especially trace organic chemicals and their toxicological effects Aesthetics and public acceptance Health concerns about pathogen transmission, particularly viruses
Reference: Tchobanoglous, G. and Burton, F. L., 1991, Wastewater Engineering: Treatment, Disposal, and Reuse, Metcalf and Eddy Inc., 3rd Edition, McGraw-Hill, Inc.	

APPENDIX B

EFFECTIVENESS OF LAND TREATMENT TECHNIQUES

Effectiveness of Land Disposal Techniques

Item	Approximate Efficiency of Removal[a] (%)		
	Spray/Irrigation	Flood/Irrigation[b]	Rapid Infiltration Ponds (SAT)
BOD	99	80	99
SS	99	80	99
Nitrogen	80-90	80	80
Phosphorus	99	80	90
Heavy Metals	99	10-30	95
Organic Compounds	99	50	90
Viruses	99	90	99
Bacteria	99	90	99
Total Cations	0-75	0-50	0-75
Total Anions	0-50	0-10	0-50

[a]: The efficiencies of the three methods should not be compared with each other because each is affected by its own set of local conditions, application

[b]: Percentages are best estimates in light of limited information

Reference: Arceivala, S. J., 1998, Wastewater Treatment for Pollution Control, Tata McGraw-Hill Publishing Company Limited, Second Edition.

APPENDIX C

PERCENT REMOVAL OF ORGANIC CHEMICALS IN LAND TREATMENT

Percent Removal of Organic Chemicals in Land Treatment Systems

Substance	**SAT**
Chloroform	**>99.99**
Toluene	**99.99**
Benzene	**>99.99**
Chlorobenzene	**>99.99**
Bromoform	**>99.99**
Dibromochloromethane	**>99.99**
m-Nitrotoluene	*
PCB 1242	**>99.99**
Naphthalene	**96.15**
Pheanthrene	*
Pentachlorophenol	*
2,4-Dinitrophenol	*
Nitrobenzene	*
m-Dichlorobenzene	**82.27**
Pentane	*
Hexane	*
Diethylphthalate	**90.75**

Reference: Crites, R. W., Reed, S. C., Bastian, R. K., 2000, Land Treatment Systems for Municipal and Industrial Wastes, The Mc-Graw Hill Companies, Inc.

APPENDIX D

WATER QUALITY PARAMETERS IN THE SAT STUDIES

Water Quality Parameters in the SAT Studies		
Author(s)	**Reference Title and Year**	**Parameters**
Westerhoff and Pinney	"Dissolved Organic Carbon Transformations during Laboratory-Scale Groundwater Recharge Using Lagoon-Treated Wastewater" 2000	**DOC**
Reemtsma , Gnirss and Jekel	"Infiltration of Combined Sewer Overflow and Tertiary Municipal Wastewater: An Integrated Laboratory and Field Study on Nutrients and Dissolved Organics" 2000	**NH_4-N, NO_3-N, NO_2-N, PO_4-P, DOC, AOX**
Drewes and Fox	"Behavior and Characterization of Residual Organic Compounds in Wastewater Used for Indirect Potable Reuse" 1999	**DOC**
Drewes and Fox	"Fate of Natural Organic Matter During Groundwater Recharge Using Reclaimed Water" 1999	**DOC and ultra-hydrophobic, hydrophilic, hydrophopic acid fractions in DOC**

Water Quality Parameters in the SAT Studies (Continued)

Author(s)	Reference Title and Year	Parameters
Wiswanathan, Al Senafy, Rashid, Al-Awadi and Al-Fahad	"Improvement of Tertiary Wastewater Quality by Soil Aquifer Treatment" 1999	**TSS, COD, BOD, Phosphates, Ammonia, Nitrates, Total Coliform, Fecal Coliform, Salmonella, Streptococci**
A research team consisting of faculty and graduate students of Arizona State University, the University of Arizona, and the University of Colorado (supported by AWWARF, WERF, and NWRI)	"Soil Treatability Pilot Studies to Design and Model a Soil Aquifer Treatment System" 1998	**Pathogens, HAA, THM, DOC, Org-N, NH_3, NO_2^-, NO_3^-**
Wang, Gerba and Lance	"Effect of Soil Permeability on Virus Removal Through Soil Columns" 1981	**Poliovirus Type 1 (Strain LSc), Echovirus Type 1 (Isolate V239)**
Bouwer, Lance and Riggs	"High-Rate Land Treatment II: Water Quality and Economic Aspects of the Flushing Meadows Project" 1974	**Total Dissolved Salts, Oxygen Demand, Nitrogen, Phosphate, Fluoride, Boron, Heavy Metals, Fecal Coliform Bacteria**
Bouwer, Rice, Lance and Gilbert	"Rapid-Infiltration Research at Flushing Meadows Project, Arizona" 1980	**TDS, SS, BOD_5, COD, TOC, Total Nitrogen, NO_3-N, NO_2-N, NH_4-N, Phosphorus, Fluoride, Boron, Metals, Bacteria and Viruses**

Water Quality Parameters in the SAT Studies (Continued)		
Author(s)	**Reference Title and Year**	**Parameters**
Idelovitch and Michail	"Soil Aquifer Treatment- A new Approach to an Old Method of Wastewater Reuse" 1984	**SS, Turbidity, Algae, COD, BOD, Organic Nitrogen, Phosphorus, Cadmium, Chromium, Copper, Molybdenum, Nickel, Selenium, Detergents, Phenols, UV-254**
Amy, Wilson, Conroy, Chahbandour, Zhai and Siddiqui	"Fate of Chlorination Byproducts and Nitrogen Species During Effluent Recharge and Soil Aquifer Treatment" 1993	**DOC, TOX**
Quanrud, Arnold, Wilson and Conklin	"Effect of Soil Type on Water Quality Improvement During Soil Aquifer Treatment" 1996	**DOC, UV-254**
A research team consisting of Fox, Houston, Westerhoff, Drewes, Nellor, Yanko, Baird, Rincon, Arnold, Lansey, Bassett, Gerba, Karpiscak, Amy, Reinhard (Sponsored by AWWA Research Foundation and US EPA)	"An Investigation of Soil Aquifer Treatment for Sustainable Water Reuse" 2000	**DOC, Cations, Anions, EDTA, APEC, NTA, NDC, HAA, THM, Org-N, NH_3, NO_2, NO_3, Pathogens**

APPENDIX E

SOIL TREATABILITY PILOT STUDIES TO DESIGN AND MODEL SOIL AQUIFER TREATMENT SYSTEMS REPORT

TABLES

Appendix E.1
Soil Characteristics

Soil	Description	Unified Soil Class.	Saturated Hydraulic Conductivity (ft/day)	Estimated Clay Sized Content (% by wt)*	CEC (meq/100 g)**	Total Organic Content (% by wt)
Agua Fria Sand	Poorly Graded Sand	SP	238***	0	2.4	0.32
Sweet water	Poorly Graded Silty Sand	SP-SM	53***	0	5.7	0.70
South Pond Silt	Silty Sand	SM	3.6	<1	6.9	0.97
North Pond Silt	Silty Sand	SM	0.6	<1	7.1	1.14
Ag. Field Clay	Low Plasticity Clay	CL	0.1	15	22.3	3.03

* percent by weight

** milli-equivalent per 100 grams

*** estimated from recompacted specimens

Appendix E.2
Water quality characteristics of WWTP effluents used in study

Effluent	Type	NH_3-N (mg/L)	NO_x-N (mg/L)	Total-N (mg/L)	TOC/DOC (mg/L)*
Phoenix 91st Ave. WWTP Effluent	Dechlorinated Denitrified	1.0-3.0	1.0-6.0	4-10	8-10
	Chlorinated Denitrified	1.0-3.0	1.0-6.0	4-10	8-10
	High Rate Activated Sludge (Chlorinated)	10-30	0-8.0	10-40	13-15
Tucson Roger Road WWTP Effluent	Secondary Trickling Filter*	15-25	0-2.0	15-30	15-25
	Tertiary-Pressure Filter	15-25	0-2.0	15-30	10-15
	Primary	20-35	0-1.0	25-40	40-50

*DOC is a measure of residual organic carbon following filtration using a 0.45 μm filter.

Appendix E.3
Summary of operating conditions for North Pond silt columns field columns (#1 - 6)

Schedule	Wetting Time	Drying Time	Cycles	Dates of Operation	Base Boundary Condition
Schedule 1	7 days	7 days	1-16	May 94 to November 94	0 cm on all columns cycles 1-7 100 cm on all columns cycles 8-16
Schedule 2	3 days	4 days	17-32	November 94 to March 95	100 cm on all columns
Schedule 3	3 days	7 days	33-42	March 95 to July 95	100 cm on all columns
Schedule 4	12 days	7 days	43-47	July 95 to September 95	100 cm on #1, #3, and #5 0 cm on #2, #4, and #6

Appendix E.4

Average Influent and Effluent Concentrations of DOC for One-meter Columns Fed Secondary Effluent from the Roger Road Wastewater Treatment Plant in Tucson

Soil Type	DOC (mg/L)		Cycles Tested
	Influent	Effluent	
Agua Fria sand*	12.16±1.76	6.39±0.85	13-20
Sweetwater sand loam	**12.41±2.00**	**5.45±0.88**	**13-20**
North Pond silt*	11.08±1.02	6.24±0.22	4-10
Agua Fria sand**	13.31±1.01	11.37±1.21	13-20
Sweetwater sandy loam**	14.64±1.00	13.21±0.95	13-19
North Pond silt**	11.08±0.89	8.22±0.89	6-11

* repacked

** repacked inhibited

APPENDIX F

LS AND SL SOIL TEXTURAL DESIGN

Appendix F.1 LS Design and Preparation

Using USDA Soil Classification Triangle, LS is aimed to have the following texture (Table F.1):

Table F.1: Anticipated Minimum and Maximum Sand, Silt and Clay Fractions in LS Sample

Sand (%)	Clay (%)	Silt (%)
80.00-85.00	5.00-10.00	7.00-15.00

Using Table F.1, the mass calculations for LS specimen is done. It is aimed to have 82 % sand in the specimen.

The sand specimen mass that is going to be used during mixture of the sand and the Gölbaşı specimens (SCL) to obtain LS is calculated as follows:

$$0{,}82 = \frac{56{,}72 + x}{100 + x}$$

$$82 + 0{,}82x = 56{,}72 + x$$

$$25{,}28 = 0{,}18x$$

$$x = 140{,}4\,g$$

where,

x= The sand mass to be used per 100 g of Gölbaşı specimen (g).

$$y = \frac{20}{100 + 140,4} x100 = 8,32\ \%$$

y= silt fraction in the LS sample (%).

$$z = \frac{23,28}{100 + 140,4} x100 = 9,68\ \%$$

z= clay fraction in the LS sample (%).

Hence, when 140.4 g of the sand is added to 100 g of Gölbaşı specimen, the following texture will be realised (Table F.2):

Table F.2 : Calculated Texture for LS

Sand (%)	Clay (%)	Silt (%)
82.00	9.68	8.32

Sand and Gölbaşı mass ratio of 140 g: 100 g is used to obtain around 15-20 kg mass of LS to fill an acrylic column.

Appendix F.2 SL Design and Preparation

Using USDA Soil Classification Triangle, SL is aimed to have the following texture (Table F.3):

Table F.3 : Anticipated Minimum and Maximum Sand, Silt and Clay Fractions in SL Sample

Sand (%)	Clay (%)	Silt (%)
60.00-70.00	10.00-20.00	10.00-20.00

When 44.3 g of sand is added to 100 g of Gölbaşı sample, the SL sample having the following texture can be prepared (Table F. 4):

Table F.4: Calculated Texture for SL

Sand (%)	Clay (%)	Silt (%)
70.00	16.14	13.86

15-20 kg of SL sample is prepared to fill an acrylic column.

Appendix F.2 SL Design and Preparation

SCL sample from Gölbaşı is only sieved using 2.00 mm sieve and 15-20 kg SCL sample is prepared.

APPENDIX G

OPERATIONAL SCHEDULE OF SAT APPLICATION

Operational Schedule of SAT Application			
STARTING/ FINISHING DATES	APPLICATION TIME (d)	WATER TYPE	MODE OF OPERATION
29.07/22.08.2000	24	Primary Wastewater	Ponded (All Columns)
DRYING PERIOD			
25.08/30.08.2000	5	0.01 M $CaSO_4$	Ponded (All Columns)
$CaSO_4$ APPLICATION STOPPED			
05.09/12.09.2000	7	0.01 M $CaSO_4$	Ponded (All Columns)
13.09/18.09.2000	5	0.01 M $CaSO_4$ Application (SCL & SL Columns) Synthetic Wastewater Application (LS Column)	Ponded (All Columns)
19.09/25.09.2000	6	Synthetic Wastewater Application (All Columns)	Ponded (All Columns)*
DRYING PERIOD			
27.09/ 08.11.2000	42	Secondary Wastewater	**7 d wetting/ 7 d drying Periods*** Ponded (All Columns)

<table>
<tr><th colspan="4">Operational Schedule of SAT Application (Continued)</th></tr>
<tr><th>STARTING/ FINISHING DATES</th><th>APPLICATION TIME (d)</th><th>WATER TYPE</th><th>MODE OF OPERATION</th></tr>
<tr><td>09.11/20.12.2000</td><td>42</td><td>Secondary Wastewater</td><td>3 d wetting/ 4 d drying Periods*
Ponded (All Columns)</td></tr>
<tr><td colspan="4">DRYING PERIOD</td></tr>
<tr><td>08.01/12.03.2001</td><td>55</td><td>Secondary Wastewater</td><td>Slow Rate Infiltration
No ponding (All Columns)</td></tr>
<tr><td>Total Operation Days</td><td>199</td><td colspan="2">*: SCL and LS <i>are aerated, but SL is not aerated</i></td></tr>
</table>