DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DETERMINATION OF QUALITY CHANGES IN TREATED WASTEWATER DURING PERCOLATION THROUGH THE SOIL MEDIA

by
Mesut AK

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İZMİR

DETERMINATION OF QUALITY CHANGES IN TREATED WASTEWATER DURING PERCOLATION THROUGH THE SOIL MEDIA

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We have read the thesis entitled **"DETERMINATION OF QUALITY CHANGES IN TREATED WASTEWATER DURING PERCOLATION THROUGH THE SOIL MEDIA"** completed by **MESUT AK** under supervision of **ASSIST. PROF. DR. ORHAN GÜNDÜZ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

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DETERMINATION OF QUALITY CHANGES IN TREATED WASTEWATER DURING PERCOLATION THROUGH THE SOIL MEDIA

ABSTRACT

A laboratory-scale soil aquifer system (SAT) was investigated in this thesis to determine the quality changes that occur in secondary treated wastewaters during percolation through soil media. The experimental setup consisted of soil-packed vertical columns, which were equipped with multiple ports at different depths for effluent sample collection. The system was operated with two different operational cycles that consisted of three-wetting/four-drying days and seven-wetting/seven-drying days. All experimental studies were carried out in columns that contained an effective soil depth of seventy-five centimeters using silt loam soil collected from an agricultural field in Menemen (Izmir). The experiments were conducted with synthetically prepared wastewater and with the secondary treated effluents of Cigli (Izmir) municipal wastewater treatment plant.

In the first part of the thesis, the removal of dissolved solids, organic matter and nutrients were investigated from synthetic secondary treated wastewater (SSTWW) and real secondary treated wastewater (RSTWW). Temperature, pH, salinity, electrical conductivity, total dissolved solids, oxidation-reduction potential, dissolved oxygen, total organic carbon, chemical oxygen demand, ammonium-nitrogen, nitrate-nitrogen, nitrite-nitrogen, total nitrogen and phosphate-phosphorus were measured during the first part of the thesis and their changes during percolation through soil columns were assessed based on fundamental removal mechanisms. First stage experimental studies were carried out for fifty-five and twenty-five week periods using SSTWW and RSTWW, respectively. In the second part of the thesis, fate of heavy metals was investigated through the columns operated with synthetic single metal solutions. Copper, lead and zinc were selected for experimental studies carried out for twenty-one weeks.

Overall, it could be concluded that laboratory-scale SAT system was effective in the removal of dissolved solids, organic matter, nitrogen, phosphate and heavy metals. Biodegradation, adsorption, ion exchange, precipitation and filtration were found to be the most effective mechanisms for polishing of secondary treated wastewater using SAT system.

Keywords: Soil aquifer treatment (SAT), soil columns, organic matter, nutrients, heavy metals, wastewater reuse, wastewater polishing, secondary treated wastewater.

ARITILMIŞ ATIKSULARIN TOPRAK ORTAMINDAN SÜZÜLMESİ SIRASINDAKİ KALİTE DEĞİŞİMLERİNİN BELİRLENMESİ

ÖZ

Bu tezde, ikincil arıtılmış atıksuların toprak ortamı boyunca süzülmesi sırasındaki kalite değişimlerini belirlemek için laboratuvar ölçekli bir toprak akifer arıtma (TAA) sistemi incelenmiştir. Toprak dolu dikey kolonlardan oluşan deney düzeneği, çıkış suyu örneklerini toplamak için farklı derinliklerde numune alma vanaları ile donatılmıştır. Sistem, üç-ıslak/dört-kuru gün ve yedi-ıslak/yedi-kuru günden oluşan iki farklı işletim döngüsü ile işletilmiştir. Tüm deneysel çalışmalar, yetmiş beş santimetre etkin toprak derinliğinde Menemen (İzmir)'deki bir tarımsal araziden alınan milli killi toprak kullanılarak sürdürülmüştür. Deneyler, sentetik olarak hazırlanmış atıksu ve Çiğli (İzmir) kentsel atıksu arıtma tesisi ikincil arıtılmış çıkış suyu ile yapılmıştır.

Tezin ilk bölümünde, sentetik ve gerçek atıksudan çözünmüş katıların, organik maddelerin ve nutrientlerin giderilmesi araştırılmıştır. Tezin ilk kısmı süresince, sıcaklık, pH, tuzluluk, elektriksel iletkenlik, toplam çözünmüş katılar, oksidasyon redüksiyon potansiyeli, çözünmüş oksijen, toplam organik karbon, kimyasal oksijen ihtiyacı, amonyum azotu, nitrit azotu, nitrat azotu, toplam azot ve fosfat fosforu ölçülmüştür ve onların toprak kolonları boyunca süzülmesi sırasındaki değişimleri, temel giderim mekanizmalarına dayanarak değerlendirilmiştir. Deneysel çalışmaların ilk aşaması, sentetik ve gerçek atıksu için sırasıyla elli-beş ve yirmi-beş hafta süreyle devam etmiştir. Tezin ikinci kısmında, tekli metal içeren çözeltiler ile işletilen kolonlar boyunca ağır metallerin davranışı incelenmiştir. Yirmi-bir hafta süren deneysel çalışmalar için bakır, kurşun ve çinko seçilmiştir.

Genel olarak, laboratuvar ölçekli TAA sisteminin, çözünmüş katıların, organik maddelerin, azotun, fosforun ve ağır metallerin giderilmesinde önemli derecede etkili olduğu sonucuna varılabilir. Biyolojik parçalanma, adsorpsiyon, iyon değişimi, çökelme ve filtrasyon, ikincil arıtılmış atıksuların TAA sistemi ile iyileştirilmesinde en etkili mekanizmalar olarak bulunmuştur.

Anahtar sözcükler: Toprak akifer arıtımı (TAA), toprak kolonları, organik madde, besin maddeleri, ağır metaller, atıksuların yeniden kullanımı, atıksu iyileştirme, ikincil arıtılmış atıksu.

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CHAPTER ONE
INTRODUCTION

1.1 The Problem Statement

Water is necessary for the existence of all living beings, without which ecosystem and human life could not survive. Although water is one of the most common components of the world, the available water for human life is limited. As shown in Table 1.1 (Peavy et al., 1985), about 97.3% of the water sources are found in the oceans as saline water. Ice caps and glaciers constitute about 2.1% of all water resources but are not considered to be readily available for human use. Consequently, only less than 1% is considered to be freshwater that could be directly used by humans (Peavy et al., 1985). Unequal areal distribution of water throughout the world further complicates the problem and limits human access to safe fresh water.

As a result of the rapid growth of population coupled with urbanization and increased living standards, the demand for water is constantly increasing in most parts of the world (Nadav et al., 2012; Viswanathan et al., 1999; Westerhoff & Pinney, 2000; Yun-zheng & Jian-long, 2006). Climate change and its influences on the quantity and quality of water resources further complicate the problem of water supply. Hence, reuse of treated municipal wastewaters is increasingly becoming popular in many parts of the world (particularly in arid and semiarid regions) (Akber et al., 2008; Candela et al., 2007; Drewes et al., 2003; Nadav et al., 2012; Quanrud et al., 1996; Viswanathan et al., 1999; Yu et al., 2006). Considering the scarcity of available water resources, effluents of municipal wastewater treatment plants are now considered to be a notable alternative resource for replenishing ever-declining groundwater reserves throughout the world. Particularly, when treated by suitable technologies, treated municipal wastewaters could serve as viable option to mitigate the detrimental consequences of climate change on water resources (Cha et al., 2004; Ernst et al., 2000; Idelovitch et al., 2003; Laws et al., 2011; Xue et al., 2008).

Table 1.1 Water distributions in the world

Location	**Volume, 10^{12} m^3**	**% of total**
Land areas		
Freshwater lakes	125	0.009
Saline lakes and inland sea	104	0.008
Rivers	1.25	0.0001
Soil moisture	67	0.005
Groundwater	8,350	0.61
Ice caps and glaciers	29,200	2.14
Total land area (rounded)	37,800	2.8
Atmosphere (water vapor)	13	0.001
Oceans	1,320,000	97.3
Grand Total (rounded)	1,360,000	100

The percentage of industrial effluents in municipal wastewater and the wastewater treatment steps (primary, secondary or tertiary treatment) implemented are the two most important parameters for the effective reuse of municipal wastewater (Ernst et al., 2000). Municipal wastewater can be treated by a treatment method before being reused in order to ensure some standards. Although secondary treatment is mainly intended to decrease the amount of dissolved organic matter, secondary treated wastewater still includes some organic components in addition to variable amounts of nutrients, trace metals, suspended solid and pathogens (Thawale et al., 2006; Viswanathan et al., 1999; Westerhoff & Pinney, 2000; Yun-zheng & Jian-long, 2006; Zhang et al., 2007). Hence, prior to the reuse of the secondary treated wastewater, some advanced treatment technologies are deemed necessary to reduce these constituents present in wastewater.

Accordingly, advanced treatment technologies (i.e., ion exchange, reverse osmosis, activated carbon, etc.) can be implemented to improve the quality status of secondary treated wastewater before it could be reused to augment diminishing water supplies. Yet, the use of these advanced technologies is quite limited because of high capital and operation costs (Ernst et al., 2000; Hussain et al., 2006; Viswanathan et al., 1999; Westerhoff & Pinney, 2000).

1.2 Soil Aquifer Treatment (SAT) System

Soil aquifer treatment (SAT) systems are typically more suitable for advanced treatment of secondary treated wastewaters with lower costs, no chemical requirement, tolerance to seasonal changes and numerous side benefits including but not limited to in-situ renewal of scarce water resources. Furthermore, advantages such as simple technology requirement and prolonged reliability and durability further facilitate the use of land treatment of secondary wastewaters for reuse purposes (Funderburg et al., 1979; Nema et al., 2001; Thawale et al., 2006; Viswanathan et al., 1999). On the other hand, there are some disadvantages such as the requirement for annual removal of accumulated organic matter and occasional skimming of the top few centimeters of the soil to facilitate the reduced infiltration rates due to algal growth (EPA, 2003).

SAT is considered to be one of the most important land treatment techniques, which is also known as rapid infiltration. A schematic of a SAT system is given in Figure 1.1 (Miotlinski, 2010).

SAT system is primarily based on the infiltration of treated wastewater from large-scale recharge basins through the vadose (unsaturated) zone. The percolated wastewater finally arrives the native groundwater aquifer (saturated zone) and is stored in the unconfined aquifer. During this percolation and storage, nitrogen, phosphorus, dissolved organics, heavy metals and pathogens are significantly removed. Furthermore, an additional polishing also occurs in the native groundwater aquifer by dilution and horizontal dispersion (Nema et al., 2001). Based on this principle, SAT is used in many countries around the world (particularly in arid and semi-arid regions; i.e., Israel, Kuwait, etc.) in order to reuse treated wastewater (Candela et al., 2007; Fox et al., 2001; Idelovitch et al., 2003; Nadav et al., 2012; Quanrud et al., 1996; Viswanathan et al., 1999). Effluents of SAT system could be considered as a possible water resource, mainly for irrigation (Nijhawan et al., 2013).

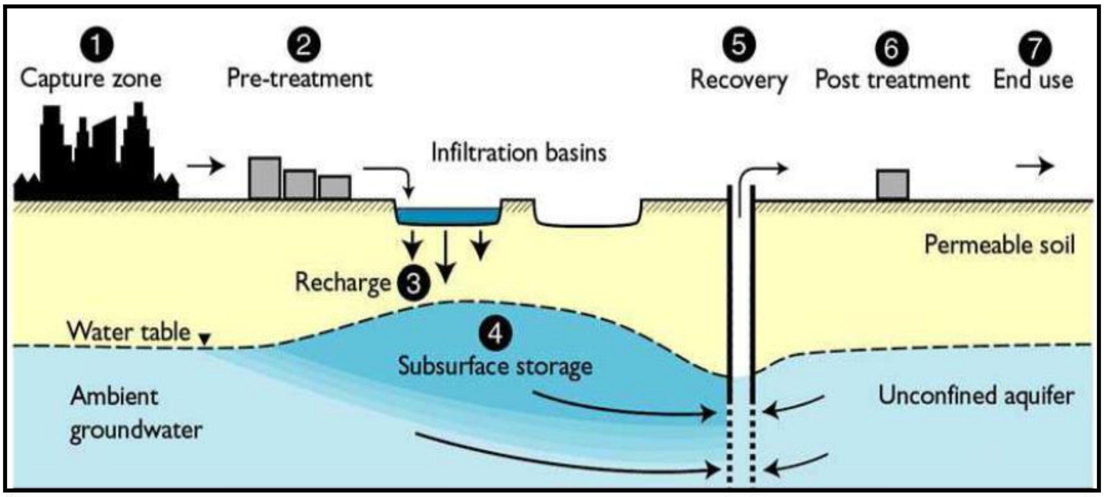

Figure 1.1 A SAT system

1.2.1 Removal Mechanisms in SAT System

Filtration, adsorption, ion exchange, precipitation and microbial degradation are the most effective treatment mechanisms in SAT system (Amy & Drewes, 2007; Essandoh et al., 2011; Lee et al., 2004; Quanrud et al., 1996, 2003b; Shuang et al., 2007; Viswanathan et al., 1999; Yun-zheng & Jian-long, 2006). The long-term performances of some typical removal mechanisms of a SAT system are given in Table 1.2 (Idelovitch, 2003; Viswanathan et al., 1999).

Non-biodegradable organics, suspended material, trace metals and phosphorus are removed by physical and chemical mechanisms at some limited capacity. Chemical precipitation and adsorption are mainly effective on the removal of heavy metals and phosphorus (Cha et al., 2006; Fox et al., 2005; Idelovitch et al., 2003; Lee et al., 2004; Lin et al., 2004; Reemtsma et al., 2000; Viswanathan et al., 1999). Removal of bacteria, on the other hand, typically occurs due to filtration during percolation through soil matrix (Viswanathan et al., 1999).

Table 1.2 Removal mechanisms and long-term performance in SAT

Parameter	Removal Mechanism	Duration
Suspended materials	Filtration	Limited, long time
Dissolved organics	Biodegradation Adsorption	Forever Limited time
Nitrogen	Filtration Nitrification Denitrification Adsorption	Limited, long time Forever Forever Limited time
Phosphorus	Chemical precipitation Adsorption	Limited, long time Limited, long time

Although biodegradation and adsorption are the two major removal mechanisms for dissolved organic carbon (DOC) is during SAT, the dominant mechanism is considered to be biodegradation (Drewes et al., 2003; Ernst et al., 2000; Quanrud et al., 2003a; Rauch & Drewes, 2004, 2005, 2006; Xue et al., 2009). Biodegradation can occur under aerobic or anoxic conditions (Drewes & Jekel, 1998; Westerhoff & Pinney, 2000). Drewes & Jekel (1998) showed that removal of organohalogens is more effective under anoxic conditions. Xue et al. (2009) have measured about 3% adsorption of the initial DOC concentrations and concluded that the basic removal mechanism for DOC is biodegradation in a SAT system. Furthermore, the results obtained from some SAT systems that have been in operation for long years revealed that there was not any organic carbon accumulation in the soil matrix, which further demonstrated the fact that biodegradation was the major removal mechanism for organic matter (Fox et al., 2005; Drewes & Jekel, 1998; Quanrud et al., 2003b; Wilson et al., 1995).

The removal of total nitrogen and ammonium demonstrate a similar behavior to DOC. Nitrogen and ammonium are removed with filtration, adsorption and nitrification/denitrification processes in a SAT system. During infiltration, most of the ammonium is oxidized to nitrate due to aerobic bioprocesses (nitrification). If anoxic conditions occur in the soil matrix or groundwater, nitrate is eventually transformed into nitrogen gas. Due to the fact that oxygen is mostly consumed in the top layer of the soil matrix by microorganisms depending on amount of organic compounds, nitrate can be removed by denitrification at lower layers of the soil matrix and within saturated layer (Gungor & Unlu, 2005; Idelovitch et al., 2003; Yun-zheng & Jian-long, 2006).

SAT systems are typically operated in alternating wetting and drying cycles in order to create suitable conditions for nitrification/denitrification processes. During the wetting period (saturated conditions), the soil surface is clogged due to the suspended solids deposition and bacterial growth in soil spaces. This clogging layer blocks the infiltration of wastewater and prevents the penetration of oxygen into the soil matrix. Upon ceasing of wastewater application, SAT system is allowed to dry after the wetting period. During the drying period (unsaturated conditions), SAT system is maintained at high infiltration rate and enhanced oxygen penetration into the soil matrix, thus creating elevated purification capacities (Idelovitch et al., 2003; Quanrud et al., 1996; Westerhoff & Pinney, 2000).

1.2.2 Effective Parameters in SAT System

Performance of SAT system is mainly affected by the degree of pretreatment of the applied wastewater, the soil type in the infiltration basin, the wetting/drying cycles as well as air temperature and hydraulic and mass loading rates.

Pretreatment of wastewater is one of the most important parameters in SAT due to the risk of clogging of soil matrix with residual pollutants coming from treated wastewater (Pavelic et al., 2011). Sharma et al. (2008) have conducted a research on the effect of pretreatment by using different wastewater effluents treated to diverse levels. When primary, secondary and tertiary treated effluents were used in a SAT system as influent wastewater, maximum DOC removal efficiencies were observed to be 62%, 94% and 80%, respectively. DOC removal efficiencies obtained from a

SAT system for different levels of treated wastewater effluents are given in Table 1.3 (Sharma et al., 2008).

Table 1.3 DOC removal efficiencies in SAT system for different stages treated wastewater effluents

Stages of treated wastewater	Influent DOC to column (mg/L)	Effluent DOC from column (mg/L)	DOC removal (%)
Primary	9-35	7-21	12-62
Secondary	2-24	1.5-16	10-94
Tertiary	5-20	2-14	19-80

These results indicate that secondary treated wastewater is more effective in achieving higher DOC removal values. Furthermore, tertiary treatment is typically not required prior to SAT application. On the other hand, application of the primary treated wastewater created too much ponding in infiltration basin and excessive algae growth that caused clogging in the soil matrix. Consequently, it was clearly seen that secondary treated wastewater was the optimum pretreated wastewater for use in a SAT system.

Using different wetting/drying cycles relatively improves the effectiveness of a SAT system. Drying periods are essential in order to restore aerobic conditions after wetting periods. The duration of a drying period depends on the duration of the preceding wetting period, the characteristics of wastewater and soil type. Typically, the duration of a drying period should be at least equal to the duration of the wetting period or longer. Because of increasing water viscosity and decreasing to microbial activity due to lower air temperatures, the infiltration rate in a SAT system is generally decreased in winter. In such a case, the wetting period may be shortened and the drying period could be extended (EPA, 2003; Idelovitch et al., 2003; Nadav et al., 2012; Quanrud et al., 1996). On the other hand, longer wetting periods might facilitate the initiation of the denitrification process. Lance & Whisler (1972) reported that NH_4^+ and organic N were transformed to NO_3^- by oxidation between 2-9 wetting days, but denitrification was not observed. Whereas, they observed that longer wetting days resulted in the initiation of the denitrification process and finally produced N_2 gas. The effect of the different wetting days on the nitrogen removal with constant 5 drying days in soil column using secondary treated wastewater are given in Table 1.4 (Lance & Whisler, 1972).

Table 1.4 The effect of the different wetting days on the nitrogen removal with constant 5 drying days in soil column using secondary treated wastewater

Wetting days	**Influent N to column (mg)**	**Effluent N from column (mg)**	**N removal (%)**
2	1,641.5	1,714.8	-4
9	4,298.1	3,108.9	28
16	6,811.2	4,547.3	33.2
23	9.893.4	6,685.7	33.9

As shown in this table, longer wetting periods resulted more effective nitrogen removal by nitrification/denitrification process.

Soil type and particle size distribution is another important parameter that influences the removal performances of a SAT system. The soil used in a SAT system should be coarse enough to ensure efficacious infiltration rate, but also should be fine enough to ensure good filtration. Sharma et al (2008) have made a study on effect of soil types on DOC removal during SAT using secondary treated wastewater. The results are given in Table 1.5 (Sharma et al., 2008).

The results of this study indicated that sandy loam soils was more powerful for DOC removal, when compared to other soil types that are typically used in SAT systems such as loamy sand, sandy loam and fine sand (Esser, 1999; Quanrud et al., 1996; Sharma et al., 2008).

It was clearly shown in Table 1.5 that the performance of a SAT system increases with travel (hydraulic residence) time and travel distance (Cha et al., 2004; Laws et al., 2011; Sharma et al., 2008). Travel distance typically depends on depth to groundwater level and distance to recovery wells. On the other hand, high hydraulic and organic loading rates cause lower performance in a SAT system (Nema et al., 2001; Zhang et al., 2007). Effective parameters in the performance of a SAT system are given in Figure 1.2 for different inputs and outputs of the system (AWWARF, 1998).

Table 1.5 Effect of soil types on DOC removal during SAT using secondary treated wastewater

Soil type	**Influent DOC (mg/L)**	**Travel distance (m)**	**Travel time (days)**	**Removal efficiencies (%)**
Sandy loam	14	0.82	7	59-73
	11	1	1	54
	15	2.5	3	53
Poorly graded sand	4-12	1	1-2	26-48
Silty sand	12	1	3	44
Silica sand	4-8	0.3	1	33-46
	8	1	1	29
	11-14	5	2-4	15-30
Poorly graded silty sand	13	1-2	2-4	56

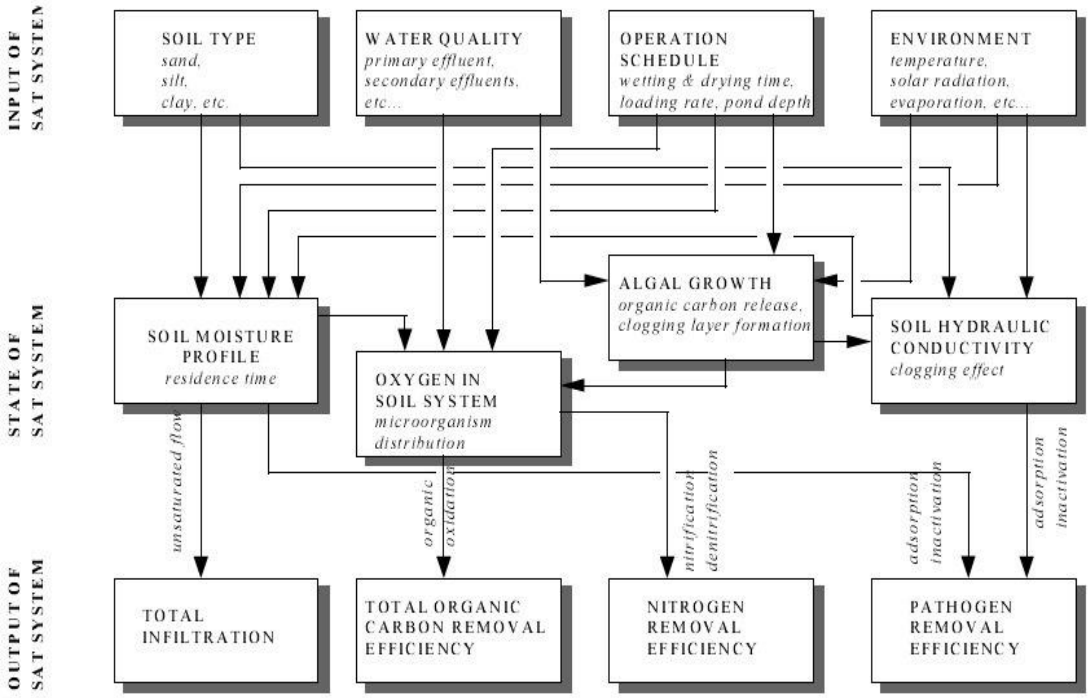

Figure 1.2 Effective parameters in SAT system for different inputs and outputs of the system

1.3 Objectives and Scope of the Thesis

Based on these fundamentals, the main objective of this thesis to determine the quality changes that occur in a secondary treated domestic wastewater during its percolation through soil media and to figure out the benefits of a SAT system. Centered around this main objective, this thesis also intends to investigate the best operation conditions of a laboratory-scale SAT system and to investigate the performance of this system on the removal of organic matter, nutrients (phosphorous, nitrogen and species) and heavy metals. In this regard, the thesis aimed to investigate the performance of a SAT system as a simple and low cost alternative advanced wastewater treatment technology using a laboratory-scale experimental setup. Treatability studies are conducted for organic matter and nutrients using synthetic secondary treated wastewater (SSTWW) and real secondary treated wastewater (RSTWW), and performance comparisons between the two wastewaters are made. Changes of heavy metal concentrations through the columns were investigated using three heavy metal solutions. The behavior of numerous water quality parameters are assessed under distinct wetting and drying periods.

With the above mentioned objectives, this thesis was organized in five chapters. In Chapter 1, problem statement and objective of the study are presented. The following section, Chapter 2, continue with literature review, where the current state-of-the-art in organic matter, nutrients and heavy metal removal using SAT system is presented. In Chapter 3, the materials and methods used in the thesis are described. The details of laboratory-scale SAT system and operational conditions are introduced. In addition, properties of the soil and secondary treated wastewater used in the studies are given. In Chapter 4, analysis and data interpretations are discussed in order to determine of optimum operational conditions in laboratory-scale SAT system. The outcomes of the study are presented in Chapter 5, where the conclusions achieved with this thesis and recommendations for further research are discussed.

CHAPTER TWO
LITERATURE REVIEW

An extensive literature is available for SAT and infiltration systems. The removal of organic carbon is the main area of research in SAT literature, whereas only a few studies were done for investigating the removal of nutrients and heavy metals. This chapter is intended to present the major findings of SAT systems and to demonstrate the state-of-the-art in this active research area.

2.1 Organic Carbon Removal by SAT System

Quanrud et al. (1996) evaluated secondary treated wastewater quality improvement in bench-scale soil column using different soil types. Soil columns were packed with homogenized soil samples including silty sand, sand and sandy loam. Non-purgable DOC and UV absorbance at 254 nm were measured in order to observe the quality changes of secondary treated wastewater during the study. Non-purgable DOC was significantly removed in SAT columns containing silty sand (44%), sand (48%) and sandy loam (56%). Notable differences between sand and sandy loam was observed for the removal of UV-absorbing organics (Quanrud et al., 1996).

Quanrud et al. (2003b) investigated the sustainability of organic removal and fate of organic matter during percolation through a SAT system. The study was conducted in a field-scale SAT system for 5 years using municipal wastewater. Two infiltration basin were utilized in these studies where one was mature (about 10 years old) and the other one was a new infiltration basin. Average DOC removal values were determined to be higher than 90% during percolation through the native 37 m depth in the vadose zone. Hydrophilic fractions of DOC were primarily removed from the wastewater during SAT operation. Average trihalomethane formation potential (THMFP) removal was observed to be 91% through the vadose zone. It was illustrated that wetting/drying periods were not significantly effective in the removal of organic matter (Quanrud et al., 2003b).

Fox et al. (2005) examined the influence of soil type in order to achieve highest organic carbon removal by a SAT system. Five distinct soil types were used for column studies. Laboratory-scale column experiments have shown that the accumulation of organic matter was not detected below a depth of 8 cm from the soil surface. A total organic matter accumulation value of less than 20% of the value given to the columns was observed near the soil surface and water-soil interface coming from biomass and associated organic carbon. Eventually, this study provided that SAT system could be used to remove organic carbon from secondary treated wastewater without any accumulation due to adsorption (Fox et al., 2005).

Westerhoff & Pinney (2000) used an aerated lagoon-treated wastewater in order to investigate DOC transformation using laboratory-scale soil columns for a period of 64 weeks. DOC removal was observed to range between 39% and 70% during the study. At the end of the study, it was observed that biodegradation was major removal mechanisms for DOC and occurred over a short depth of soil matrix during the laboratory-scale soil column study (Westerhoff & Pinney, 2000).

Shuang et al. (2007) investigated the fate of dissolved organic matter in secondary treated wastewater during SAT. The removal of dissolved organic matter, its THMFP and fractions from secondary treated wastewater was investigated using laboratory-scale SAT system soil columns. This study illustrated that dissolved organic matter, trihalomethane and its fractions were effectively removed during SAT. The removal of DOC occurred at an average value 72.35% essentially within the top 50 cm of soil depth (Shuang et al., 2007).

Xue et al. (2008) studied the reduction of dissolved organic matter (DOM) and THMFP in a laboratory-scale SAT system. The reduction of mass and THMFP of DOM fractions in secondary treated wastewater effluent was investigated. The results showed that the laboratory-scale SAT columns were strongly successful to remove DOC and trihalomethane fractions. Hydrophobic acid (HPO-A), transphilic acid (TPI-A), hydrophilic fraction (HPI) and DOC were removed with average values of 61.1, 54.9, 75.0 and 66.0%, respectively in laboratory-scale soil columns (Xue et al., 2008).

Xue et al. (2009) examined behavior and characteristics of DOM using soil column. They conducted biodegradability tests in order to determine biological transformation of DOM. DOC removal was observed to be about 70% during the column study that represented the SAT system. The reduction of 27.2% of DOC was obtained via sorption and anaerobic biodegradation. While sorption and anaerobic biodegradation did not significantly affect the fluorescence properties of DOM, aerobic biodegradation significantly altered the chemical structure of fluorescence components in DOM (Xue et al., 2009).

Rauch & Drewes (2004) conducted a study in order to determine the removal potential of SAT system for bulk organic matter. Four bulk organic carbon fractions that were isolated from secondary treated wastewater were used to observe the fate of effluent organic matter (EfOM) during groundwater recharge. These bulk organic carbon fractions were hydrophilic organic matter (HPI), hydrophobic acids (HPO-A), colloidal organic matter (OM) and soluble microbial products (SMPs). Studies showed that HPI and colloidal OM were easily biodegraded in the first 30 cm of soil surface, and a part of colloidal OM was removed by filtration or physical adsorption. HPO-A and SMPs were more resistant to biodegradation (Rauch & Drewes, 2004).

Rauch & Drewes (2005) carried out biological organic carbon removal in groundwater recharge systems. Results showed that organic carbon removal efficiencies were increased by higher microbial biomass. Similarly, it was found that higher initial organic carbon concentrations produced more microbial biomass in the column. Three organic carbon fractions (natural organic matter, effluent organic matter, and glucose and glutamic acid) were used for the removal studies in soil column. It was observed that higher DOC removal and microbial biomass rates occurred in easily biodegradable fractions of organic carbon. DOC removal essentially occurred in the first 10 cm of infiltration soil surface in where more microbial biomass was formed (Rauch & Drewes, 2005).

Rauch & Drewes (2006) examined the biological removal of effluent-derived organic carbon during soil infiltration. The relationship between organic carbon removal and soil biomass were examined during infiltration. Conventionally treated wastewater was used as the influent for groundwater recharge. A positive correlation was found between biodegradable organic carbon (BOC) and soil biomass concentration in collected soil samples from SAT sites. Furthermore, growth of the soil biomass was limited with the BOC concentration in recharge effluents. Finally, it was found that BOC was mainly removed in first 30 cm of the soil where soil biomass concentrations were significantly increased (Rauch & Drewes, 2006).

Amy & Drewes (2007) studied the fate of wastewater effluent organic matter (EfOM) and trace organic compounds during SAT. Non-humic components in EfOM were easily removed in shorter travel times/distances than humic components. Humic components were removed under long-term anoxic conditions by biodegradation. Biodegradation was determined to be the dominant removal mechanism for DOC. Some hydrophobic organic compounds might also be partially removed by adsorption. DOC removal was observed to range between 50% and 75% after dilution with native groundwater (Amy & Drewes, 2007).

Zhang et al. (2007) evaluated organics removal in combined wastewater that included restaurant wastewater, discharge from toilets and a gas station effluent through shallow soil infiltration treatment (SSIT). This study was simultaneously maintained using a field and laboratory-scale SSIT system in an effective depth 30cm. Soil column experiments were done in order to determine biological and abiological effects on real and laboratory-scale SSIT system. After 10 months operation period, COD removal efficiencies were observed to be 75.8% and 94.0%, in the real field (Shanghai, Chine) and laboratory-scale SSIT system, respectively. The results clearly showed that more organics were removed in the laboratory-scale SSIT system at room temperature. Furthermore, temperature and hydraulic loading rate were found to be the most important parameters that influence the removal efficiency of organic pollutants in SSIT system (Zhang et al., 2007).

Sharma et al. (2008) investigated the performance of a SAT system using different influent water quality and process conditions. Sandy loam, poorly graded sand, silty sand, silica sand and poorly graded silty sand were used as different soil types during the study. DOC removal efficiencies were observed to range between 50% and 60% for secondary and tertiary treated wastewater effluents, and were found to be higher than the values obtained from primary treated wastewater effluent. The removal of DOC mainly occurred in first 1.5m of soil column where aerobic conditions were predominant. The results indicated that the sandy loam soil was more powerful for DOC removal when compared to other soil types (Sharma et al., 2008).

2.2 Nutrient Removal by SAT System

Viswanathan et al. (1999) studied the utilization and improvement of tertiary treated wastewater for irrigation using SAT system. Their studies were conducted in a real infiltration area called Sulaibiyah in Kuwait for 112 days. Tertiary treated wastewater was collected from Ardiya, Jahra and Riqqa treatment plants. Quality of tertiary treated wastewater was significantly improved during SAT. Removal efficiencies of chemical oxygen demand (COD) and biological oxygen demand (BOD) were measured about 70 and 81%, respectively. On the other hand, removal of nutrients as phosphate, ammonia and nitrate were observed about 80, 100 and 21%, respectively. Consequently, it was decided that the treated wastewater by SAT system was suitable for unrestricted irrigation (Viswanathan et al., 1999).

Idelovitch et al. (2003) investigated the long-term performance of a SAT system. The studies were made in Dan Region SAT area in Israel. This SAT system has been utilized to reuse treated wastewater since 1977. During the studies, removal of BOD, COD, total nitrogen and total phosphorus were calculated as 98, 85, 57 and 99%, respectively. All of suspended solids were removed during SAT. The results showed that the SAT system could be considered as a significant treatment technique for unrestricted irrigation of municipal wastewater in areas where hydrogeological conditions are suitable for groundwater recharge (Idelovitch et al., 2003).

Gungor & Unlu (2005) evaluated removal efficiencies of nitrite and nitrate in SAT columns. Laboratory-scale SAT soil columns were used in order to determine the effect of soil type and infiltration conditions on nitrite and nitrate removal. Three different soil types (sandy clay loam (SCL), loamy sand (LS) and sandy loam (SL) textures) were utilized to fill each columns,. All soil columns were operated in two different wetting/drying periods; 7 wetting/7 drying days and 3 wetting/4 drying days. At the end of the study, it was found that infiltration rate and length of wetting period were important parameters in nitrogen removal in a SAT system. Denitrification performance of the columns operated as 7 wetting/7 drying days were observed to be better than 3 wetting/4 drying days. Furthermore, the column operated with LS soil was showed to give the best nitrogen removal performance (95%) using 7 wetting/7 drying days operation period (Gungor & Unlu, 2005).

Akber et al. (2008) examined the feasibility of long-term irrigation with municipal tertiary treated wastewater using pilot-scale SAT system in Kuwait. The removal efficiencies of biological oxygen demand (BOD), organic carbon (OC) and ammonia were about 100, 90 and 90% respectively. In addition, bacteria were also removed with 50-100% efficiency depending on its type. The results of this study indicated that SAT system was suitable for long-term irrigation like previous studies (Akber et al., 2008).

2.3 Heavy Metal Removal by SAT System

Lin et al. (2004) studied the heavy metal retention and partitioning in a large-scale SAT system. Cu, Ni and Zn were measured in short-term adsorption experiments that significantly correlated with pH. The studies showed that surface adsorption and precipitation on Fe oxides and/or carbonate were mainly responsible to metal retention in soil. Cu primarily partitioned into the oxide component (32.0%) whereas Zn primarily partitioned into the carbonate component (51.6%) (Lin et al., 2004).

Lee et al. (2004) investigated the sorption behaviors of heavy metals (Cd, Cr and Pb) in a SAT system. This study was conducted to investigate the feasibility of SAT system for three metals with laboratory-scale soil column experiment. In addition, possible desorption of sorbed metals was detected for both continuous water condition and acidic water to pH 4.3 injection. Two-level fractional factorial analysis was used in this study. Powerful four factors on Pb sorption were found to be TOC in solution, Pb concentration in solution, soil particle size and flow rate. These four factors were also converted to coefficients in order to constitute an empirical model and predict the metal sorption onto soil. At the end of the all studies, it was reported that heavy metals in wastewater could be effectively removed in a SAT system without metal desorption even in acid rain conditions (Lee et al., 2004).

CHAPTER THREE
MATERIALS AND METHODS

3.1 Experimental setup

3.1.1 Design of Soil Columns

A multi-column SAT system was constructed in laboratory conditions. The experimental setup consisted of six identical thermoplastic columns of 120 cm length and 10 cm inner diameter, a feeding tank, a feeder assembly, six distributor lines and a peristaltic pump. The feeding tank was used only when the columns were operated with real secondary treated wastewater in order to ensure room temperature in wastewater samples coming from the refrigerator. Owing to the fact that the SSTWW was daily prepared (not stored in the refrigerator), the columns were directly fed with the SSTWW. The experimental setup and sampling ports are given in Figure 3.1, Figure 3.2 and Figure 3.3.

Each column was equipped with a series of ports at multiple depths from soil surface (10, 20, 30, 50 and 75 cm) in order to collect the effluent samples. Before the columns were packed with the soil sample, the bottom of each column was filled with a gravel layer of 10 cm thickness in order to prevent clogging of the column outlet. Columns were then packed with soil to a distance of 10 cm below of the overflow weir (top port). The columns were operated under gravity flow conditions with 10 cm ponding depth. Thus, 10 cm ponding depth of wastewater above the soil surface was guaranteed in each column. A peristaltic pump was used to supply wastewater to the top feeder assembly, from which distributor lines served to each column. The peristaltic pump was connected to a storage tank of 10 L capacity. The pump speed was set such that a constant head upper boundary condition of 10 cm was maintained in each column, while minimizing overflow from the column. During operation of the columns, samples were collected from sampling ports and stored in plastic bottles that were sealed to prevent air entry.

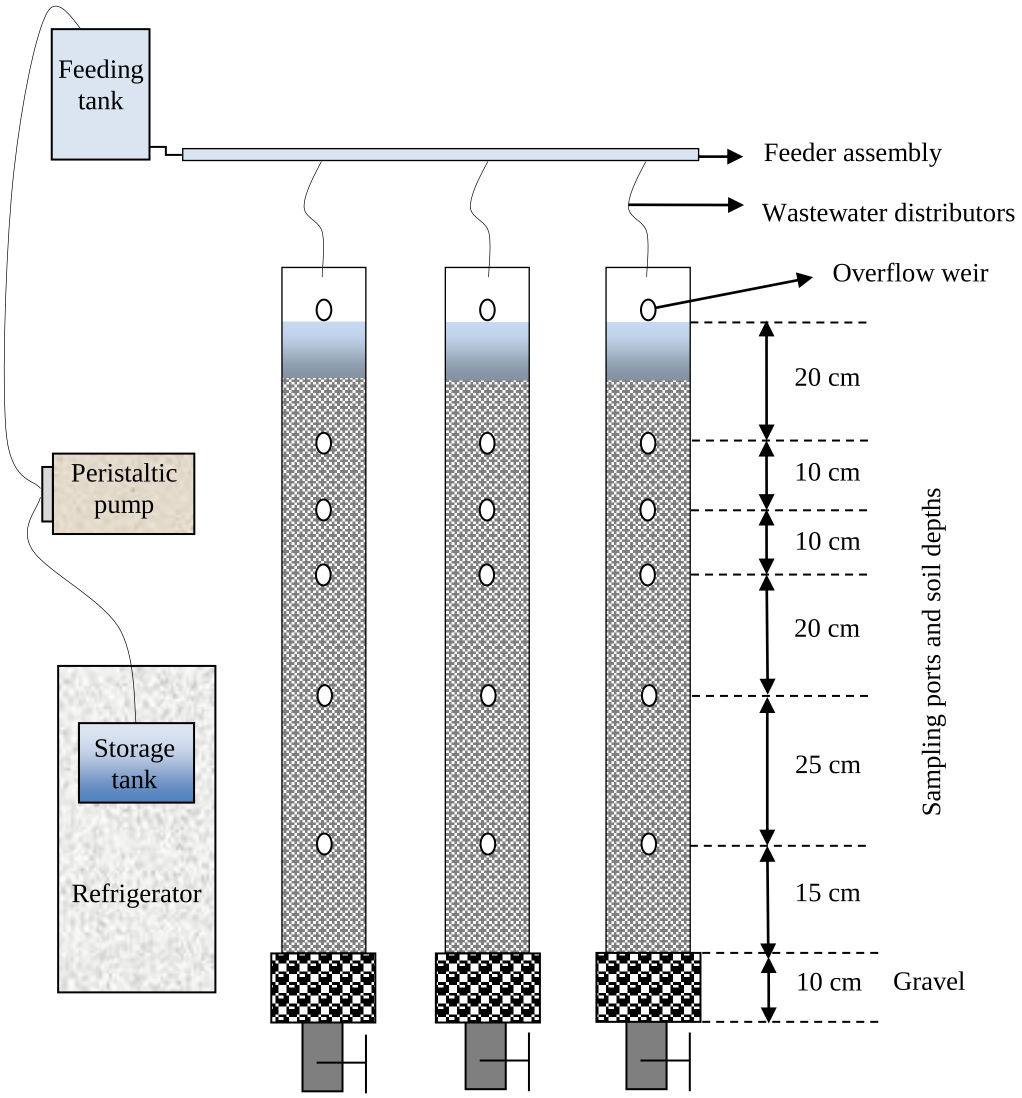

Figure 3.1 A schematic diagram of experimental set-up (laboratory-scale SAT system)

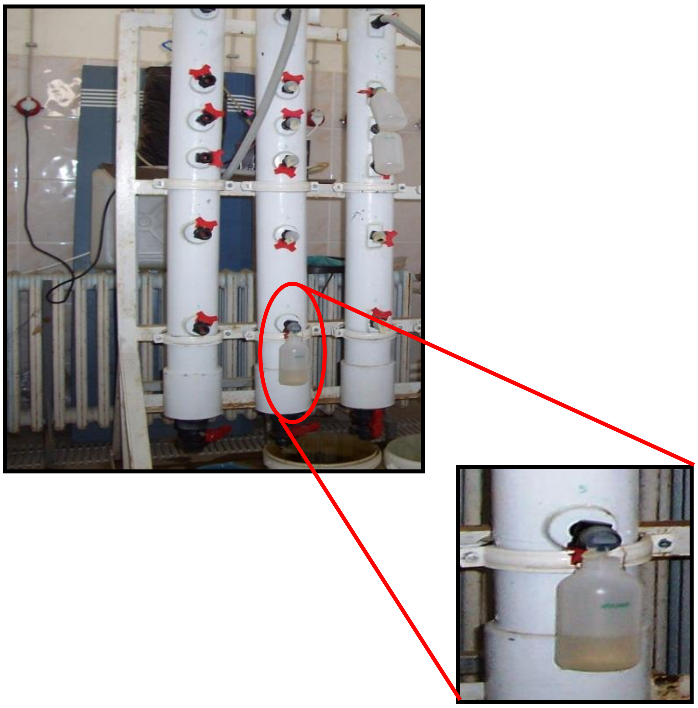

Figure 3.2 Experimental setup and sampling

Figure 3.3 Full view of experimental setup

3.1.2 Operation of Soil Columns

Experimental procedure can be summarized as (i) removal studies with SSTWW (Run 1), (ii) removal studies with RSTWW (Run 2), and (iii) removal studies with heavy metal containing distilled water (Run 3). Operational conditions were summarized in Table 3.1 for all experimental studies.

Table 3.1 Operational conditions for all experimental studies

	Influent	**Cycles**	**Operation time (weeks)**
Run 1	SSTWW	(3w/4d) and (7w/7d)	55
Run 2	RSTWW	(3w/4d) and (7w/7d)	25
Run 3	Heavy metal solutions	(3w/4d)	21

During the experimental studies of Run 1 and 2, the columns were operated with synthetic and real secondary treated wastewater. A total of five columns were used; two columns for Run 1, two columns for Run 2 and the last column with distilled water, simultaneously with Run 1 studies. One column was operated by distilled water in order to determine the influence of background contamination originating from the soil. Two of the remaining four columns was operated in two-week cycles consisting of 7 days of wetting followed by 7 days of drying (7w/7d), the other two columns was operated in one-week cycle consisting of 3 days of wetting followed by 4 days of drying (3w/4d) for each of Run 1 and Run 2 studies.

Run 1 studies started in May 2010; Run 2 and 3 studies started in December 2011. Soil columns were operated in closed laboratory conditions without any additional climatic temperature control inside the laboratory during the entire period of all studies. Two columns were operated for 55 weeks with SSTWW and the other two columns were operated for 25 weeks with real secondary treated effluents of Izmir-Cigli WWTP during the studies conducted as a part of Run 1 and 2.

Four columns were operated with synthetically prepared heavy metals solutions for Run 3 studies. One of these four columns were operated with deionized water and the remaining three columns were operated with single heavy metal solutions of Cu, Pb and Zn on a 3w/4d cycle system for 21 weeks.

Each of the Run 1, 2 and 3 studies started with new soil samples. While Run 1 studies were initiated directly with SSTWW, before Run 2 studies were initiated with the real secondary treated wastewater, two columns that used for Run 2 studies were operated by distilled water for four weeks in order to remove background contamination originating from the soil. Same operation was made before Run 3 studies with deionized water for four weeks.

3.2 Soil Samples and Properties

Soil samples were collected from a field in Menemen that belongs to Menemen Agricultural Research Institute in Izmir (Figure 3.4). Some physical and chemical properties of the soil collected from the top 20 cm are given in Table 3.2 (Gocmez, 2006). Additionally, major constituents and minor elements of these soil samples are given in Table 3.3 and Table 3.4, respectively.

Table 3.2 Some properties of soil obtained from Menemen region (0-20 cm depth)

Parameters	**Soil**		
pH	7.67		
Electrical Conductivity (EC)	1.156 dS/m		
Structure	Silt loam		
Organic Matter	1.5 %		
C / N	4.8		
$CaCO_3$	6.0 %		
Cation Exchange Capacity (CEC)	23.56 meq/100g		
Saturation	60 %		
Total N	0.18 %		
Permeability (cm/h)	2 hours	6 hours	Average
	8.640	7.488	8.064

Table 3.3 Major constituents of soil obtained from Menemen region (0-20 cm depth)

Parameters	**Unit**	**MDL**	**Value**
SiO_2	%	0.01	59.37
Al_2O_3	%	0.01	13.83
Fe_2O_3	%	0.04	4.61
MgO	%	0.01	2.57
CaO	%	0.01	4.75
Na_2O	%	0.01	2.01
K_2O	%	0.01	2.75
TiO_2	%	0.01	0.75
P_2O_5	%	0.01	0.26
MnO	%	0.01	0.06
Cr_2O_3	%	0.002	0.013
LOI	%	-5.1	8.8
Sum	%	0.01	99.81
Ni	ppm	20	86.0
Sc	ppm	1	12.00

MDL: Minimum Detection Limit

Figure 3.4 The field in Menemen where soil samples are collected

Table 3.4 Minor elements of soil obtained from Menemen region (0-20 cm depth)

Parameters	**Unit**	**MDL**	**Value**
Ba	ppm	1	566
Be	ppm	1	2
Co	ppm	0.2	14.0
Cs	ppm	0.1	12.7
Ga	ppm	0.5	16.3
Hf	ppm	0.1	7.9
Nb	ppm	0.1	14.1
Rb	ppm	0.1	103.3
Sn	ppm	1	4
Sr	ppm	0.5	227.5
Ta	ppm	0.1	1.1
Th	ppm	0.2	11.9
U	ppm	0.1	3.2
V	ppm	8	90
W	ppm	0.5	2.0
Zr	ppm	0.1	279.5
Y	ppm	0.1	31.0
La	ppm	0.1	34.2
Ce	ppm	0.1	71.0
Pr	ppm	0.02	7.98
Nd	ppm	0.3	29.5
Sm	ppm	0.05	5.89
Eu	ppm	0.02	1.18
Gd	ppm	0.05	5.38
Tb	ppm	0.01	0.88
Dy	ppm	0.05	4.97
Ho	ppm	0.02	1.09
Er	ppm	0.03	3.23
Tm	ppm	0.01	0.48
Yb	ppm	0.05	3.24

Table 3.4 (continued)

Parameters	**Unit**	**MDL**	**Value**
Lu	ppm	0.01	0.48
Mo	ppm	0.1	0.4
Cu	ppm	0.1	28.6
Pb	ppm	0.1	14.3
Zn	ppm	1	55
Ni	ppm	0.1	76.8
As	ppm	0.5	26.4
Cd	ppm	0.1	0.2
Sb	ppm	0.1	1.1
Bi	ppm	0.1	0.2
Ag	ppm	0.1	<0.1
Au	ppb	0.5	1.6
Hg	ppm	0.01	0.05
Tl	ppm	0.1	0.3
Se	ppm	0.5	<0.5
TOT/C	%	0.02	1.63
TOT/S	%	0.02	0.02

MDL: Minimum Detection Limit

The soil samples were air-dried, crushed and sieved using 2 mm mesh before packing the columns. Homogenized soil samples represented 0-20 cm depth obtained Menemen region.

3.3 Synthetic and Real Secondary Treated Wastewater

The SSTWW and RSTWW were used in Run 1 and 2 studies. The RSTWW samples were periodically taken from the secondary treated effluent from Cigli (Izmir) wastewater treatment plant (WWTP). The plant implements biological treatment with nutrient removal to the municipal wastewaters of the city of Izmir and currently serves a population of about 3 million inhabitants within the metropolitan area. Cigli WWTP was constructed on an area of 300,000 m^2 and designed to have an average capacity of 605,000 m^3/day (IZSU, 2010). A simple flow diagram of Cigli WWTP is given in Figure 3.5.

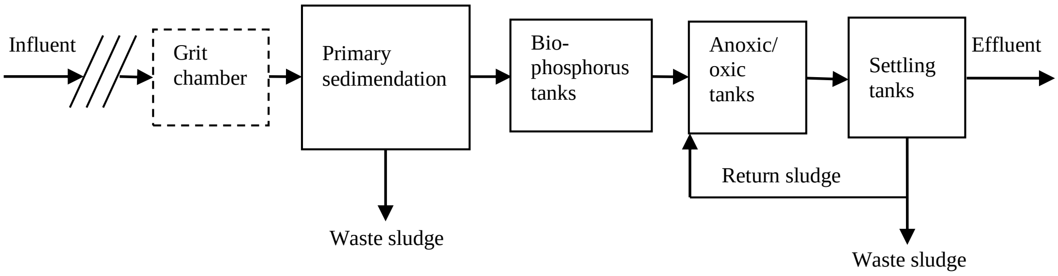

Figure 3.5 A simple flow diagram of Cigli WWTP

The average influent and effluent water quality of Cigli treatment plant is given in Table 3.5. The synthetic secondary treated wastewater was prepared according to the quality characteristics given in Table 3.5 to better represent the RSTWW composition of Cigli WWTP (IZSU, 2010). Additionally, the results of the complete characterization of influent and effluent water qualities in three WWTPs of Izmir are given in Table 3.6 (Gunduz & Simsek, 2007).

The SSTWW was prepared to represent the effluent quality of Cigli WWTP. Based on the average effluent quality given in Table 3.5, a SSTWW with respective carbon (as COD), nitrogen (N) and phosphate (P) concentrations of 100, 12 and 2 mg/L were prepared and used in column studies. D-glucose, urea and potassium phosphate were used as C, N and P source, respectively.

Table 3.5 Average influent and effluent water qualities obtained from Cigli (Izmir) WWTP

Parameters	**Influent (mg/L)**	**Effluent (mg/L)**
BOD_5	400	<20
COD	600	<100
Total suspended solids	500	<30
Total phosphorus	6	<2
Total nitrogen	60	<12

Table 3.6 Influent and effluent water qualities in three WWTPs of Izmir

Quality parameter	Cigli WWTP		Guneybati WWTP		Havza WWTP	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
pH	7.29	7.06	7.27	7.00	7.65	7.62
Temperature (ºC)	25.6	26.4	23.4	24.4	23.3	25.6
EC (µS/cm)	8690	7920	23200	19780	1613	1491
Salinity (‰)	4.9	4.4	14.0	11.8	0.6	0.6
Cl (mg/L)	2579.9	2399.9	15699.6	15399.6	230.0	250.0
HCO_3 (mg/L)	1094	886	1278	922	1008	856
NO_3-N (mg/L)	6.5	17.0	20.0	13.5	10.5	14.5
Ca (mg/L)	123.0	118.2	239.9	208.9	90.1	91.4
K (mg/L)	65.7	62.7	168.0	142.6	72.4	72.2
Mg (mg/L)	159.4	152.1	443.4	376.0	29.0	26.5
Na (mg/L)	1368.1	1284.6	4632.1	3976.5	143.5	141.9
SAR	19.2	18.4	41.0	38.0	3.4	3.4
Al (µg/L)	26	24	<10	<10	22	11
As (µg/L)	21.6	22	19.6	18.2	15.2	7.7
B(µg/L)	890	1045	1315	1231	590	539
Be (µg/L)	<0.5	<0.5	<0.5	<0.5	<0.05	<0.05
Cd (µg/L)	<0.5	<0.5	<0.5	<0.5	0.44	0.11
Co (µg/L)	0.91	0.48	0.38	0.37	0.55	0.35
Cr (µg/L)	39.9	16.7	<5	<5	7	2.1
Cu (µg/L)	12.5	12.3	26.3	23.5	6.2	8.9
Fe (µg/L)	209	<100	107	<100	210	17
Li (µg/L)	37.1	42.5	58.4	51.3	21	18.4
Mn (µg/L)	166.3	32.0	351.0	323.6	74.6	46.4
Mo (µg/L)	3.6	2.2	2.7	2.8	0.6	1
Ni (µg/L)	41.9	26.2	<2	<2	8.9	12.3
Pb (µg/L)	2.9	1.4	<1	<1	1.1	1
Sb (µg/L)	0.54	1.39	<0.5	0.52	0.36	1.4
Se (µg/L)	22.9	21.1	76.2	60	1.3	0.9
V (µg/L)	9.9	13.6	35.9	35.7	3.1	4.1
Zn (µg/L)	105.1	89.2	31	95.6	196.7	82.9

Copper (Cu), Lead (Pb) and Zinc (Zn) were selected in order to determine the behavior of heavy metals through the SAT system for Run 3 studies. For this purpose, three synthetic metal solutions were prepared containing these three single heavy metals. Following the effluent quality given in Table 3.6, synthetic heavy metal solutions were prepared to contain Cu, Pb and Zn levels of 15, 2 and 90 µg/L, respectively.

3.4 Experimental Procedure and Analytical Methods

During Run 1 and 2 studies following parameters were measured in Dokuz Eylul University Department of Environmental Engineering laboratories:

- temperature (T),
- pH,
- salinity,
- electrical conductivity (EC),
- total dissolved solids (TDS),
- oxidation-reduction potential (ORP),
- dissolved oxygen (DO),
- total organic carbon (TOC),
- chemical oxygen demand (COD),
- ammonium nitrogen (NH_4^+ −N),
- nitrite nitrogen (NO_2^-–N),
- nitrate nitrogen (NO_3^-–N),
- total nitrogen (total–N) and
- phosphate phosphorus (PO_4^{-3}–P).

These measurements were made in samples collected from the five sampling ports of each column as well as the stock solutions during all studies. For Run 3 studies where the statuses of heavy metals are investigated, the following parameters were measured in samples collected from the five sampling ports of each column as well as the stock solution:

- the corresponding heavy metal (Cu, Pb and Zn) and
- pH.

After the RSTWW stock samples were taken from the WWTP for Run 2 studies, TDS, EC, T, ORP, DO and pH were immediately measured on site and the sample were transferred to the laboratory where it was stored in the refrigerator at 4 °C.

Samples taken from the columns were collected at the end of the first wetting day and at the end of the last wetting day for 7w/7d cycle and only at the end of the first wetting day for 3w/4d cycle.

When the samples were taken into plastic bottles of 500 mL, their caps were right away closed to prevent air entry. Some measurements were immediately made by using portable probes. TDS, EC and T measurements were made by using Hanna H1 9828; ORP, DO and pH measurements were made using Hach HQ40D. Before the samples were analyzed for COD, TOC, total nitrogen, NH_4^+ –N, NO_3^-–N, NO_2^-–N and PO_4^{-3} –P, all samples were centrifuged at 8000 rpm (7000 g) for about 20 minutes in order to remove suspended solids from the liquid phase using Sigma 2-16 Centrifuge. Additionally, the supernatant samples were filtered using 0.45μm Millipore filter. Thereafter, clear supernatants were stored at 4˚C in the refrigerator until analysis. Prior to analysis, all samples were brought to room temperature.

COD analysis was done using the closed-reflux colorimetric method according to the Standard Methods (Greenberg et al., 1989). TOC analyses were conducted using Teledyne Tekmar Apollo 9000 Combustion TOC Analyzer. NO_3^-–N, NO_2^-–N and PO_4^{-3} –P analysis were done using Dionex ICS-3000 ion chromatography (IC). Total nitrogen and NH_4^+ –N measurements were done using Merck kits (Kit ID: 114537 and 14752.0001-2, respectively). Heavy metal analyses were done using Perkin Elmer Optima 2100 DV inductively coupled plasma optical emission spectrometer (ICP-OES). In order to prepare single heavy metal solutions, Merck ICP standards were used, with lot numbers of HC073556, HC077864 and HC090981 for copper lead and zinc, respectively.

Standard Plate Count Method was used for calculating the number of bacteria (colony-forming unit-CFU) per gram of sample by dividing the number of colonies by the dilution factor multiplied by the amount of specimen added to liquefied agar.

All experiments and measurements were done with two or three duplicates and arithmetic averages were used throughout the study.

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Analysis of the Columns operated with SSTWW and RSTWW

During Run 1 and Run 2 studies, samples were taken at the end of the first wetting day (7w/7d-first day) and at the end of the last wetting day (7w/7d-last day) for 7w/7d cycle and only at the end of the first wetting day (3w/4d) for 3w/4d cycle. Two of the columns were operated for 55 weeks with SSTWW prepared to represent the effluent quality of Izmir-Cigli WWTP and the other two columns were operated for 25 weeks with real secondary treated effluents of Izmir-Cigli WWTP. Samples could not be collected in some weeks during the study because of clogging of ports.

The parameters measured during the first four operation weeks of Run 1 studies (i.e., acclimation period) were just used for figures that revealed changes of parameters in the last sampling ports with operation weeks, not used to calculate the basic statistics of the data (i.e., average, minimum, maximum standard deviation, 10% percentile, 50% percentile and 90% percentile).

4.1.1 Hydraulic Characteristics of Columns

During Run 1 and Run 2 studies, infiltration rates were periodically measured in both operational cycles. Average infiltration rate of the column operated as 3w/4d was higher than the 7w/7d column. Average infiltration rate during 3w/4d cycles and 7w/7d cycles were measured to be 34.4 and 28.3 cm/day respectively. Lower infiltration rates occurred at the end of the wetting periods owing to the fact that the soil became more saturated whereas higher infiltration rates occurred at the beginning of the wetting period. Additionally, infiltration rates for each operation cycle decreased through the end of the study because the soil became more compacted and clogged in time. These results are consistent with the findings reported by Gungor & Unlu (2005), Quanrud et al. (1996) and Westerhoff & Pinney (2000). For Run 1 cases, the infiltration rate for column operated as 3w/4d was measured between 28 and 45 cm/day whereas the infiltration rate for column operated as 7w/7d was in the range of 23-37 cm/day. Average hydraulic residence times during 3w/4d cycles and 7w/7d cycles were measured to be 2.18 and 2.65 day, respectively.

4.1.2 Microbiological Analysis of the Soil

In general, soil contains different numbers and kinds of microorganisms but bacteria and fungi play primarily roles in various biochemical cycles of organic compounds (Ogunmwonyi et al., 2008; Wall & Virginia, 1999). Previous studies have showed that there is a positive correlation between microbial growth and removal of organic matter and nitrogen. Since the determination of each particular microorganism species is difficult and complicated, total microorganisms were measured in this study. Determination of total microorganisms was deemed sufficient to interpret to results of study.

Microbiological analysis of the soil was made while the columns were operated with RSTWW at all sampling port depths (Table 4.1).

Table 4.1 Average number of total microorganisms in the soil at all sampling port depths

Soil depth (cm)	10	20	30	50	75
Number of total microorganisms (10^6/g soil)	459	173	47	9	3

Results indicated that number of total microorganisms decreased through the soil columns because of decreasing organic carbon concentrations along the column depth (Figure 4.23 and Figure 4.24). These results are consistent with the reports by Atals & Bartha, (1998) and Rauch & Drewes, (2005). Additionally, Atals & Bartha, (1998) reported that fungi were found primarily in the first 10 cm depth of the soil surface and were seldom observed below 30 cm. Because top of the soil contained more oxygen and organic carbon, the highest number of microorganisms was observed in the first 10 cm of the soil depth in this study, too. Consequently, the microbial biomass growth through the columns was attributed to organic carbon availability.

4.1.3 Analysis of the Column Operated with Distilled Water prior to the Studies

Simultaneously with Run 1 studies, one column was operated for four weeks with distilled water in order to determine the background contamination originating from the soil. Additionally, before Run 2 studies were started with the real secondary treated wastewater, two columns that were used for Run 2 studies were also operated by distilled water for four weeks.

Table 4.2 depicts average effluent values of some parameters for each sampling port in the column operated with distilled water prior to the studies. It is clearly seen from the Table 4.2 that TDS, EC, TOC and COD levels increased as a function of depth in the column due to the organic matter and dissolved solids originating from the soil matrix. These increases were also observed initially in the other four columns operated with each SSTWW and RSTWW. As a result of dissolution of alkali minerals present in the soil media in the distilled water, pH values were observed to be in the alkaline range.

Table 4.2 Average effluent values of some parameters for each sampling port in the column operated with distilled water prior to the studies

Soil Depth (cm) **Parameters**	**10**	**20**	**30**	**50**	**75**
pH	8.21	8.02	8.22	7.83	7.72
TDS (mg/L)	54	79	97	114	191
EC (µS/cm)	109	160	198	231	382
TOC (mg/L)	12.43	14.51	17.03	30.79	43.52
COD (mg/L)	27.13	32.17	39.74	64.97	107.86

4.1.4 Temperature Changes

Temperatures of samples were measured during Run 1 and Run 2 studies after the samples were taken from the five sampling ports of each column as well as the stock solution. Table 4.3 depicts variations of temperature with soil depth in the columns operated with SSTWW and RSTWW. As reported in Table 4.3, the temperature values of influent wastewaters were measured in the range of 20.34–28.64 ºC and 20.05–24.62 ºC for the SSTWW and RSTWW, respectively.

Temperature of samples varied temporarily as a function of seasonal climatic conditions. Changes of average temperature through the columns operated with SSTWW and RSTWW are given in Figure 4.1 and Figure 4.2, respectively. While Run 1 studies conducted during all seasons in a year, Run 2 studies were mostly done in winter periods. For this reason, temperature values during Run 2 studies were measured lower than Run 1 studies.

It is clearly seen in Figure 4.1 and Figure 4.2 that temperature of samples did not significantly change through all columns. A small decrease in temperature through the column was observed at the 7w/7d-last day of Run 2 studies, because of exposure to low air temperature during 7 days wetting period.

4.1.5 pH Changes

pH values of samples were measured during Run 1 and Run 2 studies after the samples were taken from the five sampling ports of each column as well as the stock solution. Table 4.4 depicts variations of pH with soil depth in the columns operated with SSTWW and RSTWW. As reported in Table 4.4, the pH values were measured in the range of 5.41–8.08 and 7.13–8.22 for influent SSTWW and RSTWW, respectively. Average initial pH values during Run 1 studies were measured lower than Run 2 studies, since the pH of distilled water is generally lower than 7 (Sandhyarani, 2011).

Table 4.3 Variations of temperature with soil depth in the columns operated with SSTWW and RSTWW

	Temperature values (°C) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						7w/7d-first day						7w/7d-last day					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	23.72	23.69	23.39	23.47	23.35	23.43	23.31	22.91	22.90	22.84	22.80	22.90	24.00	23.61	23.66	23.69	23.71	23.60
Minimum	20.34	20.59	20.31	19.83	19.84	19.45	20.34	19.57	19.59	19.28	19.29	19.18	20.63	20.20	20.26	20.25	20.24	20.31
Maximum	28.64	29.19	28.76	28.75	28.44	27.50	28.42	28.37	28.24	28.18	27.02	27.06	28.64	27.70	27.60	27.70	27.80	27.10
Standard deviation	2.37	2.41	2.23	2.36	2.31	2.23	2.30	2.26	2.24	2.27	2.10	2.35	2.25	2.24	2.22	2.17	2.31	2.29
10% percentile	20.88	20.83	20.64	20.83	20.70	20.59	20.80	20.28	20.33	20.26	20.31	20.03	21.89	21.12	21.38	21.42	21.05	21.11
50% percentile	23.18	23.26	22.66	22.98	22.72	23.20	22.73	22.53	22.54	22.33	22.23	22.44	23.22	22.82	23.04	22.86	24.21	24.22
90% percentile	26.89	26.94	26.08	26.87	26.65	25.86	25.95	25.25	25.14	25.18	25.25	25.76	27.01	26.63	26.75	26.57	26.42	26.73
	Temperature values (°C) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	21.63	21.71	21.55	21.40	21.44	21.22	21.89	21.43	21.42	21.58	21.38	21.26	21.35	21.28	21.15	21.28	21.18	20.74
Minimum	20.05	20.03	20.05	19.97	19.58	20.01	20.05	20.09	20.12	20.09	20.11	20.18	20.24	20.06	19.74	20.06	20.03	19.97
Maximum	24.62	24.43	24.18	24.08	23.98	23.73	24.62	23.36	23.25	23.18	23.06	22.99	23.31	23.38	23.33	23.22	23.26	21.64
Standard deviation	1.52	1.46	1.36	1.41	1.36	1.18	1.87	1.39	1.34	1.34	1.27	1.31	1.12	1.35	1.28	1.29	1.08	0.81
10% percentile	20.18	20.53	20.15	20.07	20.02	20.03	20.13	20.10	20.13	20.15	20.11	20.19	20.26	20.08	19.88	20.09	20.08	20.02
50% percentile	21.35	21.28	21.28	21.14	21.24	21.07	21.21	21.13	21.03	21.50	20.89	20.50	21.35	21.36	21.12	21.45	21.09	20.67
90% percentile	23.52	23.86	23.63	23.44	23.34	22.70	24.12	23.23	23.18	23.14	23.02	22.89	22.43	22.63	22.46	22.55	22.27	21.50

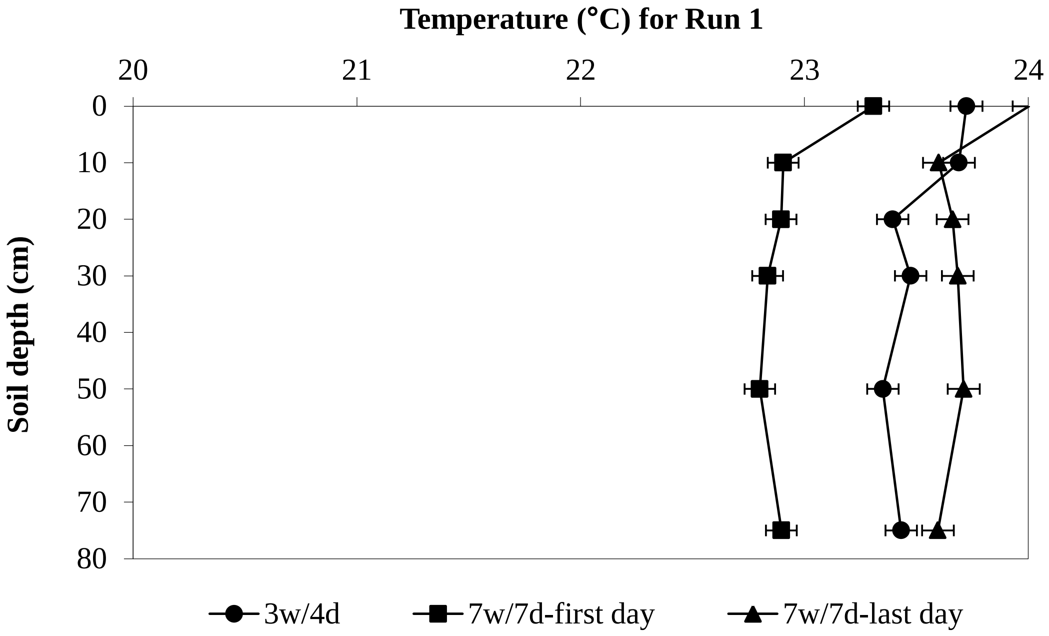

Figure 4.1 Changes of average temperature through the columns operated with SSTWW

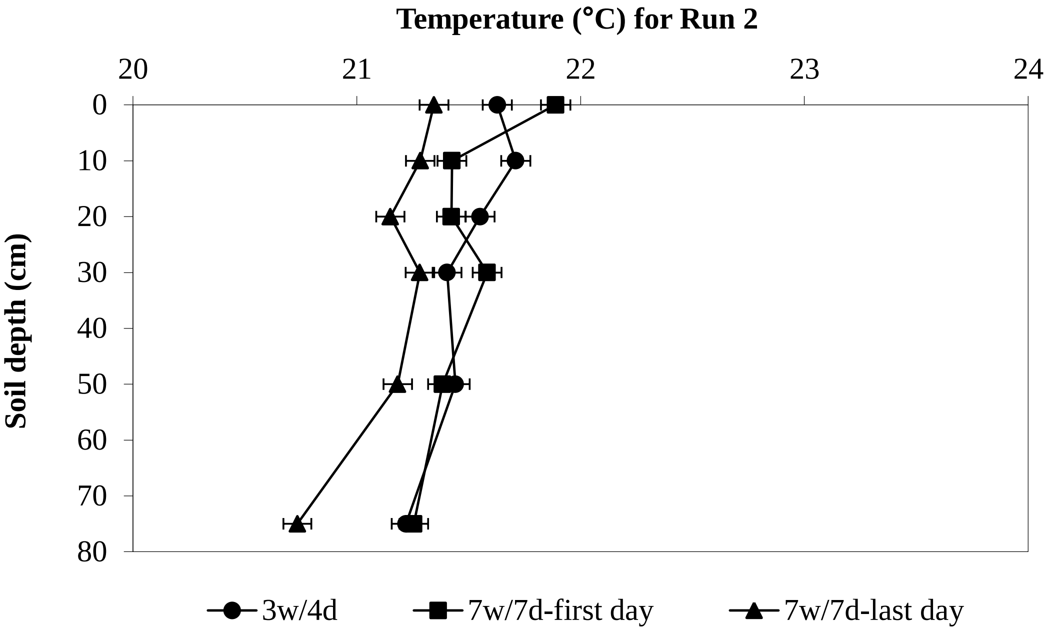

Figure 4.2 Changes of average temperature through the columns operated with RSTWW

Table 4.4 Variations of pH with soil depth in the columns operated with SSTWW and RSTWW

	pH values in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						7w/7d-first day						7w/7d-last day					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	6.98	7.04	7.05	7.11	7.24	7.46	7.02	7.30	7.31	7.33	7.28	7.38	6.92	7.33	7.25	7.27	7.27	7.45
Minimum	5.41	5.88	6.03	6.07	6.68	6.91	5.41	6.35	6.43	6.58	6.49	6.93	6.02	6.62	6.33	6.64	6.78	7.05
Maximum	8.06	7.63	7.51	7.49	7.63	7.89	7.82	8.08	7.96	8.05	7.56	7.96	8.06	7.81	7.72	7.66	7.57	7.78
Standard deviation	0.60	0.47	0.39	0.33	0.24	0.23	0.67	0.49	0.43	0.35	0.30	0.22	0.54	0.31	0.33	0.28	0.21	0.24
10% percentile	6.21	6.47	6.48	6.56	6.82	7.12	6.19	6.43	6.46	6.82	6.84	7.20	6.30	7.04	6.96	6.98	7.04	7.19
50% percentile	7.22	7.23	7.19	7.19	7.27	7.48	7.30	7.44	7.40	7.42	7.38	7.37	7.05	7.31	7.25	7.31	7.33	7.44
90% percentile	7.68	7.51	7.43	7.38	7.48	7.71	7.73	7.66	7.71	7.65	7.50	7.52	7.38	7.66	7.56	7.56	7.51	7.77
	pH values in the columns operated with real wastewater (Run 2)																	
	3w/4d						7w/7d-first day						7w/7d-last day					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	7.45	7.64	7.69	7.71	7.69	7.61	7.57	7.75	7.78	7.76	7.81	7.77	7.32	7.71	7.73	7.77	7.76	7.80
Minimum	7.13	7.46	7.46	7.45	7.40	7.36	7.35	7.58	7.65	7.62	7.66	7.60	7.13	7.65	7.60	7.69	7.61	7.79
Maximum	7.75	7.73	8.16	8.14	8.14	8.18	7.75	8.07	8.03	8.01	8.17	8.22	7.54	7.77	7.81	7.82	7.80	7.81
Standard deviation	0.20	0.09	0.15	0.16	0.16	0.28	0.16	0.16	0.13	0.14	0.17	0.21	0.16	0.05	0.08	0.05	0.07	0.01
10% percentile	7.20	7.50	7.58	7.57	7.54	7.40	7.35	7.60	7.65	7.63	7.67	7.60	7.17	7.65	7.65	7.72	7.69	7.79
50% percentile	7.38	7.67	7.64	7.68	7.67	7.50	7.60	7.72	7.74	7.72	7.73	7.71	7.31	7.71	7.76	7.78	7.78	7.80
90% percentile	7.72	7.72	7.82	7.86	7.82	8.13	7.74	7.90	7.92	7.91	8.03	8.06	7.52	7.76	7.80	7.81	7.80	7.81

Changes of average pH through the columns operated with SSTWW and RSTWW are depicted in Figure 4.3 and Figure 4.4, respectively. Due to the presence of alkali minerals in the soil media (soil pH value was reported as 7.67 in Table 3.2), pH values rapidly increased within the first 10 cm of the soil and generally demonstrated a gradual decline thereafter for each run. This situation can be attributed to the soil pH. The initial pH values of both SSTWW and RSTWW were generally lower than the soil pH. Therefore, when the both wastewater comes into contact with the soil, the pH was increased. In addition, pH changes through the columns also depended on chemical reactions and microbiological activities.

4.1.6 Salinity Changes

Salinity values of samples were measured during Run 1 and Run 2 studies after the samples were taken from the five sampling ports of each column as well as the stock solution. Table 4.5 depicts variations of salinity with soil depth in the columns operated with SSTWW and RSTWW. It is obviously seen in Table 4.5; influent salinity values of RSTWW were tremendously higher than influent SSTWW and also came from soil media. Salinity values were measured in the range of 0.01–0.20 PSU during Run 1 studies, whereas higher salinity values were measured from 0.73 to 1.72 PSU during Run 2 studies due to seawater intrusion to the sewerage system.

Changes of average salinity through the columns operated with SSTWW and RSTWW are depicted in Figure 4.5 and Figure 4.6, respectively. Findings indicated that salinity was increased through the columns operated with SSTWW due to dissolved materials originating from the soil media, whereas this situation was conversely observed in the columns operated with RSTWW. The high salinity in the RSTWW was associated with seawater intrusion to the sewerage system. This high salinity was removed through the soil media generally by filtration and adsorption on the soil surface.

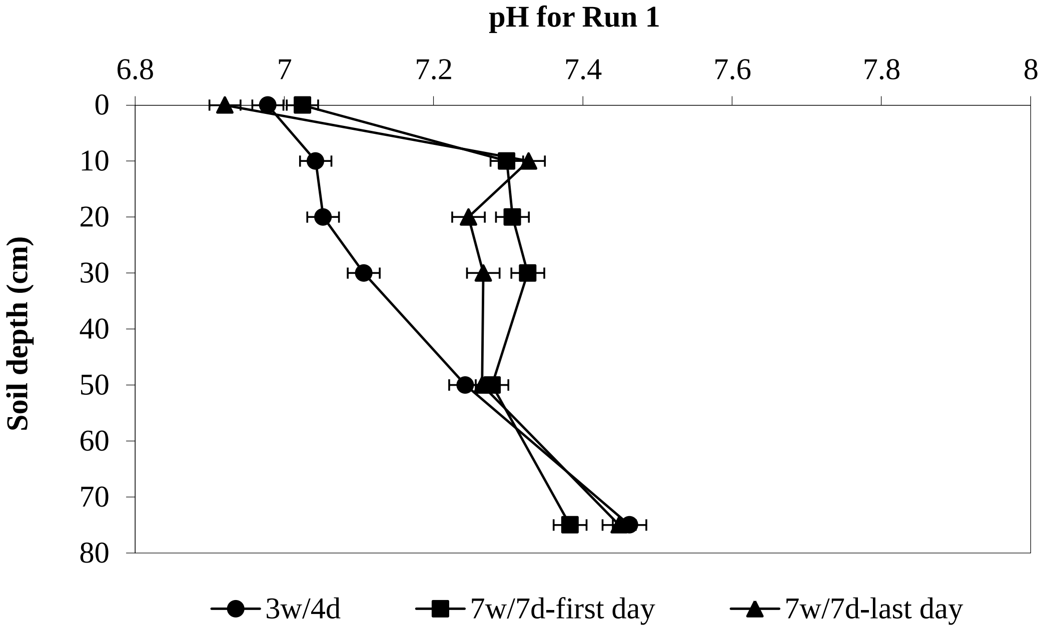

Figure 4.3 Changes of average pH through the columns operated with SSTWW

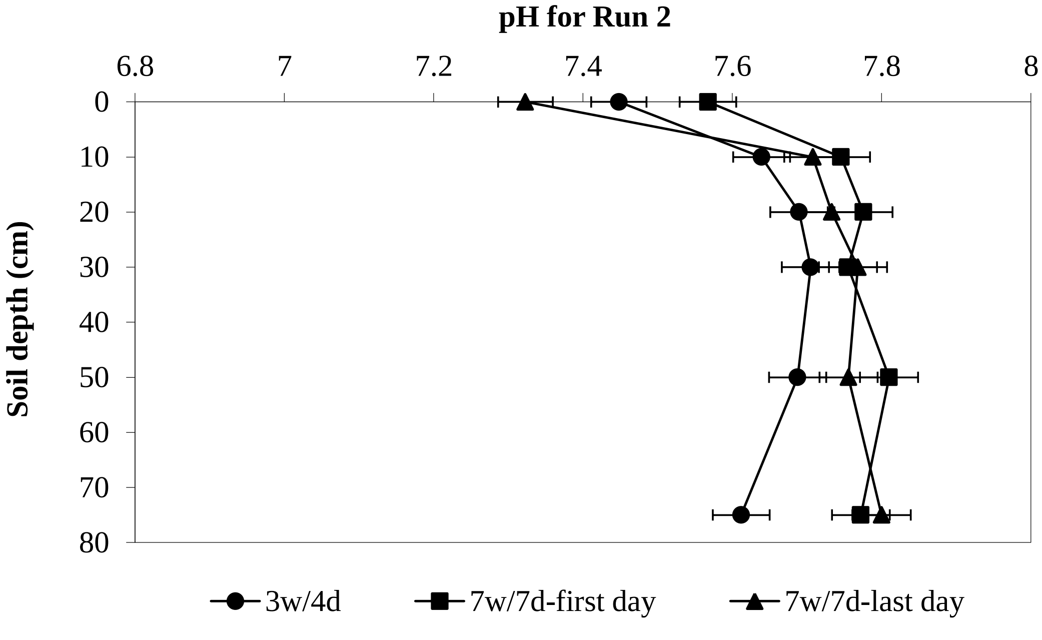

Figure 4.4 Changes of average pH through the columns operated with RSTWW

Table 4.5 Variations of salinity with soil depth in the columns operated with SSTWW and RSTWW

	Salinity values (PSU) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	0.01	0.03	0.04	0.06	0.08	0.12	0.01	0.03	0.04	0.05	0.08	0.15	0.02	0.02	0.04	0.05	0.08	0.13
Minimum	0.01	0.02	0.02	0.02	0.04	0.07	0.01	0.02	0.02	0.03	0.04	0.11	0.01	0.00	0.02	0.02	0.03	0.11
Maximum	0.03	0.07	0.09	0.13	0.16	0.19	0.02	0.08	0.10	0.12	0.15	0.20	0.03	0.05	0.10	0.11	0.18	0.19
Standard deviation	0.01	0.01	0.01	0.02	0.03	0.02	0.01	0.01	0.02	0.02	0.03	0.03	0.01	0.01	0.02	0.03	0.05	0.03
10% percentile	0.01	0.02	0.02	0.04	0.05	0.10	0.01	0.02	0.03	0.03	0.05	0.12	0.01	0.01	0.02	0.03	0.04	0.11
50% percentile	0.01	0.03	0.04	0.05	0.06	0.11	0.01	0.03	0.03	0.05	0.07	0.14	0.01	0.02	0.03	0.04	0.06	0.12
90% percentile	0.02	0.04	0.05	0.08	0.12	0.14	0.02	0.04	0.04	0.08	0.12	0.20	0.02	0.03	0.07	0.11	0.15	0.15
	Salinity values (PSU) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	1.38	1.28	1.24	1.19	1.14	1.00	1.36	1.25	1.22	1.19	1.14	0.99	1.38	1.25	1.22	1.19	1.13	1.11
Minimum	1.13	1.08	1.01	0.83	0.81	0.73	1.13	1.06	0.84	0.90	0.88	0.93	1.19	1.11	1.10	1.00	0.84	1.05
Maximum	1.72	1.43	1.46	1.38	1.41	1.27	1.72	1.40	1.46	1.38	1.41	1.06	1.69	1.34	1.37	1.40	1.35	1.20
Standard deviation	0.18	0.11	0.13	0.15	0.15	0.30	0.20	0.13	0.20	0.16	0.16	0.07	0.16	0.09	0.10	0.13	0.18	0.08
10% percentile	1.16	1.13	1.08	1.02	0.97	0.58	1.14	1.09	1.00	1.01	0.99	0.94	1.26	1.15	1.14	1.08	0.95	1.06
50% percentile	1.36	1.30	1.23	1.20	1.15	1.12	1.38	1.29	1.27	1.24	1.15	0.98	1.33	1.26	1.21	1.16	1.12	1.09
90% percentile	1.65	1.39	1.39	1.37	1.30	1.24	1.55	1.37	1.41	1.35	1.28	1.04	1.53	1.34	1.33	1.33	1.33	1.18

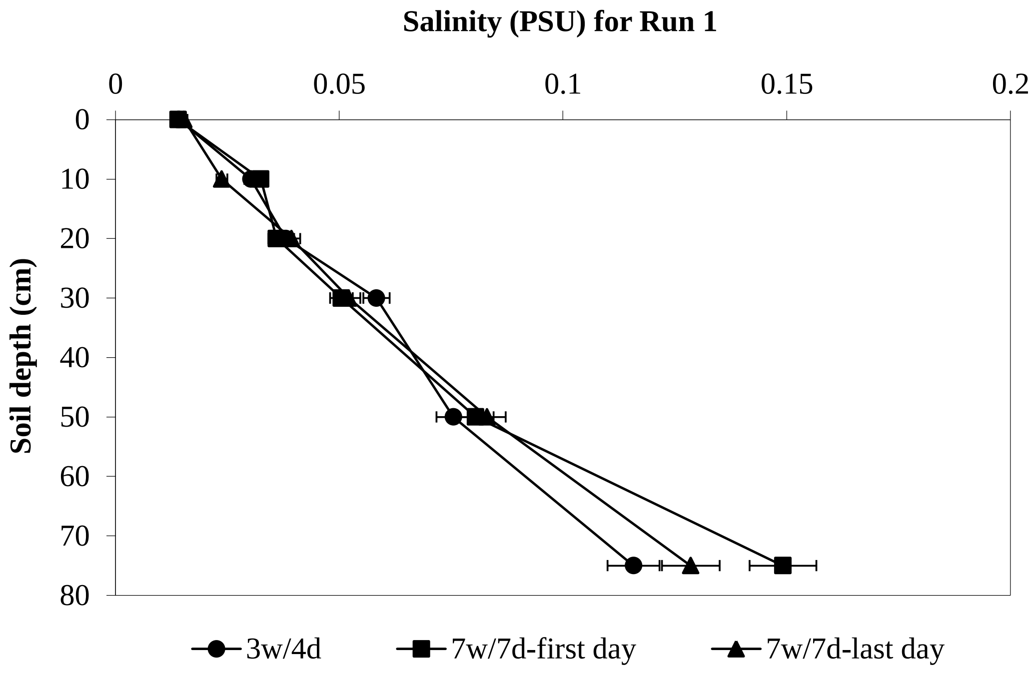

Figure 4.5 Changes of average salinity through the columns operated with SSTWW

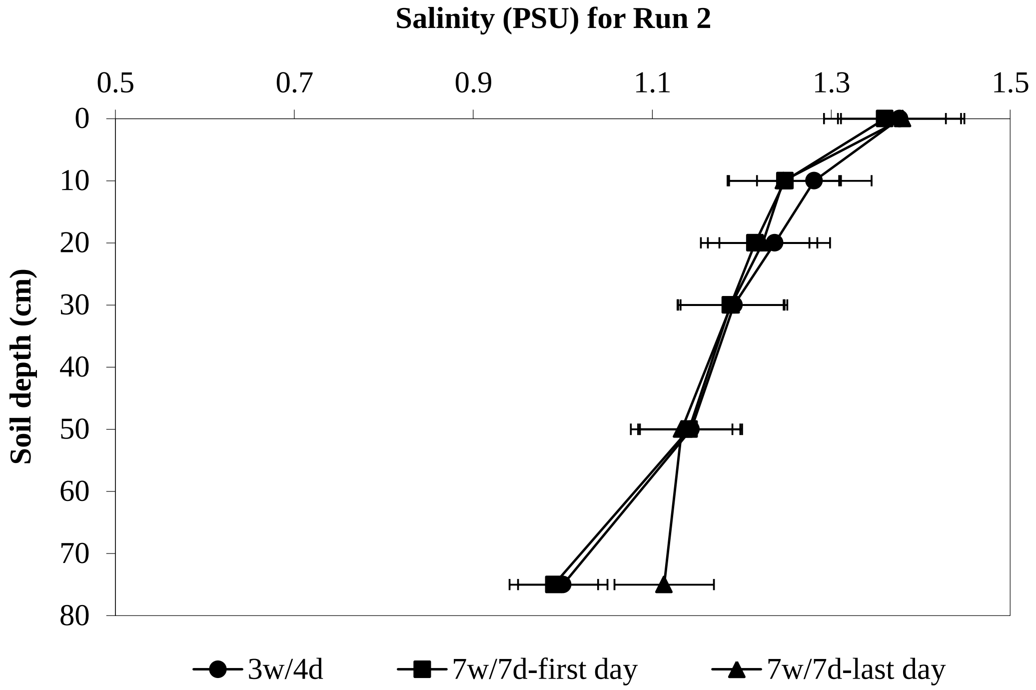

Figure 4.6 Changes of average salinity through the columns operated with RSTWW

Salinity changes in the last sampling ports were plotted as a function of operation weeks and are depicted in Figure 4.7 and Figure 4.8 in the columns operated with SSTWW and RSTWW, respectively. As seen in Figure 4.7, salinity values were measured to be even higher than initial salinity values during Run 1 studies. In addition, the salinity through the last sampling ports was decreased as the operation weeks passed since the dissolved ions came from the soil media declined in time. In contrast to Run 1 studies, higher salinity removal was achieved in the first operation weeks during Run 2 studies, because of high filtration and adsorption capacity of the soil matrix at the beginning of Run 2 studies.

4.1.7 Electrical Conductivity (EC) Changes

Table 4.6 depicts variations of EC with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution. As depicted in Table 4.6, influent EC values of RSTWW were notably higher than influent SSTWW and also came from soil media similar to salinity values. The high EC in the RSTWW was attributed to the seawater intrusion to the collector system as well as the sewerage system of the City of Izmir, which is morphologically located on the shore and sewer lines are mostly below groundwater table. The initial EC values were measured in the range of 14–58 μS/cm and 2195–3286 μS/cm for influent SSTWW and RSTWW, respectively. In addition, it was measured to range between 14–419 μS/cm and 874–3286 μS/cm during all Run 1 and Run 2 studies, respectively.

Changes of average EC through the columns operated with SSTWW and RSTWW are shown in Figure 4.9 and Figure 4.10, respectively. Results indicated that EC changes were shown to be similar to salinity changes. In essence, EC increased through the columns operated with SSTWW due to dissolved materials originating from the soil media, whereas it decreased through the columns operated with RSTWW due to adsorption and filtration of dissolved materials through the soil matrix in the RSTWW.

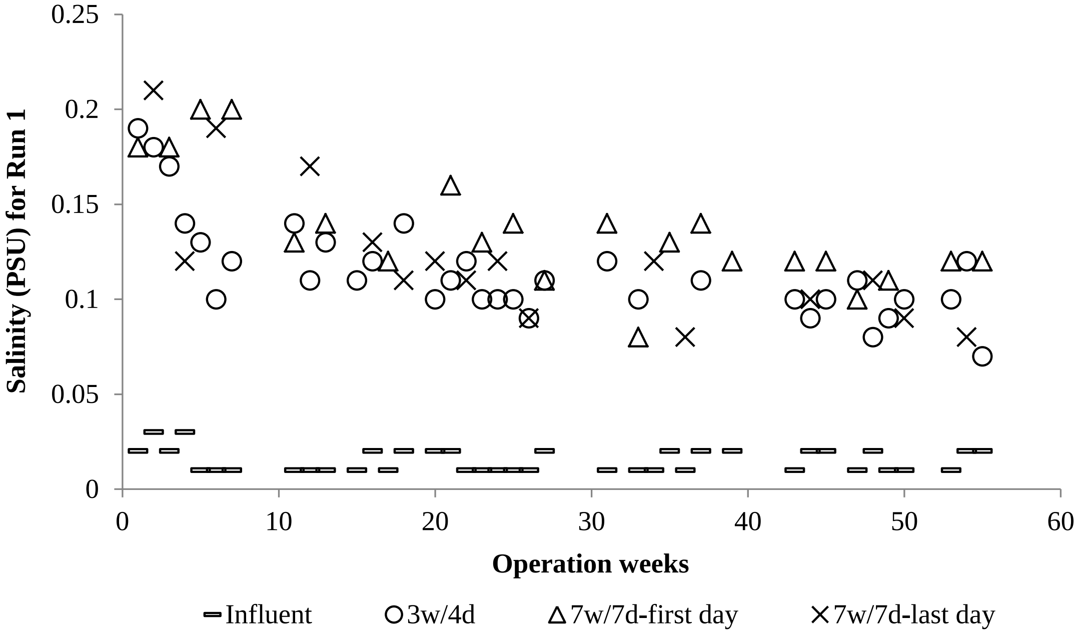

Figure 4.7 Changes of salinity in the last sampling ports with operation weeks in the columns operated with SSTWW

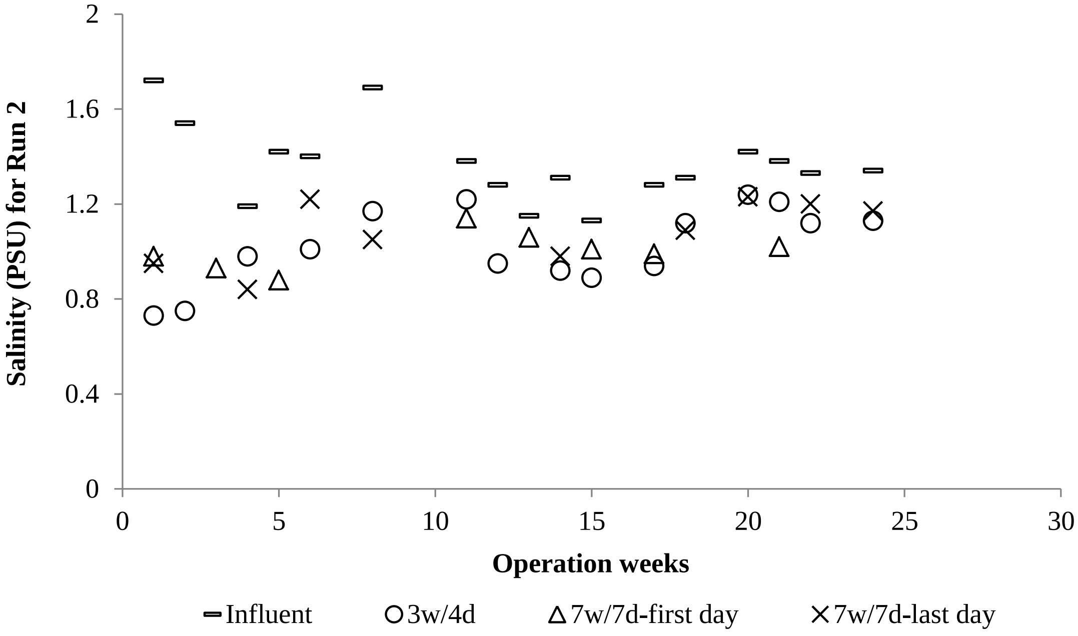

Figure 4.8 Changes of salinity in the last sampling ports with operation weeks in the columns operated with RSTWW

Table 4.6 Variations of EC with soil depth in the columns operated with SSTWW and RSTWW

	EC values (µS/cm) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	34.83	66.31	86.97	125.81	163.08	247.30	37.21	62.16	74.26	95.79	159.95	299.83	33.29	54.46	77.43	105.38	177.45	273.67
Minimum	14.00	38.00	40.00	49.00	84.00	146.00	20.00	37.00	42.00	58.00	98.00	234.00	14.00	38.00	44.00	54.00	78.00	234.00
Maximum	58.00	148.00	194.00	268.00	312.00	394.00	58.00	98.00	106.00	180.00	244.00	419.00	56.00	72.00	174.00	224.00	384.00	393.00
Standard deviation	12.12	22.16	28.78	43.21	62.31	55.06	10.88	18.11	15.32	25.95	45.57	50.45	14.18	10.68	34.95	57.98	105.90	60.55
10% percentile	20.50	47.00	57.00	85.50	103.00	204.00	23.60	41.60	58.40	69.40	104.00	250.00	17.20	40.80	50.60	64.00	96.00	234.00
50% percentile	34.00	60.00	84.50	119.00	137.00	236.00	34.00	62.00	73.00	94.00	150.00	292.00	33.00	56.00	67.00	82.00	118.00	252.50
90% percentile	51.00	94.50	115.00	176.00	249.00	307.20	50.40	88.40	90.80	114.60	228.00	336.80	52.90	64.00	119.00	210.40	314.00	334.50
	EC values (µS/cm) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	2631.20	2481.09	2392.82	2317.44	2229.94	1972.78	2615.75	2436.29	2409.00	2265.00	2212.00	1941.80	2648.86	2349.20	2382.67	2308.83	2193.71	2242.75
Minimum	2195.00	2107.00	1978.00	1636.00	1592.00	874.00	2195.00	2068.00	2084.00	1776.00	1733.00	1660.00	2321.00	1981.00	2154.00	1956.00	1655.00	1988.00
Maximum	3286.00	2753.00	2870.00	2660.00	2706.00	2424.00	3286.00	2706.00	2680.00	2570.00	2594.00	2222.00	3204.00	2582.00	2648.00	2672.00	2600.00	2558.00
Standard deviation	306.43	195.94	241.37	278.43	271.09	531.69	351.61	229.36	216.90	259.72	241.58	215.22	272.36	234.31	172.21	238.94	335.44	265.09
10% percentile	2252.00	2210.00	2100.60	2008.50	1932.50	1209.20	2202.70	2143.00	2126.60	1971.30	1993.80	1730.00	2450.00	2107.40	2222.00	2092.00	1861.40	2010.50
50% percentile	2618.00	2507.00	2374.00	2317.50	2256.00	2208.00	2632.50	2522.00	2504.00	2344.50	2278.00	1925.00	2596.00	2374.00	2359.00	2273.50	2104.00	2212.50
90% percentile	3043.20	2658.00	2666.80	2645.00	2493.50	2390.40	2947.20	2634.00	2597.80	2493.00	2430.80	2160.00	2901.60	2554.00	2567.00	2561.00	2571.20	2499.20

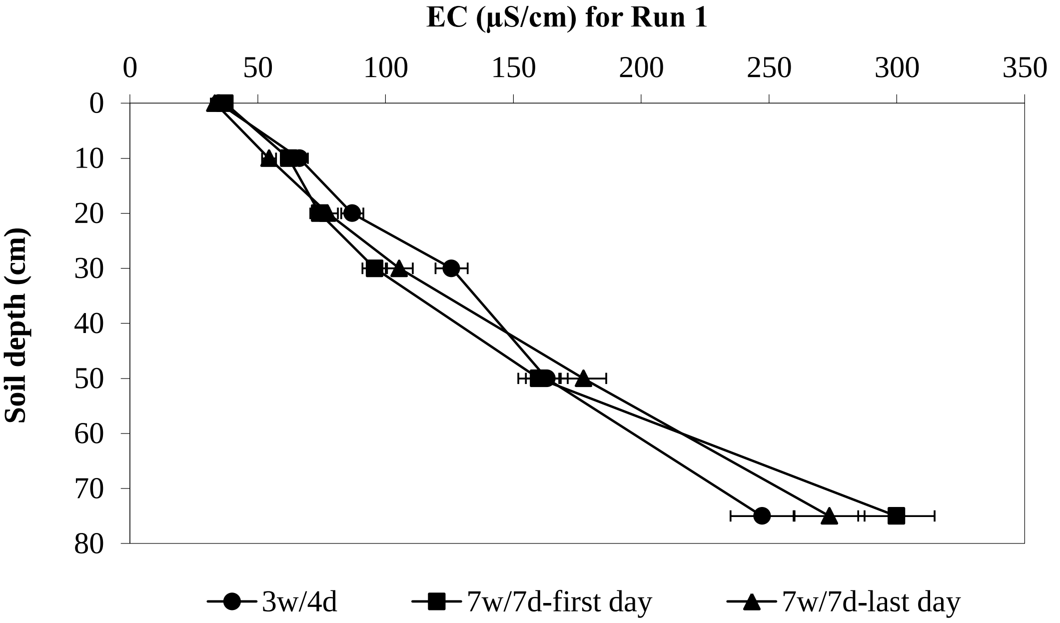

Figure 4.9 Changes of average EC through the columns operated with SSTWW

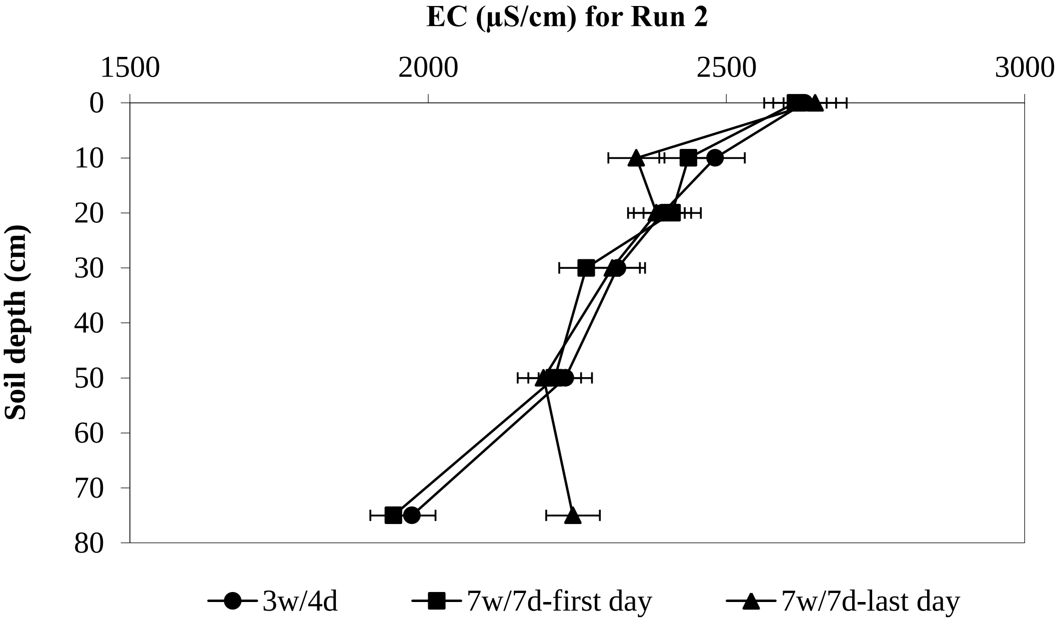

Figure 4.10 Changes of average EC through the columns operated with RSTWW

Starting from about average 37.2 µS/cm, EC was increased to an average value of 299.8 µS/cm through the columns operated with SSTWW, whereas average EC demonstrated a decline from an average value of 2648.9 to an average value of 1941.8 µS/cm through the columns operated with RSTWW.

Changes of EC in the last sampling port as a function of operation weeks are depicted in Figure 4.11 and Figure 4.12 in the columns operated with SSTWW and RSTWW, respectively. A similar pattern to the salinity changes was observed in EC changes with operation weeks. While the EC values were more increased through the last sampling port in the first weeks of operation, it reached a more stable pattern in later weeks of operation because the dissolved materials originating from the soil media declined in time.

4.1.8 Total Dissolved Solids (TDS) Changes

Table 4.7 reports variations of TDS with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution. The initial TDS values were measured in the range of 7.00–30.00 mg/L and 1098.00–1644.00 mg/L for influent SSTWW and RSTWW, respectively. Additionally, the range of 7.00–209.00 mg/L and 437.00–1644.00 mg/L were reported in Table 4.7 for TDS values during all Run 1 and Run 2 studies, respectively.

Starting from about average 18.3 mg/L, TDS was increased to about average 153.9 mg/L through the columns operated with SSTWW, whereas average TDS demonstrated a decline from about average 1334.0 to 971.2 mg/L through the columns operated with RSTWW. A small amount of removal was achieved for TDS during Run 2 studies.

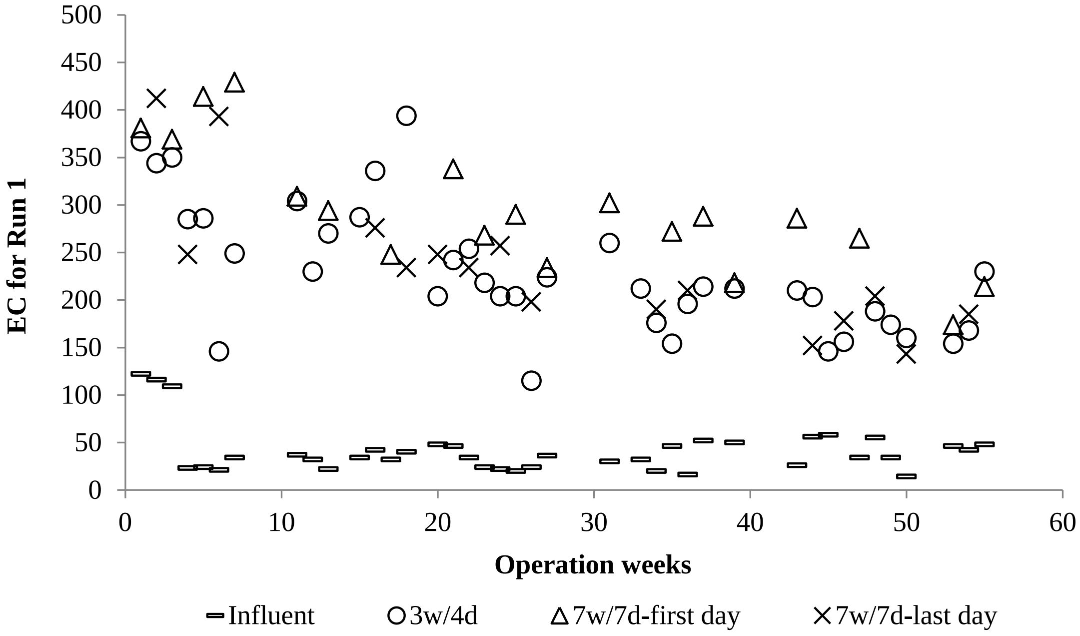

Figure 4.11 Changes of EC in the last sampling ports with operation weeks in the columns operated with SSTWW

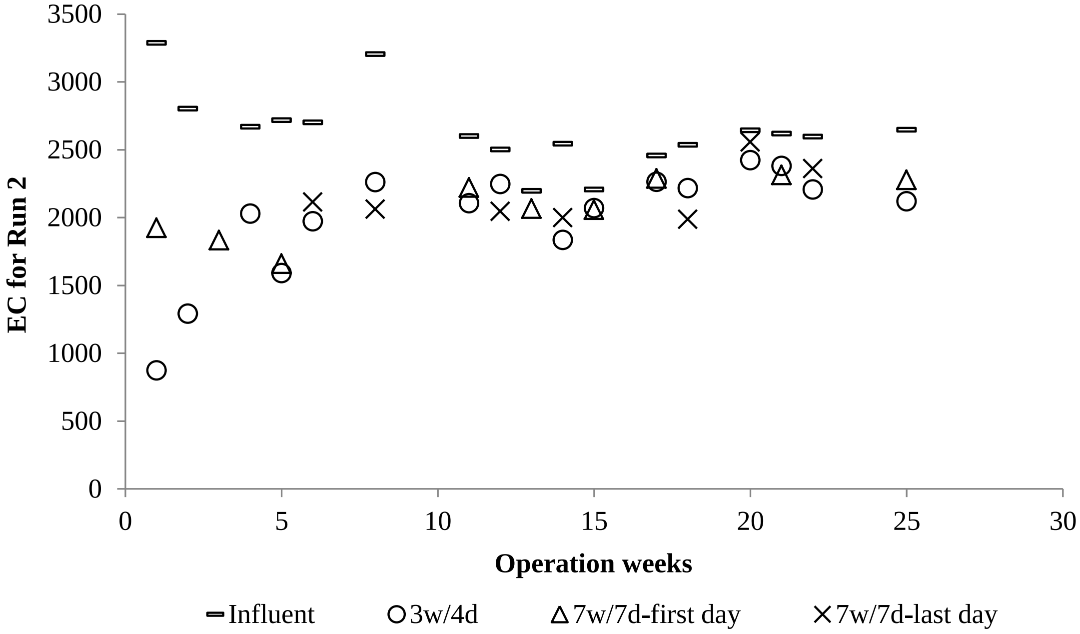

Figure 4.12 Changes of EC in the last sampling ports with operation weeks in the columns operated with RSTWW.

Because there is a relationship between salinity, electrical conductivity and total dissolved solids, TDS followed a pattern that was essentially similar to EC and salinity changes. Changes of average TDS through the columns operated with SSTWW and RSTWW are depicted in Figure 4.13 and Figure 4.14, respectively. TDS was increased through the columns operated with SSTWW because of dissolved materials originating from the soil media, whereas it was decreased through the columns operated with RSTWW owing to adsorption and filtration through the soil matrix of dissolved materials in the RSTWW.

TDS was increased through the columns operated with SSTWW due to dissolved materials originating from the soil media, whereas it was decreased through the columns operated with RSTWW. When the initial TDS values were compared for each SSTWW and RSTWW, it was clearly observed that the TDS values of SSTWW were negligible compared to TDS values real of wastewater which were mainly associated with seawater intrusion to the sewerage system.

Changes of TDS in the last sampling ports with operation weeks are depicted in Figure 4.15 and Figure 4.16 in the columns operated with SSTWW and RSTWW, respectively. A similar pattern to the salinity and EC changes was observed in the TDS changes as a function of operation weeks. Although the decrease in TDS values continued during all Run 2 studies, effluent TDS in the last sampling ports was close to the initial TDS values in recent weeks of operation (Figure 4.16). These results about TDS changes through the columns operated with RSTWW contradicted with the limited amount of literature information that is available on TDS changes during SAT systems. It was reported in different two studies that, although the influent TDS was in the range of 1000-1200 mg/L, TDS increased during the percolation through the soil matrix in a field scale SAT system through the native groundwater as an opposite findings in this study (Akber et al., 2008; Viswanathan et al., 1999). On the other hand, if the Run 2 studies continued for a longer time, TDS might have increased through the columns with starting of desorption in this study, too.

Table 4.7 Variations of TDS with soil depth in the columns operated with SSTWW and RSTWW

	TDS values (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	17.97	33.06	43.56	62.78	81.56	124.15	18.30	34.30	40.70	52.05	83.25	153.92	17.60	33.33	44.53	62.14	81.00	135.14
Minimum	7.00	19.00	24.00	20.00	42.00	73.00	10.00	19.00	21.00	29.00	49.00	117.00	7.00	19.00	22.00	27.00	39.00	117.00
Maximum	30.00	74.00	97.00	134.00	156.00	197.00	29.00	95.00	109.00	131.00	147.00	209.00	30.00	87.00	112.00	192.00	157.00	197.00
Standard deviation	6.39	11.19	14.24	21.87	31.18	27.29	5.44	16.77	17.71	22.50	26.72	27.95	7.85	17.66	27.23	45.96	41.29	28.22
10% percentile	10.00	23.00	28.50	42.50	51.50	102.00	11.90	20.90	29.60	34.80	52.00	126.00	8.80	20.80	25.40	32.50	48.00	117.00
50% percentile	17.00	30.00	42.00	59.50	68.50	119.00	17.00	31.00	36.50	47.00	75.50	147.00	17.00	30.00	34.00	41.50	59.00	124.00
90% percentile	27.00	47.00	57.50	88.00	124.50	153.60	25.10	45.40	47.60	62.10	120.20	199.40	28.00	49.80	86.20	109.90	133.00	161.60
	TDS values (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	1315.14	1241.40	1194.13	1158.53	1114.07	977.38	1306.43	1214.67	1194.33	1124.43	1099.63	971.20	1334.00	1192.80	1176.67	1154.50	1096.86	1121.50
Minimum	1098.00	1053.00	989.00	818.00	799.00	437.00	1098.00	1078.00	1042.00	888.00	867.00	830.00	1161.00	1078.00	990.00	978.00	827.00	994.00
Maximum	1644.00	1377.00	1435.00	1330.00	1353.00	1213.00	1644.00	1354.00	1340.00	1286.00	1297.00	1111.00	1601.00	1294.00	1324.00	1336.00	1300.00	1279.00
Standard deviation	158.93	100.55	125.40	144.16	139.80	282.68	190.31	109.83	118.11	140.30	129.39	107.61	128.58	85.68	112.55	119.47	167.92	132.43
10% percentile	1120.40	1117.80	1040.50	998.00	956.40	584.00	1101.00	1087.50	1055.00	972.00	981.10	865.20	1235.90	1106.40	1067.00	1046.00	930.20	1005.40
50% percentile	1303.50	1258.50	1185.50	1156.00	1124.00	1106.50	1309.00	1233.00	1222.00	1169.00	1109.00	963.00	1310.00	1187.00	1179.50	1137.00	1052.00	1106.50
90% percentile	1541.00	1333.80	1335.00	1323.80	1251.40	1197.60	1500.60	1323.50	1306.00	1252.40	1224.90	1080.20	1461.00	1278.80	1283.50	1280.50	1285.60	1249.60

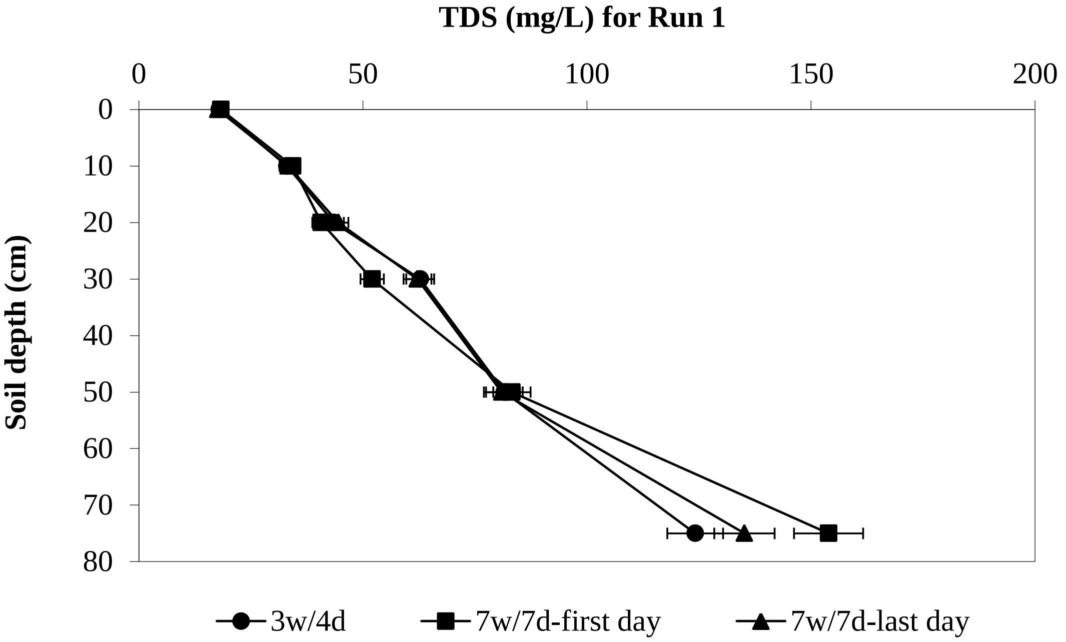

Figure 4.13 Changes of average TDS through the columns operated with SSTWW

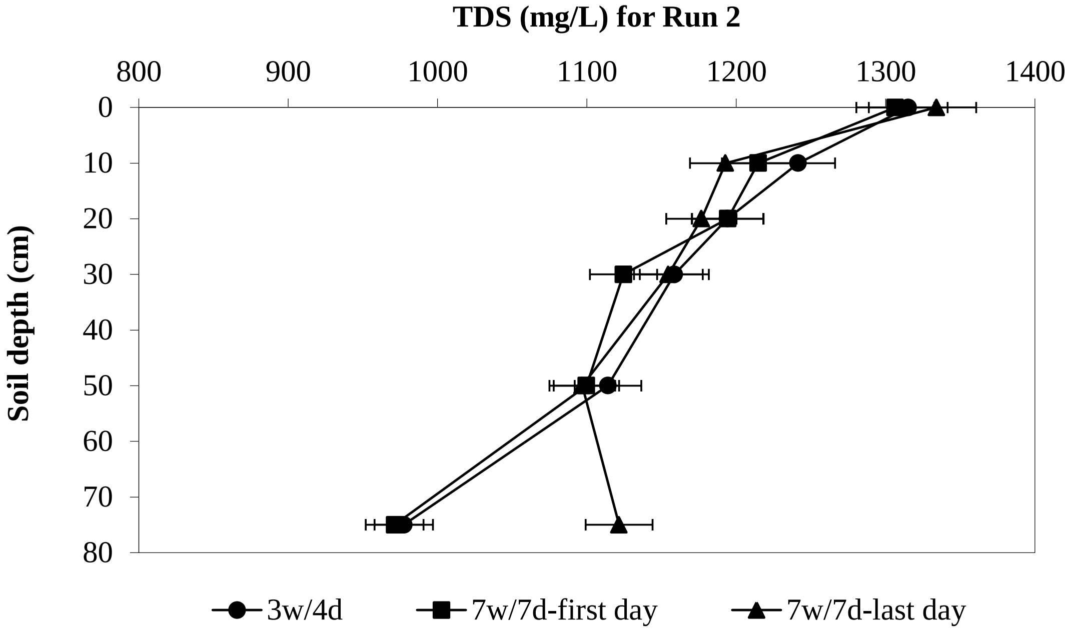

Figure 4.14 Changes of average TDS through the columns operated with RSTWW

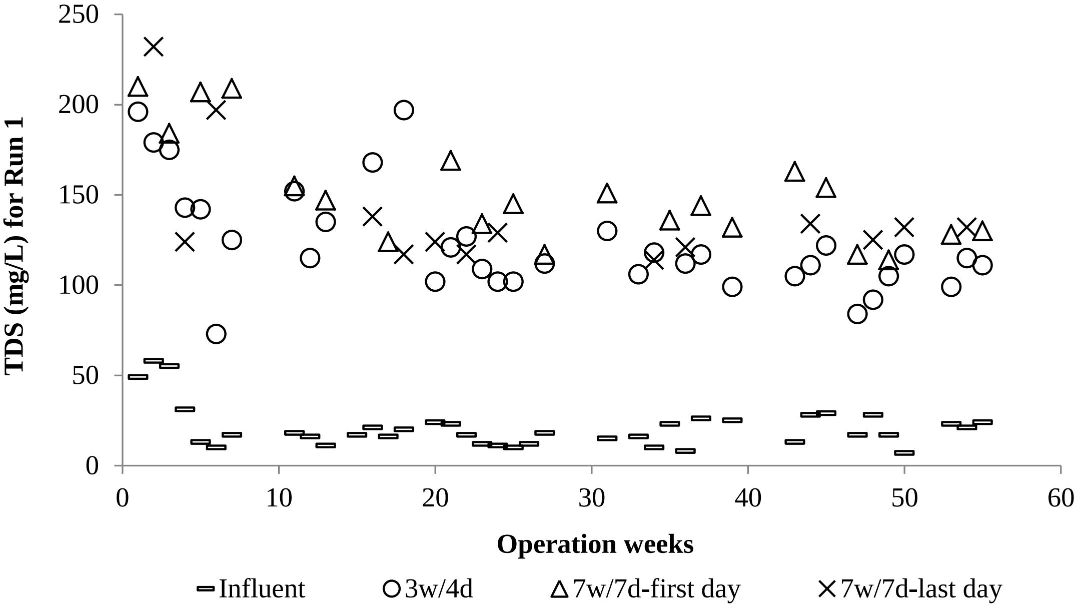

Figure 4.15 Changes of TDS in the last sampling ports with operation weeks in the columns operated with SSTWW

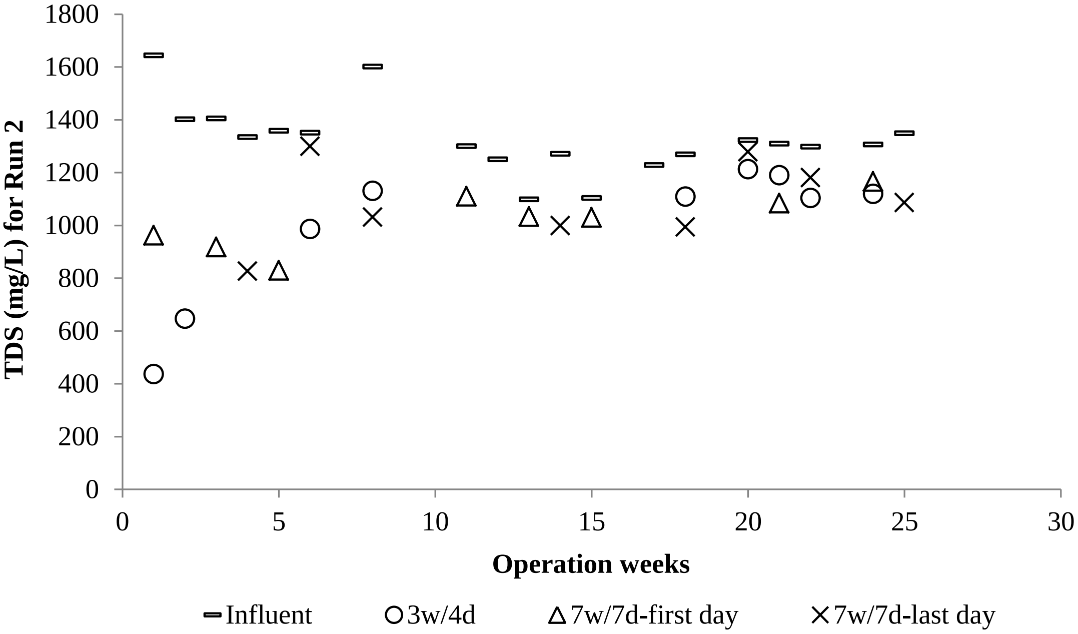

Figure 4.16 Changes of TDS in the last sampling ports with operation weeks in the columns operated with RSTWW

Since the downward soil matrix was not dried enough during the drying periods, the soil was more saturated compared to upper soil matrix. As a result of this, TDS values in the last sampling port (75 cm) of the 7w/7d-last day increased from previous sampling port (50 cm). This increase during wetting period may be an evidence for desorption of adsorbed materials to the soil media.

4.1.9 Oxidation Reduction Potential (ORP) Changes

Variations of ORP with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution are given in Table 4.8. As depicted in Table 4.8, ORP values were measured to range between 28.80–313.40 mV and 176.30–299.40 mV during Run 1 and Run 2 studies, respectively. The studies with SSTWW were conducted during the entire year, whereas studies with RSTWW were performed only during winter months of the year. Owing to the fact that microbial activities are slower in winter period, DO was consumed more slowly. Additionally, RSTWW contained more varied and specific materials. Hence, this situation may be responsible for high ORP values during Run 2 studies and the wide range ORP values obtained at Run 1 studies.

Changes of average ORP through the columns operated with SSTWW and RSTWW are given in Figure 4.17 and Figure 4.18, respectively. While average ORP dropped to about 100 mV in the columns operated with SSTWW, the minimum ORP level reached in columns operated with RSTWW was about 190 mV. These results are consistent with DO concentrations for SSTWW and RSTWW (Figure 4.19 and Figure 4.20).

ORP tends to decrease with soil depth in all columns operated with SSTWW and RSTWW. Starting from about 240 mV, average ORP was demonstrated to decrease slightly within the first 50 cm of the soil column and then had a rapid decrease towards the last sampling port in the columns operated with SSTWW. In particular, ORP values were rapidly decreased in the samples taken from the last sampling port for the 7w/7d-first day (99.6 mV) and 3w/4d (135.1 mV).

Table 4.8 Variations of ORP with soil depth in the columns operated with SSTWW and RSTWW

	ORP values (mV) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						7w/7d-first day						7w/7d-last day					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	241.30	229.11	225.00	216.21	211.39	138.05	237.21	198.45	199.84	200.91	201.59	99.66	241.10	224.00	222.17	223.45	218.00	196.74
Minimum	127.40	126.90	134.30	133.30	76.10	28.80	127.40	127.30	97.90	84.30	50.70	31.70	136.30	165.60	165.20	167.90	167.30	113.20
Maximum	313.60	296.80	287.10	275.90	256.50	262.20	312.70	308.10	296.10	268.30	280.30	250.60	306.20	287.90	284.30	266.20	262.10	257.90
Standard deviation	54.24	51.26	48.45	45.76	45.02	90.11	53.09	50.01	47.44	45.36	50.76	91.47	56.02	38.82	36.87	35.59	28.84	55.27
10% percentile	151.60	155.30	149.60	147.00	145.22	34.16	163.16	147.28	150.92	152.60	159.04	32.33	158.20	171.18	169.70	170.07	178.80	139.04
50% percentile	247.50	236.10	235.20	232.00	228.55	153.70	237.90	187.60	205.80	211.10	212.50	54.70	247.50	230.55	219.60	232.35	220.90	205.40
90% percentile	306.20	283.20	273.50	262.00	252.89	243.08	300.96	262.22	251.24	247.46	243.12	245.92	296.50	261.71	255.76	257.75	245.20	246.50
	ORP values (mV) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	236.43	225.45	218.49	213.82	210.49	187.59	242.33	222.66	218.19	213.11	210.85	206.64	244.15	217.82	211.67	208.33	201.41	199.20
Minimum	201.90	198.00	194.60	186.70	187.40	108.40	201.90	195.30	194.90	195.30	195.60	185.60	216.60	183.80	180.20	177.90	176.30	198.40
Maximum	271.70	249.30	251.00	244.20	241.00	221.60	299.40	250.40	239.70	238.60	238.40	236.50	291.70	233.50	228.00	223.60	222.90	200.10
Standard deviation	18.90	15.40	16.00	16.43	16.06	28.50	29.12	16.59	13.86	13.75	13.94	14.86	22.86	17.94	15.45	15.21	16.36	0.83
10% percentile	214.04	207.66	198.84	197.34	188.20	160.92	211.90	206.70	203.90	199.43	198.47	195.05	225.63	200.75	195.68	192.00	177.28	198.46
50% percentile	234.40	228.50	218.55	209.20	208.60	198.60	239.10	223.40	218.60	211.65	207.05	203.75	237.40	220.05	214.70	212.30	207.70	199.15
90% percentile	259.03	243.98	236.95	237.10	231.92	201.88	273.32	237.98	231.78	227.96	225.87	221.52	266.50	232.65	224.10	221.08	213.80	199.98

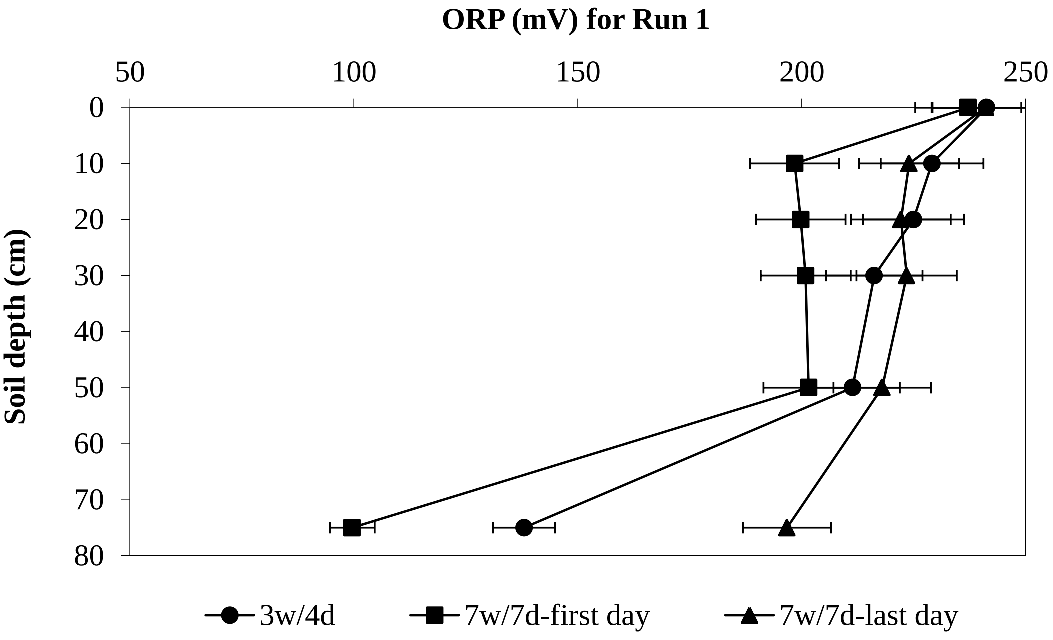

Figure 4.17 Changes of average ORP through the columns operated with SSTWW

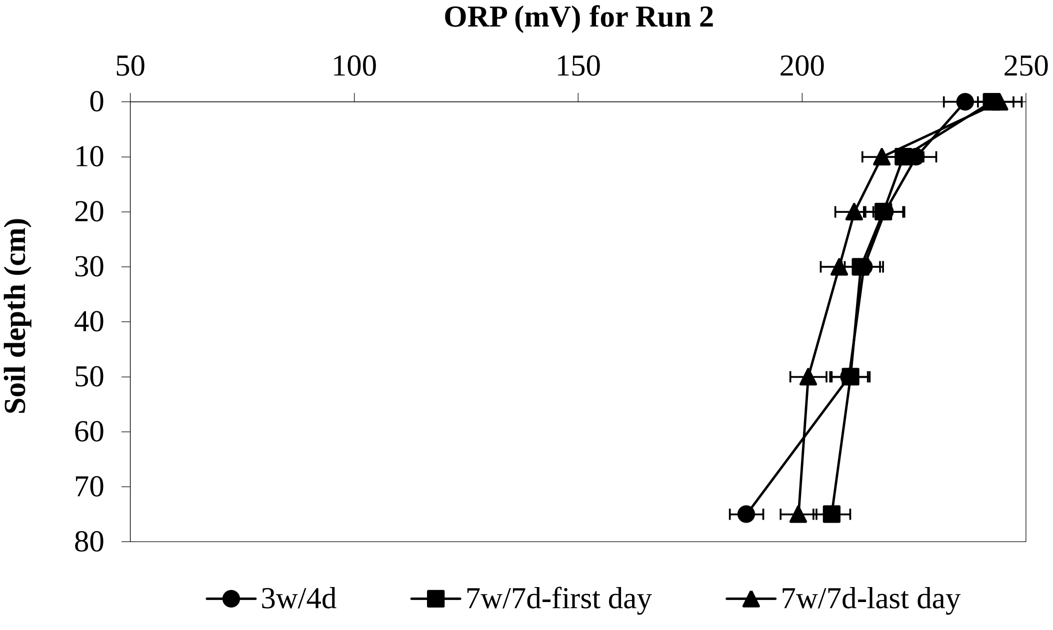

Figure 4.18 Changes of average ORP through the columns operated with RSTWW

While negative ORP values were never measured during the laboratory-scale SAT system studies conducted in this thesis (also saturated conditions during wetting days), the minimum ORP value was measured to be as 28.8 mV at the 3w/4d. These results indicated that while the oxidation conditions dominated during the operation of this laboratory-scale SAT system, reduction conditions did not occur. These findings are well supported by the results reported by Sharma et al. (2008). Sharma et al. (2008) reported that, oxic conditions dominated in the top 1.5 m of soil surface for secondary and tertiary effluents during a field-scale SAT system. Additionally, when initial ORP values were compared between SSTWW and RSTWW, no major differences were observed. Nevertheless, maximum initial ORP value was obtained in SSTWW (313.6 mV).

4.1.10 Dissolved Oxygen (DO) Changes

Variations of DO concentrations with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution are given in Table 4.9. DO concentrations were measured in the range of 2.01–8.36 mg/L and 5.21–8.26 mg/L during Run 1 and Run 2 studies, respectively.

Average DO concentration started from about 7.6 and 7.0 mg/L in the columns operated with SSTWW and RSTWW, respectively. Changes of average DO concentrations through the soil depth demonstrated differences between columns operated with SSTWW and RSTWW. While DO concentrations in SSTWW columns rapidly declined within the first 10 cm of the soil and demonstrated a little change along the columns, it was a smoother decline and a variable distribution along the columns operated with RSTWW. Changes of average DO concentrations through the columns operated with SSTWW and RSTWW are given in Figure 4.19 and Figure 4.20, respectively.

DO was consumed for biodegradation of organic matter by aerobic microorganisms in the top layers of the soil surface due to exist of higher organic matter. The SSTWW contained simpler organic compounds (D-glucose was used in this study). Thus, easily biodegradable organic carbon was removed more rapidly in the first 10 cm of the columns due to enhanced microbial activity. Since most of the organic compounds were biodegraded, there was not enough food left for microorganisms below 10 cm soil depth. Consequently, sufficient microbial growth cannot be achieved after 10 cm soil depth, and thus DO cannot be used by microorganisms, which are seen from the constant DO concentration throughout the columns below 10 cm of depth. Since RSTWW contained more complex organic compounds, some of which are not be biodegraded as easy as their simple counterparts, the biodegradation and DO consumption continued throughout the columns operated with RSTWW.

Run 1 studies continued for about one year and first 20 weeks were in hot periods of the year; between May and September. Changes of DO concentration in the last sampling ports with operation weeks are depicted in Figure 4.21 and Figure 4.22 in the columns operated with SSTWW and RSTWW, respectively. Since microbial activities increase with temperature, more DO is consumed during summer period. Additionally, it is known that DO concentration in water decreases with increasing temperature and salinity (Metcalf & Eddy, 1991). Hence, lower DO concentrations were observed in summer months during Run 1 studies. On the other hand, high salinity of the RSTWW (Table 4.5) may also be responsible from the lower initial DO concentrations observed during Run 2 studies, despite the fact that Run 2 studies were mostly conducted during winter periods.

4.1.11 Total Organic Carbon (TOC) Changes

Variations of TOC concentration with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution are presented in Table 4.10. TOC concentrations were measured in the range of 5.55–45.93 mg/L and 18.48–58.21 mg/L during Run 1 and Run 2 studies, respectively.

Table 4.9 Variations of DO concentration with soil depth in the columns operated with SSTWW and RSTWW

	DO concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	7.37	4.42	4.31	4.29	4.26	4.47	7.57	4.21	4.19	4.33	4.26	4.29	7.14	4.66	4.42	4.29	4.26	4.25
Minimum	5.49	2.58	2.27	2.12	2.51	2.45	5.99	2.67	2.15	2.75	2.26	2.22	5.49	3.28	2.81	2.01	2.11	2.42
Maximum	8.36	6.61	6.85	6.86	6.36	7.12	8.36	6.62	6.51	6.42	6.40	5.90	8.31	6.71	6.78	6.32	6.04	5.99
Standard deviation	0.84	1.04	1.10	1.11	0.95	1.43	0.72	1.17	1.34	1.19	1.30	1.16	0.96	1.14	1.22	1.23	1.12	1.02
10% percentile	6.12	2.96	3.00	3.15	2.83	2.81	6.66	2.77	2.37	2.89	2.90	2.88	5.79	3.35	2.98	2.76	3.16	3.28
50% percentile	7.44	4.62	4.30	4.17	4.27	4.50	7.92	4.52	4.41	4.25	4.20	4.34	7.22	4.25	4.43	4.27	4.18	4.06
90% percentile	8.20	5.50	5.64	5.83	5.06	6.35	8.23	5.42	5.65	5.75	5.85	5.73	8.17	6.06	5.91	5.55	5.83	5.54
	DO concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	6.85	6.42	6.41	6.30	5.76	5.74	7.00	6.50	6.54	6.45	6.43	6.25	6.66	6.45	6.49	6.61	6.56	5.85
Minimum	5.97	5.86	5.79	5.63	5.21	5.50	6.05	5.99	5.95	5.90	5.84	5.82	5.97	5.89	5.88	5.80	5.56	5.53
Maximum	7.96	7.80	7.86	7.98	7.26	6.96	7.96	7.41	7.68	7.75	7.80	7.76	7.78	7.70	8.00	8.07	8.26	6.96
Standard deviation	0.67	0.65	0.71	0.76	0.60	0.45	0.72	0.63	0.72	0.69	0.71	0.71	0.61	0.75	0.93	0.99	1.13	0.66
10% percentile	6.16	6.17	5.84	5.79	5.52	5.70	6.23	6.14	6.10	6.10	6.06	6.05	6.15	6.05	6.06	6.00	5.64	5.56
50% percentile	6.57	6.59	6.98	6.51	6.00	5.88	7.22	7.29	7.14	7.20	7.16	6.71	6.45	6.31	6.84	6.87	7.48	5.76
90% percentile	7.74	7.59	7.55	7.53	7.01	6.57	7.76	7.38	7.65	7.56	7.56	7.57	7.39	7.52	7.94	8.00	8.04	6.63

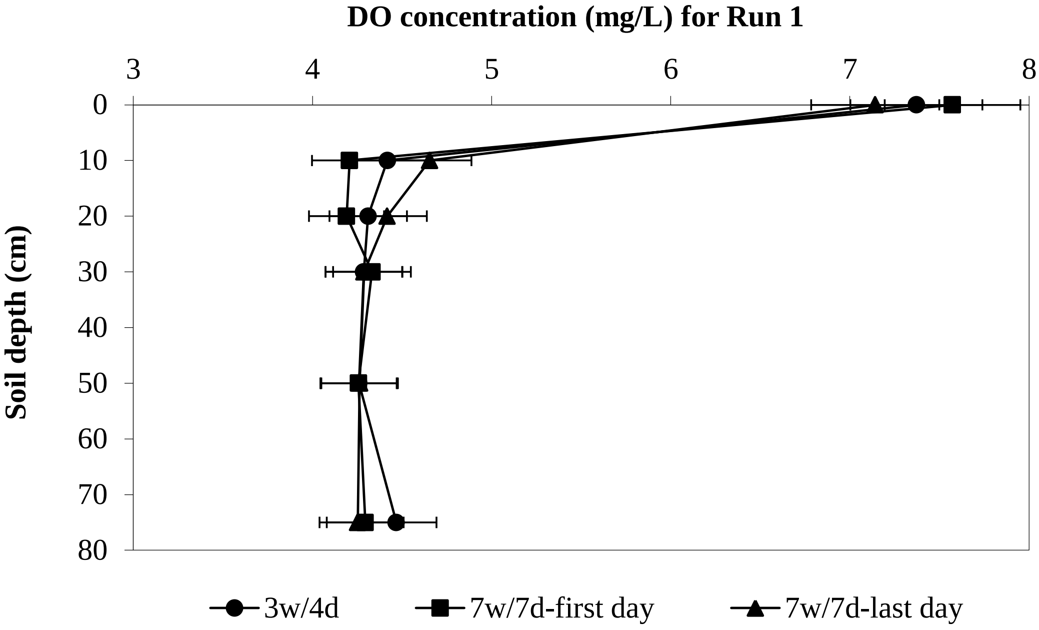

Figure 4.19 Changes of average DO concentration through the columns operated with SSTWW

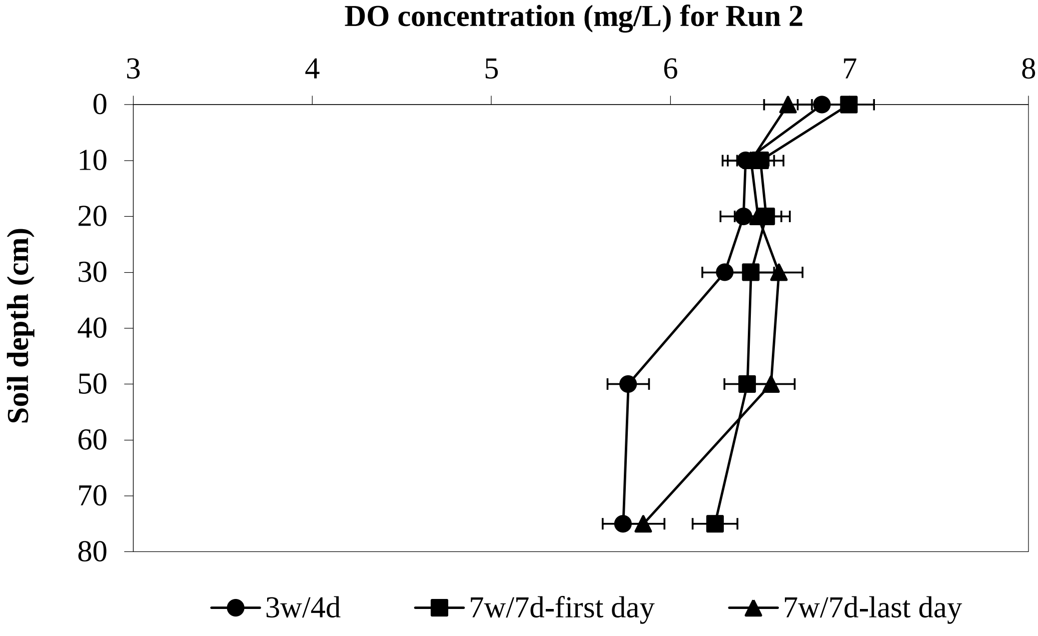

Figure 4.20 Changes of average DO concentration through the columns operated with RSTWW

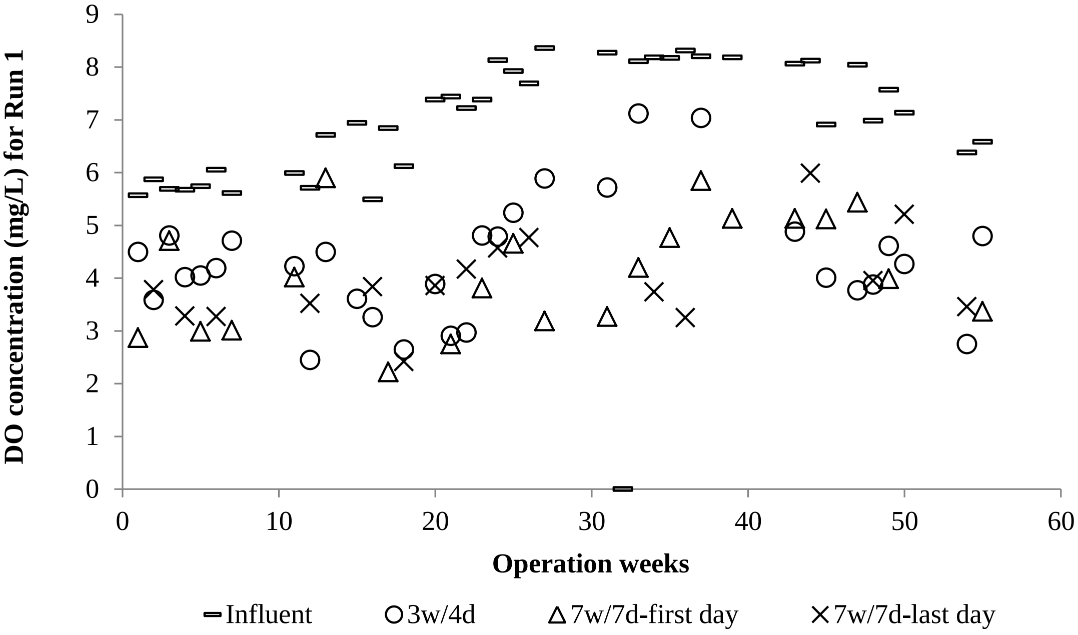

Figure 4.21 Changes of DO concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

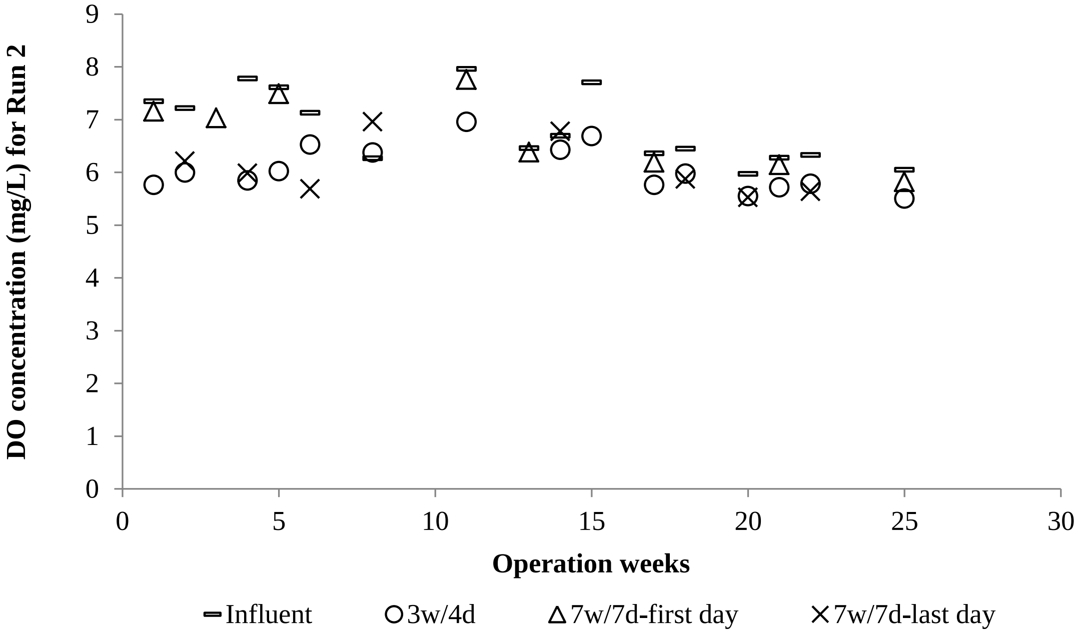

Figure 4.22 Changes of DO concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

Average TOC concentration changes through the columns operated with SSTWW and RSTWW are given in Figure 4.23 and Figure 4.24, respectively and average TOC removal efficiencies through the columns operated with SSTWW and RSTWW are given in Figure 4.25 and Figure 4.26, respectively. While starting from about 39.7 mg/L TOC concentration decreased to about 12.7 mg/L through the columns operated with SSTWW, decreasing of TOC concentration through the columns operated with RSTWW was observed from about 44.0 to 21.0 mg/L.

Table 4.11 depicts variations of TOC removal efficiencies with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column. According to Table 4.11, average TOC removal values in the last sampling ports were observed to be in the range of 42.39–85.91% and 39.47–61.66% during Run 1 and Run 2 studies, respectively. The results revealed that average TOC removal efficiencies increased along the columns operated with both SSTWW and RSTWW (Figure 4.25 and Figure 4.26). Even though the changes of average TOC removal through the soil depth demonstrated similar pattern in both the columns operated with SSTWW and RSTWW, higher removal efficiencies were generally achieved during Run 1 studies.

In the columns operated with SSTWW, TOC removal rapidly increased within the first 10 cm of the soil and then had a gradual increase thereafter. An average 55.4% removal was achieved during Run 1 studies within the top 10 cm where exposure to atmospheric oxygen was more likely. The total average removal reached to 68.2% in the entire column during Run 1 studies. In the columns operated with RSTWW, TOC removal also increased along the soil profile where about 33.7% removal was achieved in the top 10 cm and 51.1% removal was reached in the entire column during Run 2 studies.

The findings reported by Fox et al. (2005), Laws et al. (2011) and Quanrud et al. (2003b) support the results of total TOC removals in this study. On the other hand, the majority of the studies in the literature assessed organic carbon removal through

Table 4.10 Variations of TOC concentration with soil depth in the columns operated with SSTWW and RSTWW

	TOC concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						7w/7d-first day						7w/7d-last day					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Initial**	**10**	**20**	**30**	**50**	**75**	**Initial**	**10**	**20**	**30**	**50**	**75**
Average	39.50	24.08	19.22	17.06	14.78	12.69	39.70	22.26	19.01	17.38	15.57	13.86	39.25	17.75	16.39	15.98	14.14	14.26
Minimum	33.87	15.09	9.34	8.80	7.61	6.04	34.70	8.81	7.56	6.86	6.34	5.94	33.87	7.24	6.45	6.09	5.83	5.55
Maximum	45.93	39.91	31.46	33.15	29.65	20.91	44.33	34.08	31.00	29.48	27.20	26.40	45.93	35.13	33.15	29.14	25.05	26.10
Standard deviation	2.78	5.64	4.83	5.00	4.37	4.54	2.67	7.26	7.54	6.26	5.92	7.11	2.86	7.86	7.59	6.88	6.08	6.75
10% percentile	36.34	17.21	14.46	10.66	9.59	7.25	36.34	13.60	8.68	8.29	8.73	6.35	36.43	8.19	8.11	9.32	8.27	7.50
50% percentile	39.64	23.45	18.80	17.18	14.78	11.22	40.01	20.05	18.13	18.29	13.78	11.46	39.41	17.50	14.98	14.47	11.74	10.37
90% percentile	43.27	30.67	27.63	22.05	19.92	20.47	43.27	32.58	28.09	25.46	23.37	25.01	42.92	29.25	27.63	26.56	22.71	21.03
	TOC concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Initial**	**10**	**20**	**30**	**50**	**75**	**Initial**	**10**	**20**	**30**	**50**	**75**	**Initial**	**10**	**20**	**30**	**50**	**75**
Average	43.76	32.86	27.95	26.24	24.00	22.49	43.56	29.82	27.90	27.35	25.49	21.03	43.99	27.22	24.75	22.08	20.78	21.07
Minimum	37.12	25.78	24.42	23.17	21.71	20.06	37.12	26.90	23.75	22.50	21.00	18.48	38.59	24.42	23.88	20.26	18.96	20.96
Maximum	58.21	40.87	34.03	30.54	27.49	26.60	58.21	34.35	32.42	40.41	39.74	24.95	55.66	29.33	25.96	22.95	22.03	21.19
Standard deviation	7.30	4.88	2.78	2.52	2.07	1.93	8.26	3.37	4.09	6.53	7.06	2.28	6.92	2.24	0.87	1.22	1.43	0.16
10% percentile	37.85	28.15	25.36	23.33	21.96	20.74	37.49	27.04	24.18	23.41	21.54	18.90	38.97	25.03	24.08	20.94	19.37	20.98
50% percentile	40.15	32.06	28.32	25.14	23.05	21.69	39.85	28.15	26.40	25.19	23.13	20.81	41.52	27.57	24.58	22.55	21.07	21.07
90% percentile	55.66	39.54	30.69	29.36	26.33	24.30	53.36	33.59	32.29	33.45	31.80	23.39	51.26	29.14	25.56	22.84	21.96	21.16

Table 4.11 Variations of TOC removal efficiency with soil depth in the columns operated with SSTWW and RSTWW

	TOC removal efficiency (%) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	38.93	51.29	56.89	62.62	68.19	–	44.31	52.40	56.44	61.22	66.18	–	55.35	58.67	59.77	64.51	64.52
Minimum	–	9.62	22.84	22.19	30.40	45.73	–	20.88	26.22	29.83	37.29	42.39	–	17.55	18.44	23.33	41.88	43.17
Maximum	–	65.20	77.27	77.02	79.81	85.30	–	78.55	81.42	83.14	84.41	85.41	–	81.63	83.63	84.54	85.22	85.91
Standard deviation	–	13.43	11.85	11.90	10.41	10.53	–	16.25	17.85	14.69	12.86	15.06	–	18.05	18.07	16.02	13.59	14.97
10% percentile	–	23.57	34.68	45.15	50.94	52.16	–	22.50	28.29	38.41	46.96	43.10	–	28.70	30.73	37.08	43.77	45.85
50% percentile	–	41.18	52.29	57.05	63.71	72.28	–	47.79	52.46	56.20	64.00	69.59	–	58.92	60.49	61.83	68.72	73.02
90% percentile	–	58.12	61.96	71.43	76.08	80.04	–	62.56	75.81	77.88	75.97	83.95	–	77.53	77.36	73.89	77.71	79.65
	TOC removal efficiency (%) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	24.01	34.64	38.71	43.96	47.59	–	25.61	30.55	38.61	41.86	51.07	–	33.73	39.59	46.17	49.34	49.74
Minimum	–	11.18	23.79	27.82	34.51	39.47	–	7.45	12.66	28.64	31.74	42.56	–	29.37	37.48	41.96	44.27	46.42
Maximum	–	49.43	56.14	58.10	60.74	61.66	–	43.80	45.56	47.99	50.81	57.14	–	36.72	45.03	49.44	51.19	53.06
Standard deviation	–	10.62	11.23	10.07	8.97	7.75	–	13.63	13.66	6.94	6.81	5.12	–	3.29	3.64	3.18	3.38	4.69
10% percentile	–	14.16	24.27	29.54	34.63	40.43	–	12.13	15.61	32.12	34.00	45.61	–	30.48	37.55	43.11	46.25	47.08
50% percentile	–	19.69	31.80	36.44	43.10	47.56	–	25.65	37.25	38.50	43.67	51.52	–	34.42	37.93	46.63	50.95	49.74
90% percentile	–	33.19	55.34	56.96	60.01	61.48	–	39.08	42.24	45.02	47.92	56.07	–	36.43	42.96	48.86	51.14	52.39

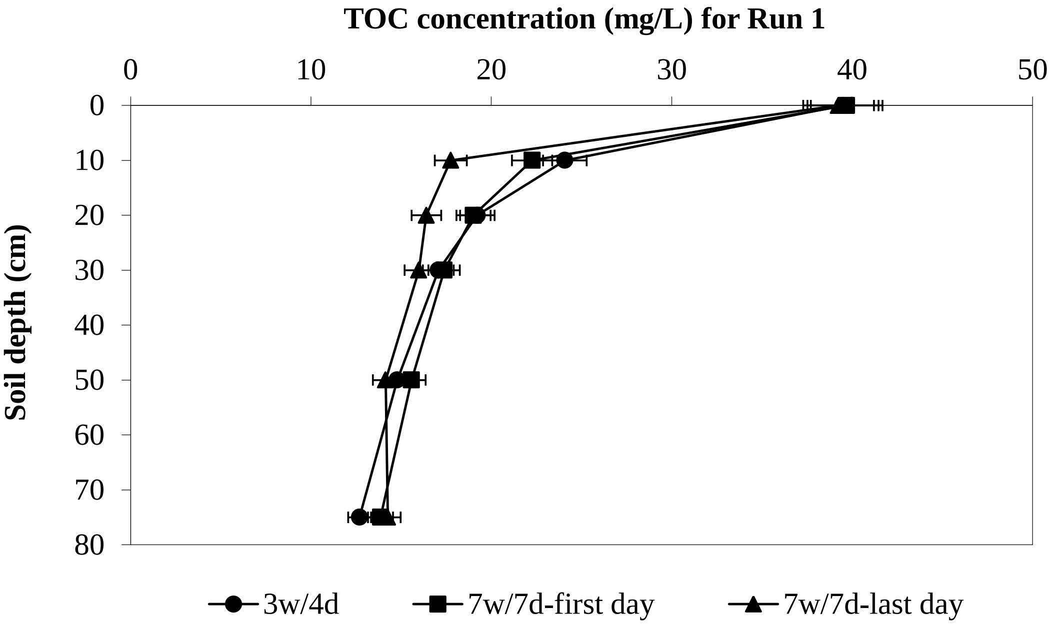

Figure 4.23 Changes of average TOC concentration through the columns operated with SSTWW

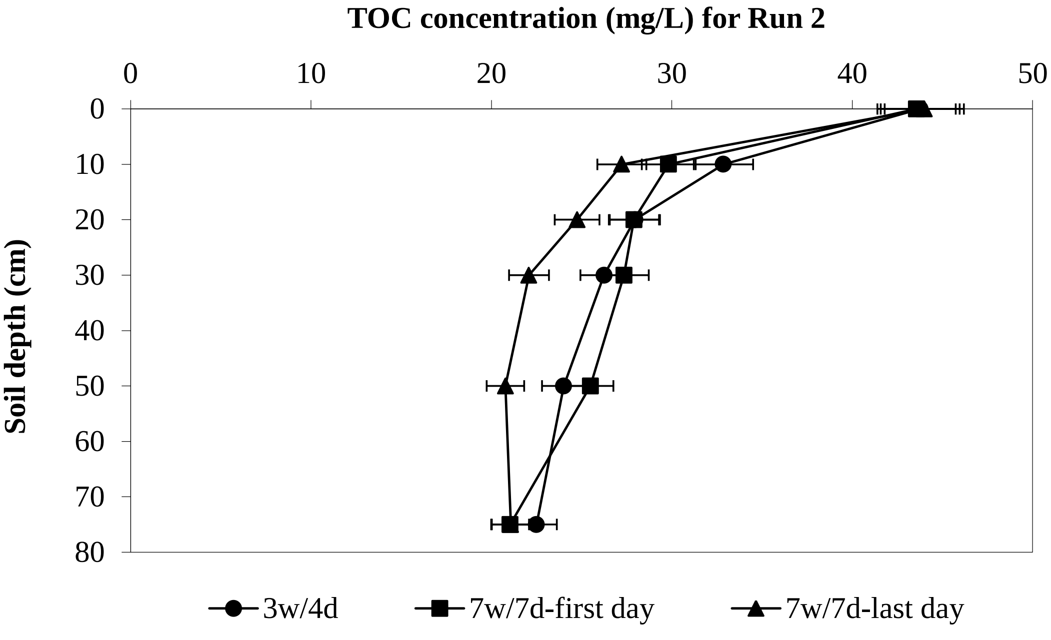

Figure 4.24 Changes of average TOC concentration through the columns operated with RSTWW

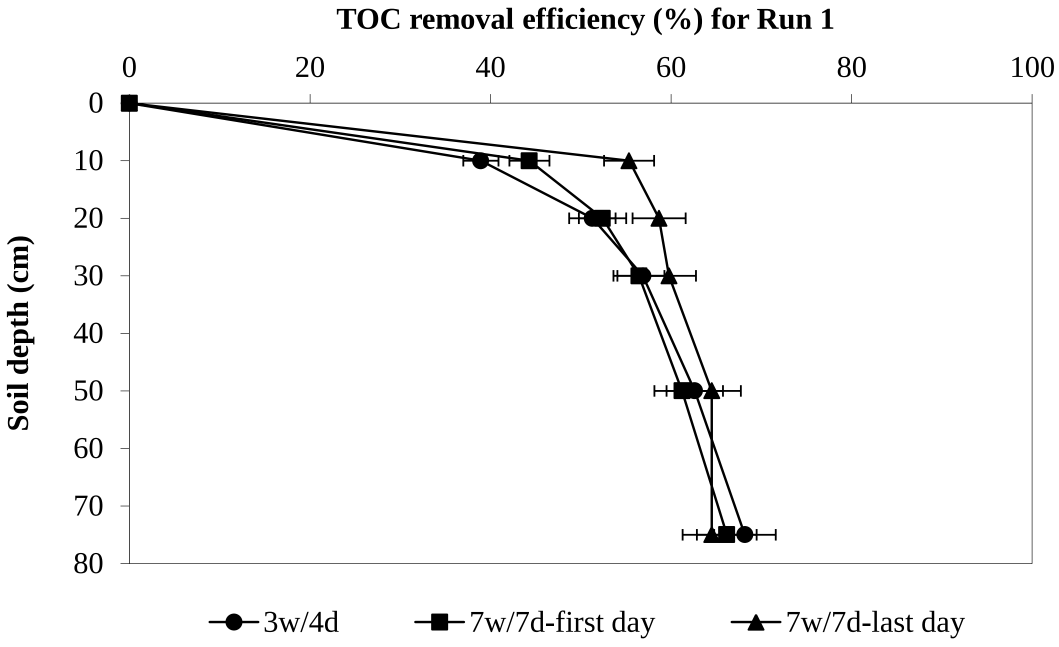

Figure 4.25 Average TOC removal efficiencies through the columns operated with SSTWW

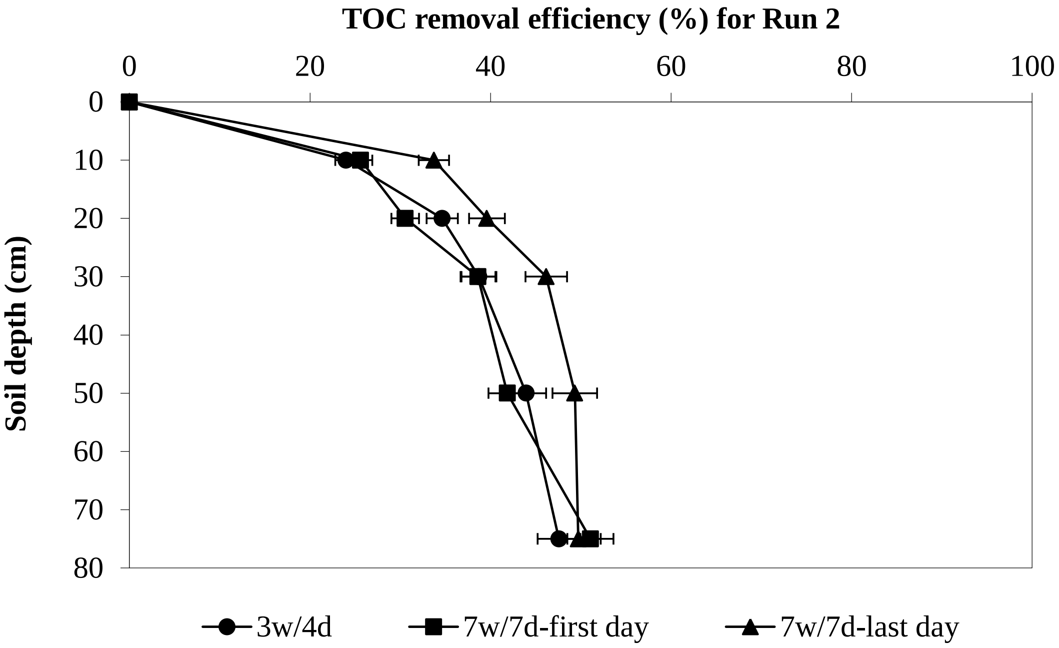

Figure 4.26 Average TOC removal efficiencies through the columns operated with RSTWW

DOC removal in SAT system. Nevertheless, Quanrud et al. (2003b) indicated that TOC and DOC concentrations did not show notable differences between each other. Amy & Drewes (2007), Sharma et al. (2008), Shuang et al. (2007) and Westerhoff & Pinney (2000) reported different organic carbon removals as DOC in quite a wide range depending on operating conditions (i.e., residence time, travel distance, organic loading, soil type, wetting/drying cycle, etc.).

TOC removal significantly occurred in the top 10 cm during Run 1 and Run 2 studies. These results are well consistent with findings by Rauch & Drewes (2005, 2006), Shuang et al. (2007) and Westerhoff & Pinney (2000). Rauch & Drewes (2005, 2006) studied on biological organic carbon removal using different organic carbon fractions during SAT system. It was observed that organic carbon removal essentially occurred within the first 10-30 cm of soil surface where more microbial biomass was present due to higher DO concentrations. The declining removal efficiencies along the columns were considered to be a general function of declining oxygen availability. Biochemically, the top 10 cm of the columns were more exposed to atmospheric oxygen that favored sharp removal of organic matter. As a result, most microbial growth was observed in the top 10 cm of the columns (Table 4.1). Consequently, easily biodegradable portion of organic carbon was removed by microorganisms in the first 10 cm where oxygen levels peaked. Complex organic compounds that are likely to be found in RSTWW could thus be removed when longer residence times were achieved through the columns. When organic matter removal efficiencies in different wastewater types were compared, it could be seen that the performance of the columns operated with SSTWW was better than the performance of the columns operated with RSTWW.

When the influence of two operating cycles were compared for the each wastewater, it could be seen that 3w/4d cycle operation performed slightly better than the 7w/7d cycle operation for SSTWW and 7w/7d cycle operation is found to be better than 3w/4d cycle operation for the RSTWW. Because longer residence times are required in order to removal complex organic compounds that are likely to be found in RSTWW by biodegradation, the highest TOC removal efficiencies for

RSTWW were observed to the last day of wetting periods of 7w/7d cycle operation obtained to the longest residence time during all studies. These results are consistent with findings by Cha et al. (2004), Laws et al. (2011) and Sharma et al. (2008).

While Run 1 studies started directly with SSTWW, Run 2 studies were started after the columns are operated with distilled water in order to remove background organic carbon originating from the soil. Hence, TOC concentrations increased through the columns during the first weeks of operation during Run 1 studies. This result is supported by the results reported by Fox et al. (2005). Changes of TOC concentration in the last sampling ports with operation weeks are depicted in Figure 4.27 and Figure 4.28 in the columns operated with SSTWW and RSTWW, respectively. As shown in Figure 4.27, TOC concentrations through the columns operated with SSTWW were measured to be always lower than influent concentrations after removing organic carbon originating from the soil matrix. When the most of the organic carbon originating from the soil was removed in the first weeks of operation, a small amount of organic carbon continued to dissolve in SSTWW for about 20 operation weeks. After about 20 weeks, the columns operated with SSTWW had no or very little organic carbon originating from the soil matrix and the columns were considered to reach stable conditions in terms of organic carbon (Figure 4.27).

Due to the fact that, the columns utilized during Run 2 studies were operated with distilled water for about 4 weeks, most of the organic carbon originating from the soil was removed. Therefore, TOC concentrations higher than the influent concentrations were not observed in the columns. Changes of TOC concentration in the last sampling ports with operation weeks during Run 2 studies demonstrated similar pattern to Run 1 studies. Although the influent TOC concentrations of RSTWW were more variable than SSTWW, the columns operated with RSTWW reached stable conditions about 15 weeks later from the beginning of operation.

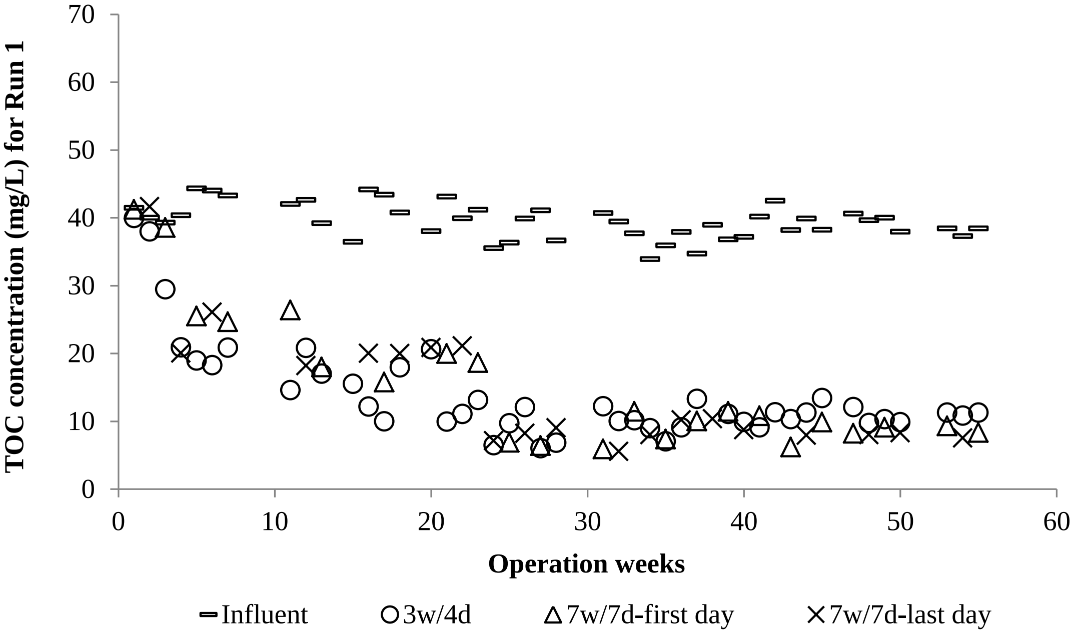

Figure 4.27 Changes of TOC concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

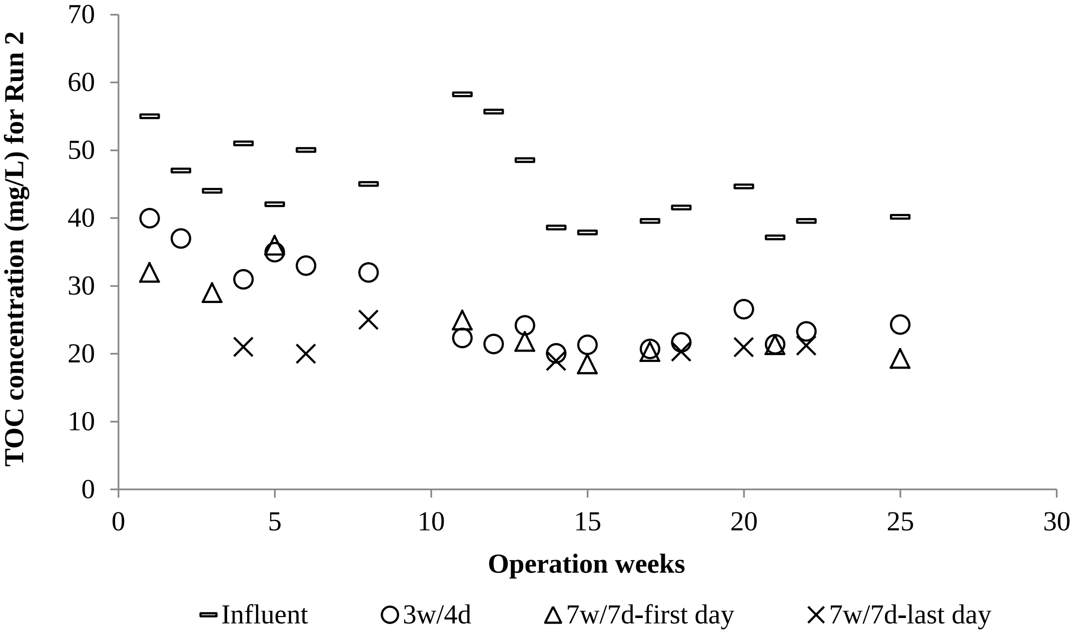

Figure 4.28 Changes of TOC concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

In general, it is difficult to distinguish between organic matter removed by biodegradation or by adsorption (Idelovitch et al., 2003). Nevertheless, previous studies revealed that the dominant mechanism in organic matter removal is always biodegradation. In this study, TOC removal efficiencies increased with operation weeks and by the time 20 weeks are reached, stable conditions in terms of organic carbon were obtained. Additionally, the removal of organic carbon continued up to end of the study without any decrease in removal performance. Moreover, most of the removal occurred in the top layer of the soil where the highest microbial biomass was observed. These results are the biggest evidence that effective removal mechanism for organic matter is biodegradation during laboratory-scale SAT system. These results are supported by numerous other studies (Amy & Drewes, 2007; Drewes et al., 2003; Ernst et al., 2000; Fox et al., 2005; Quanrud et al., 2003a; Rauch & Drewes, 2004, 2005, 2006; Xue et al., 2009).

4.1.12 Chemical Oxygen Demand (COD) Changes

There is a stoichiometric relationship between COD and TOC concentrations in wastewater. COD/TOC ratio varies from 2.0 to 2.5 for typical untreated wastewater, whereby COD concentrations can be used in order to crosscheck TOC concentrations (Metcalf & Eddy, 1991). Variations of COD concentration with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution are reported in Table 4.12. As reported in Table 4.12, COD concentrations were measured in the range of 17.03–105.34 mg/L and 21.97–124.17 mg/L during Run 1 and Run 2 studies, respectively.

Figure 4.29 and Figure 4.30 depicts changes of average COD concentration through the columns operated with SSTWW and RSTWW, respectively. Additionally, average COD removal efficiencies through the columns operated with SSTWW and RSTWW are depicted in Figure 4.31 and Figure 4.32, respectively.

Table 4.12 Variations of COD concentration with soil depth in the columns operated with SSTWW and RSTWW

	COD concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	95.53	46.12	41.56	41.14	37.92	36.80	95.95	54.04	50.39	48.43	45.63	45.21	94.83	47.17	46.75	47.31	46.47	47.73
Minimum	87.68	24.60	19.56	19.56	17.03	17.03	87.68	29.65	22.08	29.65	24.60	29.65	87.68	14.51	19.56	14.51	17.03	22.08
Maximum	105.34	59.93	54.88	57.40	57.40	52.36	105.34	70.02	64.97	62.45	62.45	54.88	102.82	57.40	57.40	59.93	59.93	62.45
Standard deviation	4.78	9.41	8.28	8.58	9.53	8.50	5.39	8.87	9.02	8.75	9.60	7.66	3.99	9.62	8.72	10.35	10.13	9.72
10% percentile	90.20	32.17	30.91	29.65	24.60	24.60	90.20	46.55	44.03	37.22	34.69	34.69	90.20	40.75	38.23	41.00	35.70	34.69
50% percentile	95.25	47.31	43.53	42.26	39.74	39.74	95.25	53.62	51.09	49.83	46.05	47.31	93.99	49.83	48.57	47.31	47.31	47.31
90% percentile	102.82	56.14	51.09	49.83	47.31	46.05	102.82	63.21	58.16	58.16	57.15	53.11	100.30	53.87	53.11	57.40	58.16	59.93
	COD concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	98.62	70.41	63.55	58.04	52.49	50.97	102.41	72.67	66.99	58.17	50.99	42.47	99.03	70.23	58.40	54.62	49.55	43.87
Minimum	75.91	24.81	21.97	27.65	24.81	21.97	78.75	47.52	44.68	44.68	33.33	30.49	81.59	61.72	47.52	36.16	33.33	33.33
Maximum	124.17	98.62	90.11	78.75	70.23	64.55	124.17	90.11	84.43	73.07	70.23	53.20	115.66	78.75	64.55	67.39	56.04	50.36
Standard deviation	14.51	23.08	19.90	15.64	12.72	9.91	14.96	14.88	14.79	9.81	10.41	7.07	13.76	7.24	6.07	10.58	8.15	5.61
10% percentile	80.45	40.42	38.44	40.71	36.16	45.53	87.83	57.74	49.79	46.67	40.14	32.76	83.29	62.85	51.78	43.26	40.14	38.44
50% percentile	98.62	70.23	64.55	56.04	51.78	51.78	101.46	70.23	67.39	57.46	50.36	41.84	101.46	70.23	60.30	57.46	53.20	44.68
90% percentile	117.93	97.20	85.56	78.75	65.97	58.88	121.90	88.40	82.72	69.10	58.88	48.66	113.95	77.61	63.14	63.14	56.04	48.66

Starting from about 95.9 mg/L, average COD concentration decreased to about 36.8 mg/L through the columns operated with SSTWW. On the other hand, average COD concentration through the columns operated with RSTWW was decreased from about 102.4 to 42.5 mg/L. The average COD concentration and removal changes through the columns demonstrated a similar pattern to the average TOC changes, because of relationship between the two parameters.

Table 4.13 reports variations of COD removal efficiencies with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column. According to Table 4.13, average COD removals in the last sampling ports were observed to be in the range of 37.41–81.12% and 31.32–71.06% during Run 1 and Run 2 studies, respectively. As revealed in Figure 4.31 and Figure 4.32, average COD removal efficiencies increased along the columns operated with both SSTWW and RSTWW. Moreover, most of the removal occurred in the first soil depths where the highest microbial biomass was observed similar to TOC removal. In the columns operated with SSTWW, about average 51.6% COD removal was achieved in the top 10 cm and about average 61.4% in the last sampling ports of the columns. Nevertheless in the columns operated with RSTWW, average 32.5% COD removal efficiency was achieved in the top 10 cm and about average 58.3% in the last sampling ports of the columns. Although the higher removal efficiencies were achieved first 10 cm of the soil depth during Run 1 studies, no major differences were detected in the total removal efficiencies in the last sampling port between both Run 1 and Run 2 studies. Even though there are the numerous studies about organic matter removal using SAT system, COD removal studies are limited in the literature. However, total removal efficiencies obtained in this study are consistent with results obtained by Zhang et al. (2007).

The 3w/4d cycle operation performed slightly better than the 7w/7d cycle operation for SSTWW to removal of COD, since the oxygen concentrations in the soil were slightly higher with shorter wetting and longer drying periods. Although the oxygen concentrations in the soil were increased more with shorter wetting and longer drying periods the columns operated with RSTWW, complex organic compounds in the RSTWW were not easily biodegraded and needed longer residence

Table 4.13 Variations of COD removal efficiency with soil depth in the columns operated with SSTWW and RSTWW

	COD removal efficiency (%) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	51,61	56,42	56,84	60,30	61,44	–	43,56	47,38	49,40	52,34	52,73	–	50,19	50,73	50,15	51,09	49,73
Minimum	–	34,53	40,29	39,73	39,73	45,03	–	30,77	34,53	37,09	34,44	37,41	–	34,53	38,09	38,09	38,71	38,71
Maximum	–	74,17	79,47	78,32	81,12	81,12	–	68,87	76,82	68,87	74,17	68,87	–	84,77	79,47	84,77	82,12	76,82
Standard deviation	–	10,26	8,89	9,33	9,98	9,04	–	9,48	9,56	9,43	10,18	8,62	–	10,32	8,80	10,52	9,91	9,60
10% percentile	–	42,17	46,26	46,26	48,98	50,97	–	31,87	37,00	38,71	39,98	44,95	–	43,31	45,33	40,65	42,45	39,95
50% percentile	–	49,65	55,01	54,55	59,86	59,38	–	44,41	47,07	50,33	51,62	51,53	–	48,39	48,98	48,98	49,68	48,98
90% percentile	–	65,82	67,98	68,85	73,78	74,15	–	50,32	53,81	59,99	63,38	64,12	–	58,79	57,62	56,39	61,20	61,85
	COD removal efficiency (%) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	30,60	36,18	41,31	46,85	48,12	–	31,78	37,15	44,88	50,15	58,28	–	32,47	41,43	45,14	49,87	55,44
Minimum	–	10,09	13,45	13,45	20,18	31,32	–	21,78	27,22	32,60	39,66	46,87	–	26,90	30,26	20,18	37,81	47,26
Maximum	–	72,47	75,62	69,32	67,32	71,06	–	47,26	50,41	50,41	63,01	66,17	–	36,38	46,64	55,67	59,15	60,39
Standard deviation	–	17,39	16,27	13,36	12,28	10,37	–	8,39	8,97	5,88	7,68	6,22	–	3,55	5,76	12,58	6,55	4,87
10% percentile	–	11,59	17,79	28,72	33,45	36,33	–	24,15	28,67	37,62	41,13	51,90	–	28,91	36,01	33,94	43,37	49,17
50% percentile	–	26,59	34,37	40,83	46,77	49,45	–	29,72	34,29	46,92	51,72	59,88	–	32,71	42,59	48,45	50,35	56,46
90% percentile	–	53,53	55,26	55,83	63,80	56,62	–	41,55	47,34	49,33	56,59	64,55	–	35,60	45,70	53,02	56,06	59,65

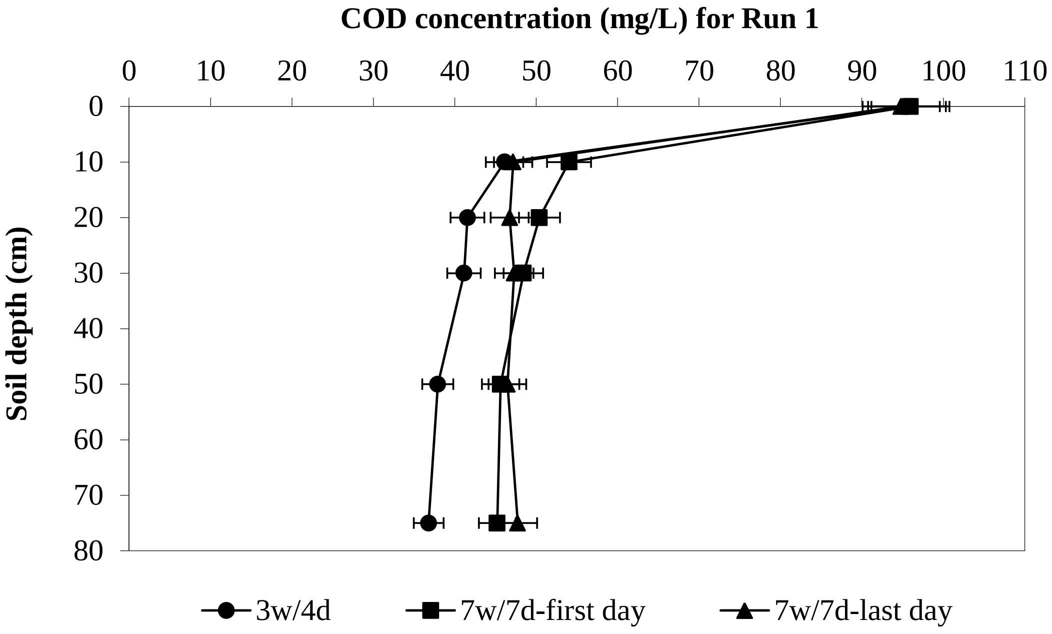

Figure 4.29 Changes of average COD concentration through the columns operated with SSTWW

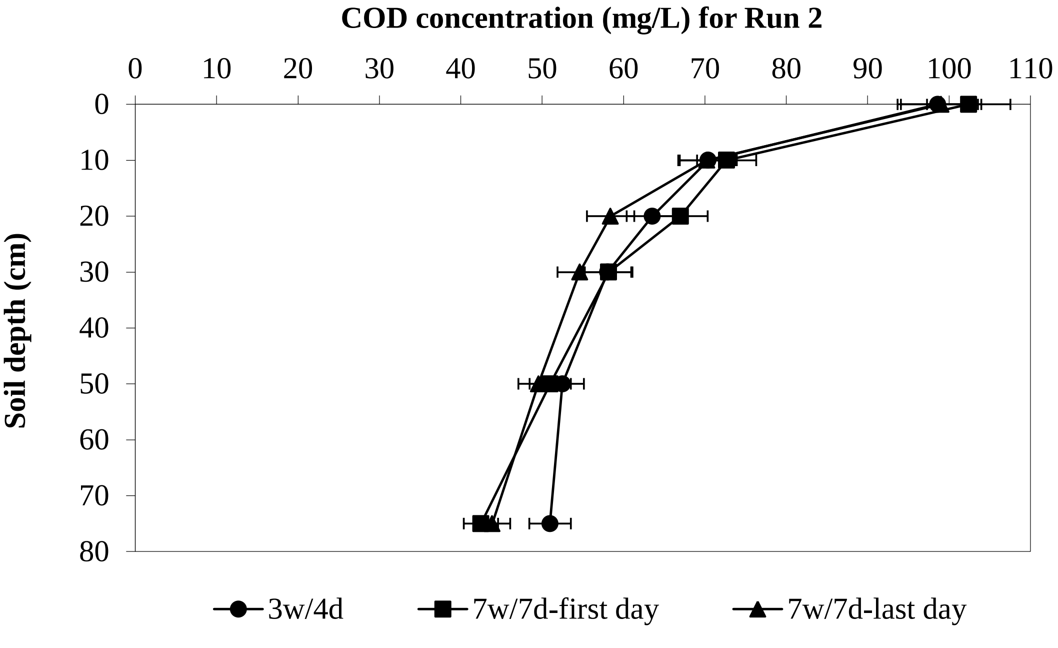

Figure 4.30 Changes of average COD concentration through the columns operated with RSTWW

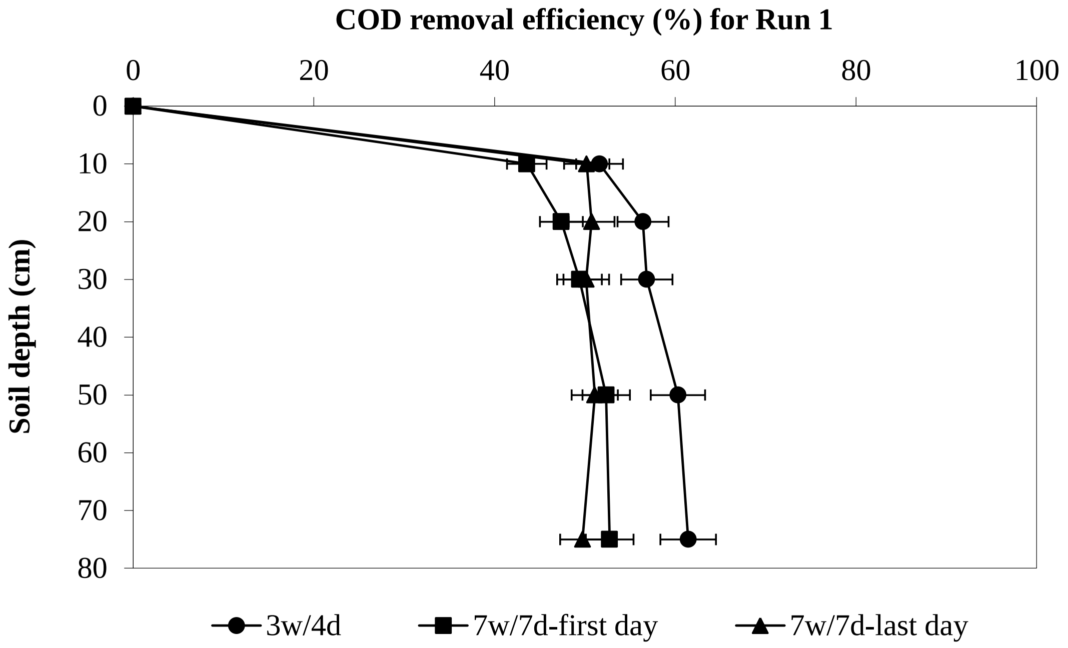

Figure 4.31 Average COD removal efficiencies through the columns operated with SSTWW

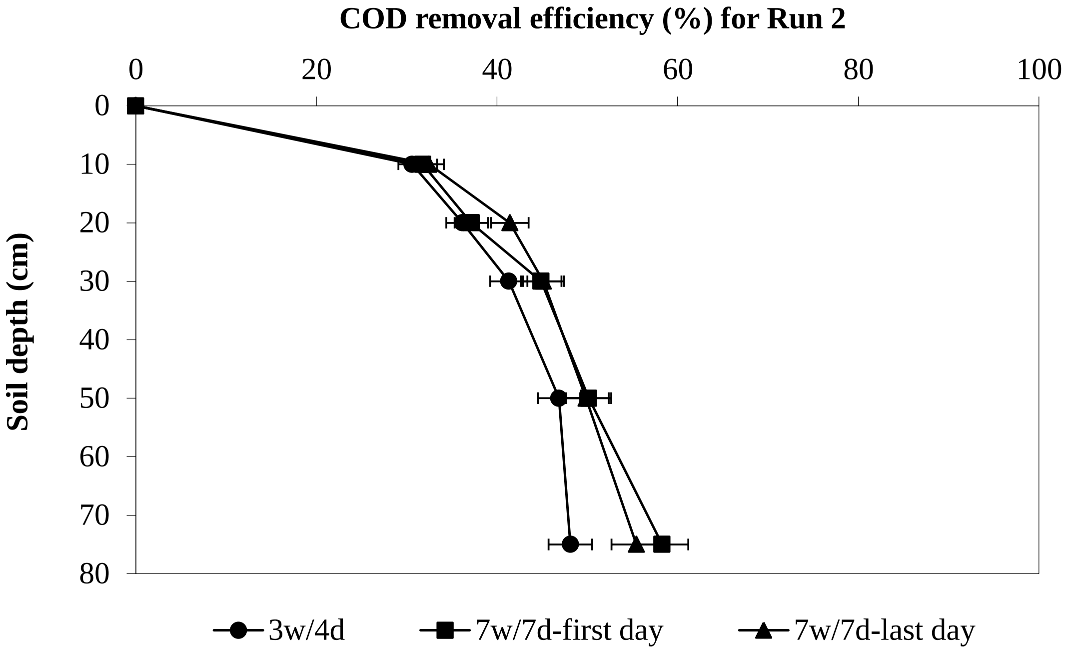

Figure 4.32 Average COD removal efficiencies through the columns operated with RSTWW

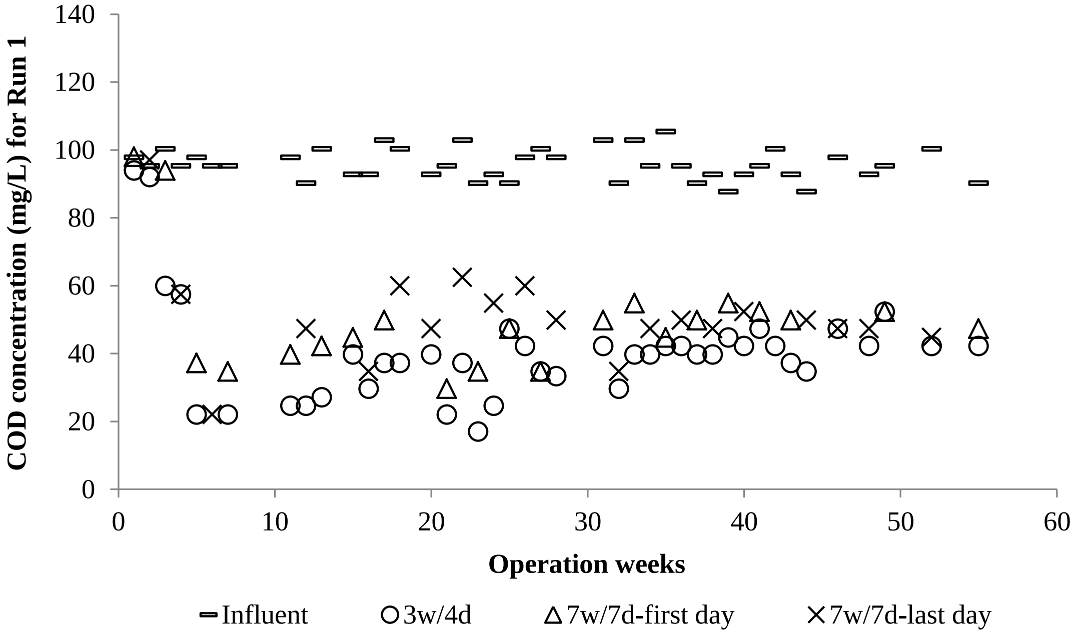

Figure 4.33 Changes of COD concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

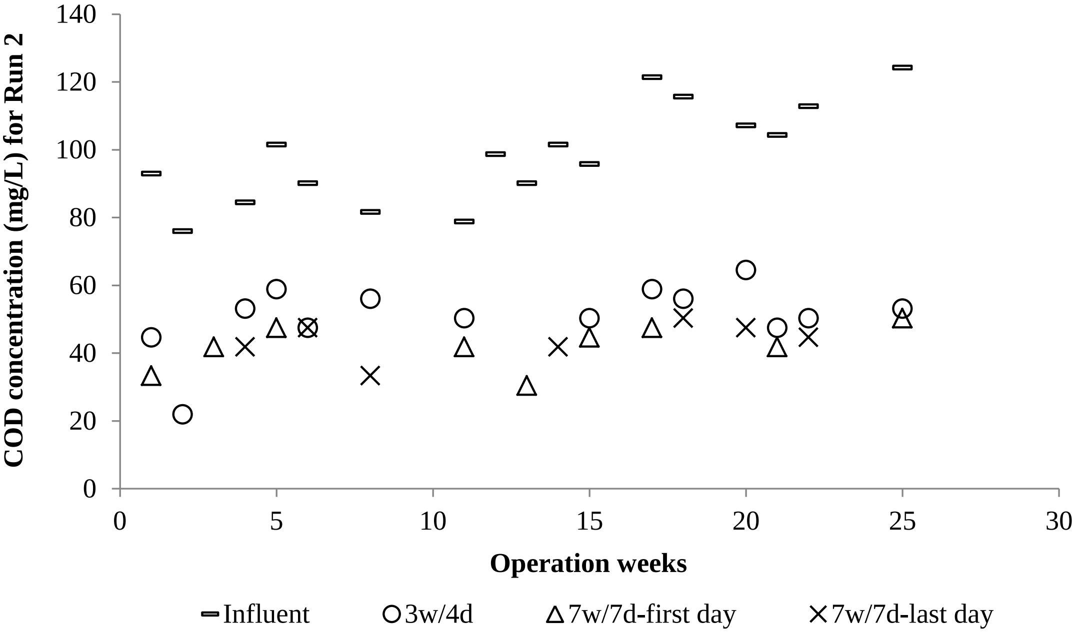

Figure 4.34 Changes of COD concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

time for biodegradation. Similarly to TOC removal changes through the columns operated with both SSTWW and RSTWW, the highest COD removal efficiencies for RSTWW were observed to the last day of wetting periods of 7w/7d cycle operation because of longer residence time.

Changes of COD concentration in the last sampling ports as a function of operation weeks are depicted in Figure 4.33 and Figure 4.34 in the columns operated with SSTWW and RSTWW, respectively. COD concentrations through the columns operated with both SSTWW and RSTWW were measured to be always lower than influent concentrations after removing organic carbon originating from the soil matrix, similar to TOC. The COD removal efficiencies were observed to be relatively stable except the first weeks of operation of Run 1 studies and continued up to end of the both Run 1 and Run 2 studies without being affected from any seasonal conditions. Although the influent COD concentrations in RSTWW were more variable, no major differences were observed in the removal efficiencies.

4.1.13 Ammonium Nitrogen (NH_4^+–N) Changes

Nitrogen forms such as organic nitrogen and ammonia were mostly converted to ammonium in secondary treated wastewater (Metcalf & Eddy, 1991). Ammonia will be oxidized to nitrite and finally to nitrate if molecular oxygen is present in wastewater (Peavy et al., 1985). Equation 4.1 and Equation 4.2 depict nitrification reactions.

$$NH_4^+ + (3/2)\,O_2 \longrightarrow NO_2^- + 2H^+ + H_2O \qquad \text{Equation 4.1}$$

$$NO_2^- + (1/2)\,O_2 \longrightarrow NO_3^- \qquad \text{Equation 4.2}$$

Variations of NH_4^+–N concentration with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution are depicted in Table 4.14. According to Table 4.14, NH_4^+–N concentrations were measured in the range of 0.03–3.79 mg/L and 0.03–2.16 mg/L during Run 1 and Run 2 studies, respectively. Removal of ammonium can occur by nitrification and adsorption via cation exchange (Dermont et al., 2008; Thornton et al., 2000). Cation exchange capacity (CEC) of the soil is 23.56 meq/100g according to Table 3.2. This CEC value is neither high nor low; it is in the range of values obtained for silt loam soil texture. In addition, CEC generally increases with increasing clay and organic matter content of soil (WSU, 2004).

Owing to existence of oxygen through the columns (Figure 4.19 and Figure 4.20), ammonium was oxidized to nitrate by microorganisms during the both Run 1 and Run 2 studies as depicted in Equation 4.1 and Equation 4.2. Nevertheless, the average NH_4^+–N concentrations increased within the first 10 cm of the soil and then mostly demonstrated a gradual decline reaching to values smaller than the influent concentration through the columns operated with SSTWW. Changes of average NH_4^+–N concentration through the columns operated with SSTWW and RSTWW are given in Figure 4.35 and Figure 4.36, respectively. Increasing of NH_4^+–N concentrations within the first 10 cm of the soil in the columns operated with SSTWW can be attributed to the fact that urea used for preparation of SSTWW, which was oxidized to other nitrogen forms (ammonium, nitrite and nitrate) during top layers of the soil. On the other hand, the average NH_4^+–N concentrations decreased from the first sampling ports to last ones along the columns operated with RSTWW.

Starting from about 1.7 mg/L, average NH_4^+–N concentrations rapidly increased to 2.4 mg/L in first 10 cm of the soil, and then demonstrated a gradual decline towards the 50 cm of the soil ports in the columns operated with SSTWW. Thereafter, a small amount of decrease in NH_4^+–N concentrations was observed in the last sampling ports of 75 cm soil depth. This situation can attribute to insufficient nitrification conditions or exhausted adsorption capacity of the soil. Average NH_4^+–N concentration was measured to be about 1.0 mg/L in 75 cm soil depth during Run 1 studies.

While ammonium concentration decreases, nitrate concentration must increase during nitrification process. However, the average NH_4^+–N concentrations were

Table 4.14 Variations of NH_4^+–N concentration with soil depth in the columns operated with SSTWW and RSTWW

	Ammonium-nitrogen concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	1.57	1.70	1.38	1.11	0.97	0.96	1.67	2.39	1.97	1.83	1.21	1.03	1.52	2.44	1.94	1.58	1.23	1.22
Minimum	0.03	0.05	0.13	0.10	0.16	0.20	0.35	0.99	0.24	0.35	0.21	0.09	0.03	0.67	0.51	0.29	0.45	0.03
Maximum	3.51	3.77	3.01	2.43	2.34	1.59	3.37	3.79	3.51	3.54	2.32	1.54	3.51	3.76	3.74	3.56	2.04	2.07
Standard deviation	1.18	1.02	0.79	0.68	0.58	0.42	1.25	1.08	1.11	1.08	0.72	0.54	1.18	1.00	1.00	0.90	0.48	0.67
10% percentile	0.20	0.29	0.42	0.18	0.31	0.33	0.42	1.09	0.81	0.63	0.46	0.34	0.15	1.05	0.84	0.71	0.53	0.43
50% percentile	1.28	1.65	1.32	1.06	0.78	1.03	1.27	2.43	1.71	1.59	1.22	1.23	1.47	2.32	1.91	1.58	1.42	1.34
90% percentile	3.34	3.20	2.65	2.15	1.66	1.47	3.35	3.50	3.34	3.12	2.14	1.52	3.17	3.60	3.37	2.76	1.63	1.84
	Ammonium-nitrogen concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	0.92	0.78	0.69	0.61	0.56	0.53	0.80	0.66	0.54	0.40	0.38	0.31	1.01	0.88	0.79	0.74	0.62	0.47
Minimum	0.04	0.05	0.10	0.05	0.05	0.22	0.04	0.04	0.06	0.03	0.05	0.06	0.19	0.17	0.18	0.14	0.11	0.13
Maximum	2.16	1.80	1.75	1.41	1.37	0.71	2.16	1.62	1.16	1.10	0.80	0.53	2.05	1.77	1.63	1.47	1.45	1.09
Standard deviation	0.80	0.72	0.63	0.53	0.50	0.19	0.86	0.61	0.50	0.45	0.30	0.24	0.78	0.76	0.69	0.62	0.60	0.43
10% percentile	0.07	0.07	0.12	0.07	0.12	0.32	0.07	0.06	0.10	0.05	0.07	0.11	0.35	0.21	0.19	0.17	0.16	0.16
50% percentile	0.55	0.46	0.37	0.42	0.24	0.59	0.42	0.43	0.37	0.26	0.35	0.33	0.55	0.68	0.61	0.58	0.32	0.33
90% percentile	2.02	1.73	1.53	1.32	1.23	0.68	1.98	1.46	1.15	1.03	0.70	0.49	2.01	1.76	1.58	1.46	1.38	0.90

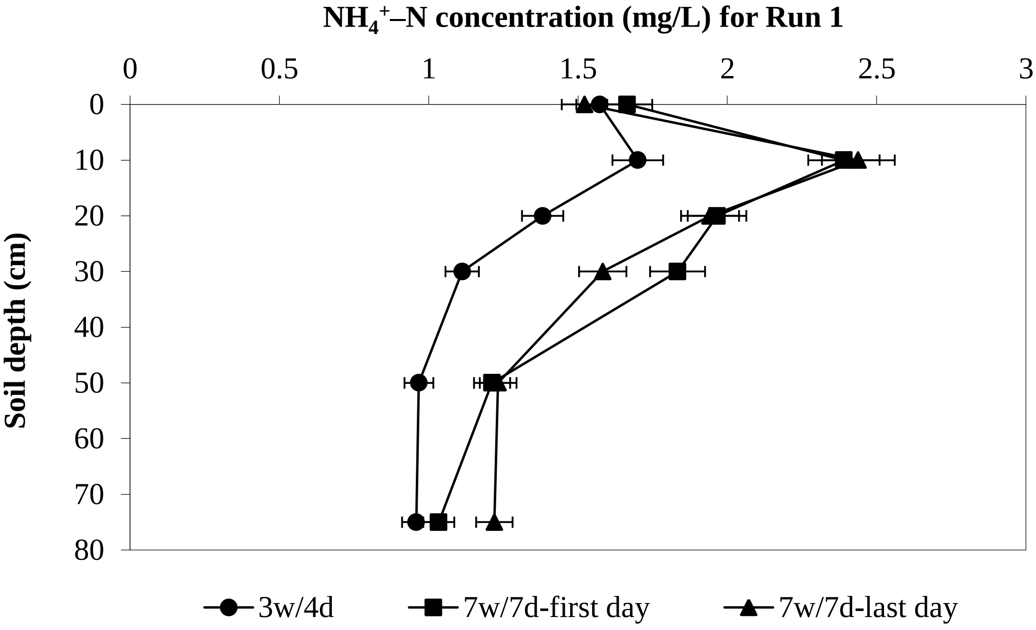

Figure 4.35 Changes of average NH_4^+–N concentration through the columns operated with SSTWW

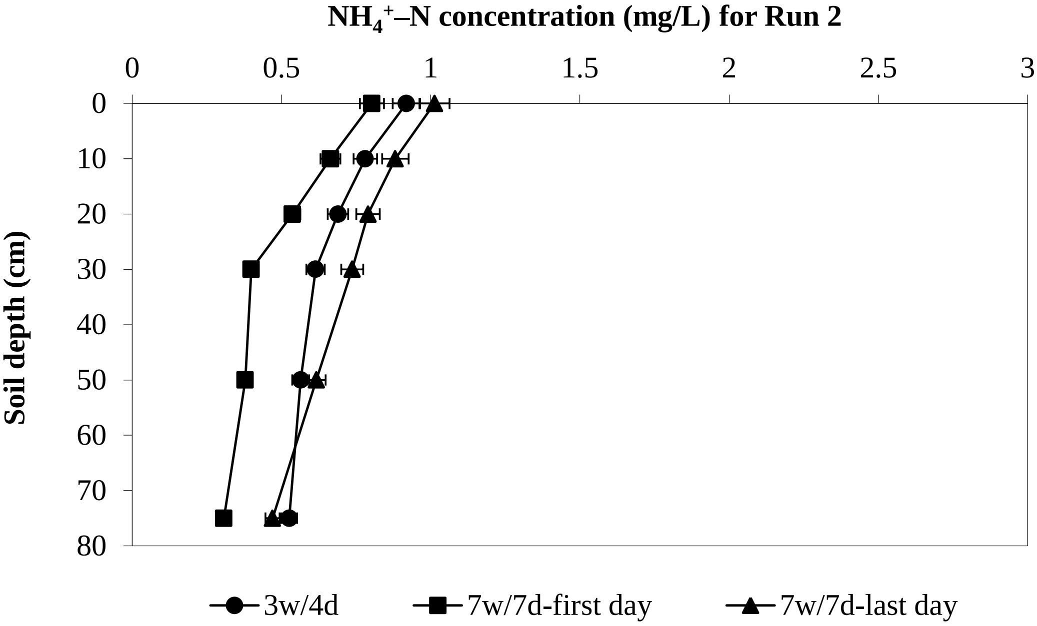

Figure 4.36 Changes of average NH_4^+–N concentration through the columns operated with RSTWW

decreased in the last sampling ports, similarly the average NO_3^-–N concentrations was also decreased (Figure 4.45) at the same depth during Run 1 studies. Furthermore, starting from about 1.0 mg/L, average NH_4^+–N concentrations was decreased to 0.3 mg/L through the last sampling ports in the columns operated with RSTWW. Similar to Run 1 studies, the average NH_4^+–N concentrations decreased through the columns operated with RSTWW, similarly the average NO_3^-–N concentrations was also decreased (Figure 4.46) during Run 2 studies. This phenomenon indicated that ammonium was simultaneously removed by adsorption and nitrification during this study as discussed by Idelovitch et al. (2003).

When two operating cycles were compared for the each wastewater type, it could be seen that 3w/4d cycle operation performed slightly better than the 7w/7d cycle operation for SSTWW and 7w/7d cycle operation was better than 3w/4d cycle operation for the RSTWW. On the other hand, it was clearly depicted in Figure 4.35 and Figure 4.36 that performance of first wetting days was better than last wetting days for each operation cycle, since DO concentration decreases during wetting period and vice versa during drying period whereby most ammonium can be oxidized to nitrate.

Average NH_4^+–N removal efficiencies through the columns operated with SSTWW and RSTWW are depicted in Figure 4.37 and Figure 4.38, respectively. Since the average NH_4^+–N concentrations increased in first 10 cm of the soil, ammonium removal did not occur within the top 30 cm of soil depth, then an average 39.1% NH_4^+–N removal was achieved in the last sampling port of 75 cm soil depth during Run 1 studies. If the NH_4^+–N concentration in 10 cm of the soil depth is taken as the starting concentration, the removal efficiency can be increased to 57.0% during Run 1 studies. However, average 61.8% NH_4^+–N removal was achieved in total during Run 2 studies. Higher NH_4^+–N removal efficiencies may be achieved if longer columns are used to ensure longer retention times.

Changes of NH_4^+–N concentration in the last sampling ports as a function of operation weeks are depicted in Figure 4.39 and Figure 4.40 in the columns operated

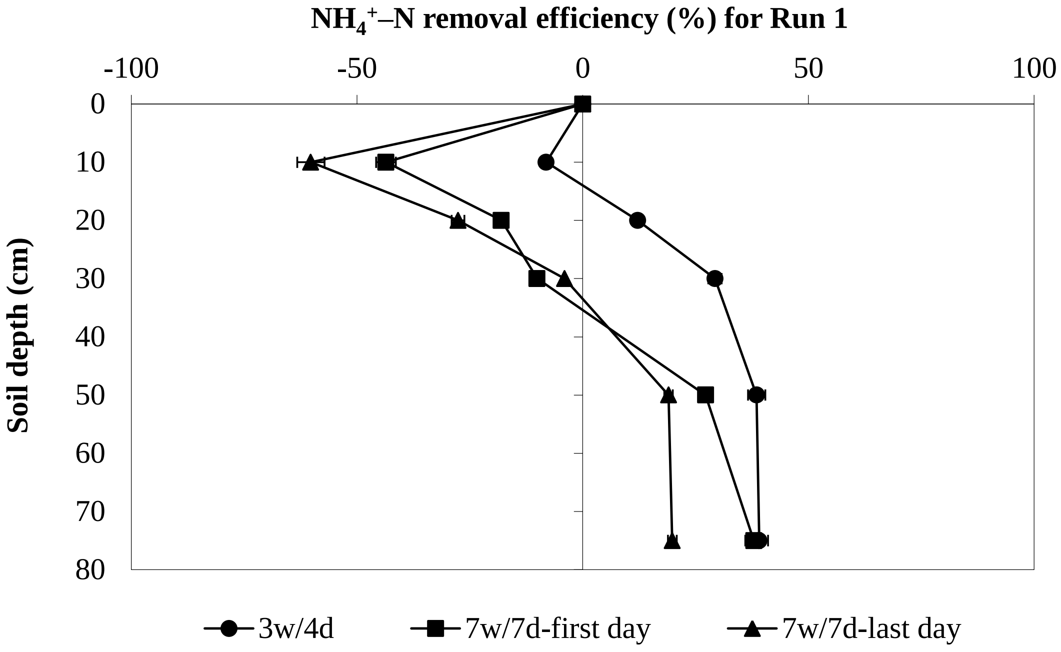

Figure 4.37 Average NH_4^+–N removal efficiencies through the columns operated with SSTWW

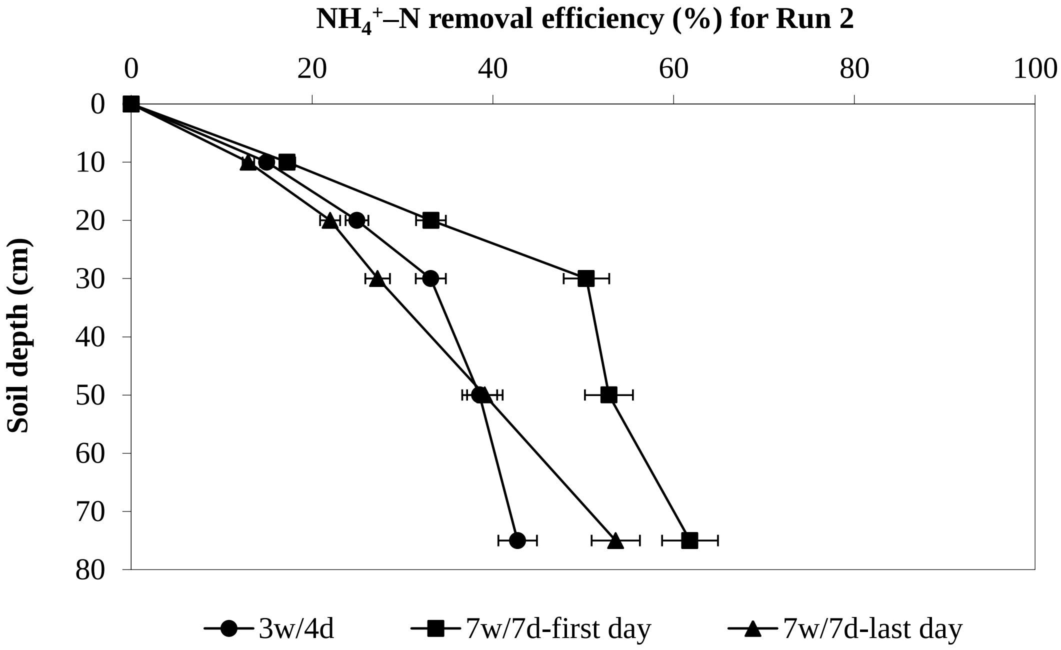

Figure 4.38 Average NH_4^+–N removal efficiencies through the columns operated with RSTWW

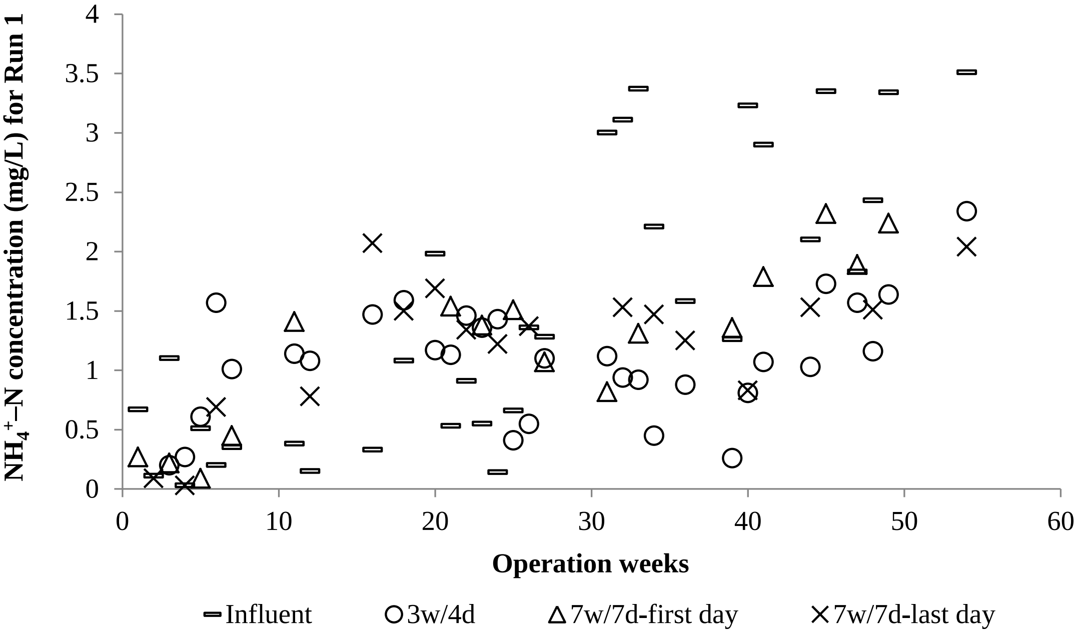

Figure 4.39 Changes of NH_4^+–N concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

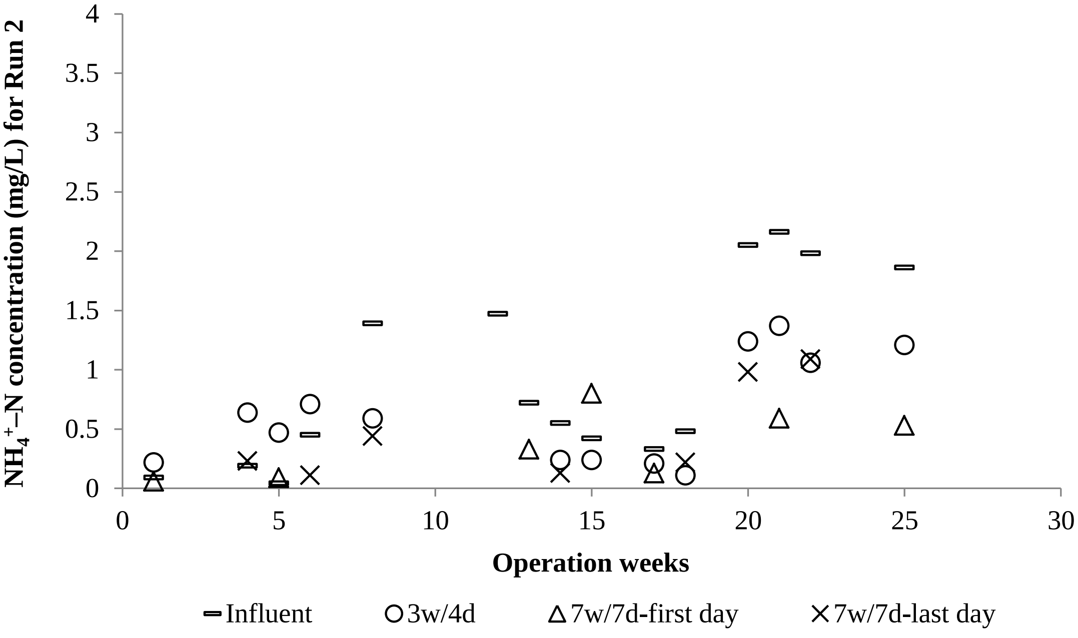

Figure 4.40 Changes of NH_4^+–N concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

with SSTWW and RSTWW, respectively. As revealed in Figure 4.39, influent NH_4^+–N concentrations increased during winter season, since nitrification was decreased with decreasing microbial activity during winter season of Run 1 studies.

4.1.14 Nitrite Nitrogen (NO_2^-–N) Changes

Nitrite immediately oxidizes to nitrate in the existence of molecular oxygen according to Equation 4.1 and Equation 4.2. Variations of NO_2^-–N concentration with soil depth in the columns operated with SSTWW and RSTWW at the five sampling ports of each column as well as the stock solution are depicted in Table 4.15. The NO_2^-–N concentrations were measured in the range of 0.00–1.00 mg/L and 0.00–0.58 mg/L during Run 1 and Run 2 studies, respectively. Owing to existence of oxygen through the columns (Figure 4.19 and Figure 4.20), nitrite was oxidized to nitrate by microorganisms during the both Run 1 and Run 2 studies.

While the influent NO_2^-–N concentrations were not detected, the average NO_2^-–N concentrations were increased up to 0.39 mg/L within the first 10 cm of the soil and then rapidly decreased up to 0.01 mg/L through the columns operated with SSTWW. Changes of average NO_2^-–N concentration through the columns operated with SSTWW and RSTWW are depicted in Figure 4.41 and Figure 4.42, respectively. Increasing of NO_2^-–N concentrations within the first 10 cm of the soil in the columns operated with SSTWW can be attributed to urea used for the preparation of SSTWW. Urea was oxidized to nitrogen forms during first depths of the soil, similar to ammonium. Additionally, ammonium was rapidly oxidized to nitrite in high molecular oxygen within the first 10 cm of soil depth because of high molecular oxygen concentration in this zone and then immediately oxidized to nitrate according to Equation 4.1 and Equation 4.2 through the columns operated with SSTWW. NO_2^-–N concentrations more increased at the first wetting days for each operation cycle than last wetting day of 7w/7d cycle within 10 cm of the soil depth because of high DO concentration.

Table 4.15 Variations of NO_2^-–N concentration with soil depth in the columns operated with SSTWW and RSTWW

	Nitrite-nitrogen concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	0.00	0.21	0.26	0.24	0.18	0.04	0.00	0.39	0.27	0.23	0.20	0.01	0.00	0.05	0.06	0.07	0.04	0.01
Minimum	0.00	0.02	0.02	0.01	0.01	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	0.01	0.93	0.73	0.70	0.86	0.09	0.00	1.00	1.00	0.86	0.67	0.02	0.01	0.37	0.41	0.68	0.45	0.06
Standard deviation	0.00	0.21	0.18	0.19	0.19	0.03	0.00	0.25	0.24	0.20	0.18	0.01	0.00	0.12	0.12	0.18	0.12	0.02
10% percentile	0.00	0.04	0.08	0.08	0.04	0.01	0.00	0.09	0.07	0.05	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50% percentile	0.00	0.15	0.21	0.18	0.09	0.03	0.00	0.41	0.22	0.19	0.12	0.01	0.00	0.00	0.01	0.02	0.01	0.00
90% percentile	0.00	0.43	0.52	0.52	0.36	0.08	0.00	0.63	0.45	0.34	0.44	0.02	0.00	0.20	0.20	0.08	0.05	0.04
	Nitrite-nitrogen concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	0.17	0.18	0.18	0.17	0.13	0.12	0.24	0.21	0.18	0.16	0.15	0.06	0.20	0.12	0.14	0.20	0.19	0.13
Minimum	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.05	0.02	0.00	0.00	0.00	0.00	0.03	0.05	0.06	0.00	0.00
Maximum	0.40	0.37	0.50	0.49	0.48	0.36	0.58	0.45	0.44	0.41	0.46	0.31	0.53	0.20	0.20	0.33	0.43	0.27
Standard deviation	0.14	0.13	0.16	0.14	0.13	0.13	0.17	0.17	0.15	0.15	0.18	0.11	0.18	0.06	0.06	0.12	0.19	0.14
10% percentile	0.00	0.05	0.04	0.06	0.00	0.00	0.04	0.08	0.05	0.03	0.02	0.01	0.05	0.06	0.07	0.08	0.02	0.02
50% percentile	0.15	0.16	0.12	0.13	0.12	0.09	0.25	0.10	0.10	0.08	0.07	0.02	0.15	0.13	0.16	0.19	0.14	0.12
90% percentile	0.34	0.34	0.41	0.32	0.20	0.28	0.39	0.44	0.37	0.34	0.45	0.15	0.39	0.17	0.20	0.32	0.42	0.24

Starting from about 0.24 mg/L, average NO_2^-–N concentrations showed a gradual decline up to 0.06 mg/L at the end of the first wetting days for each operation cycles through the columns operated with RSTWW. However, average NO_2^-–N concentrations fluctuated at the end of the last wetting days of 7w/7d cycle because of variable DO concentrations and desorption during saturated conditions.

Changes of NO_2^-–N concentration in the last sampling ports as a function of operation weeks are depicted in Figure 4.43 and Figure 4.44 in the columns operated with SSTWW and RSTWW, respectively. It was clearly seen in Figure 4.43 and Figure 4.44 that RSTWW contained higher NO_2^-–N concentrations than SSTWW because of higher influent concentrations.

4.1.15 Nitrate Nitrogen (NO_3^-–N) Changes

Nitrate is the last product of nitrification process, as depicted in Equation 4.1 and Equation 4.2. Nitrate is converted to nitrogen gas in anoxic conditions during denitrification process (Peavy et al., 1985). Equation 4.3 depicts denitrification reaction.

$$NO_3^- + (5/6)\,CH_3OH \longrightarrow (1/2)\,N_2 + (5/6)\,CO_2 + (7/6)\,H_2O + OH^-$$

Equation 4.3

Variations of NO_3^-–N concentration with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution are depicted in Table 4.16. According to Table 4.16, NO_3^-–N concentrations were measured in the range of 0.004–8.17 mg/L and 0.63–11.08 mg/L during Run 1 and Run 2 studies, respectively. Because of existence of oxygen through the columns (Figure 4.19 and Figure 4.20), as depicted in Equation 4.1 and Equation 4.2, ammonium was oxidized to nitrate by microorganisms during the both Run 1 and Run 2 studies.

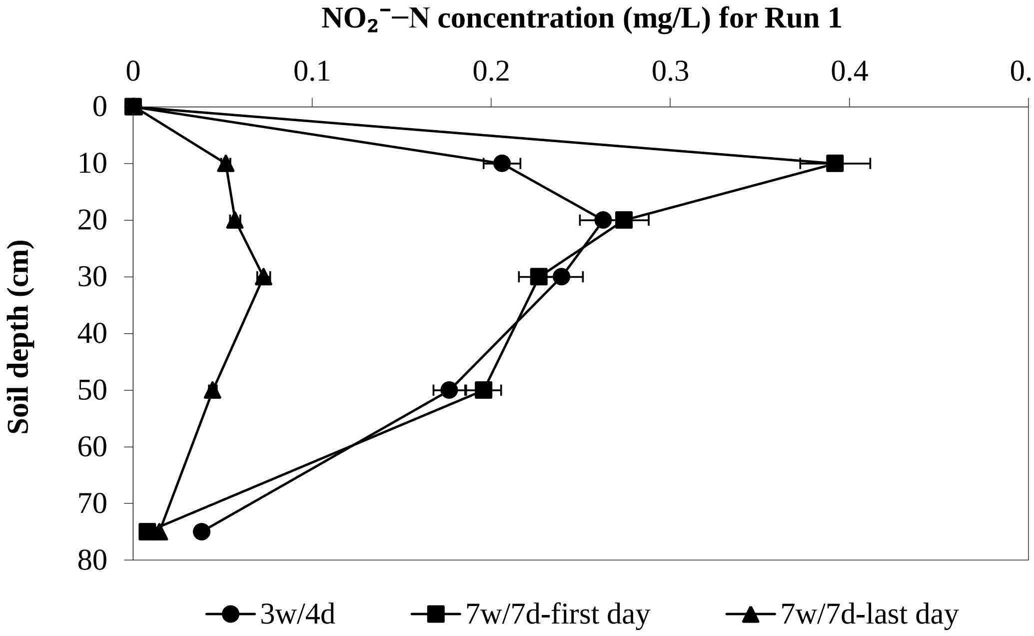

Figure 4.41 Changes of average NO_2^-–N concentration through the columns operated with SSTWW

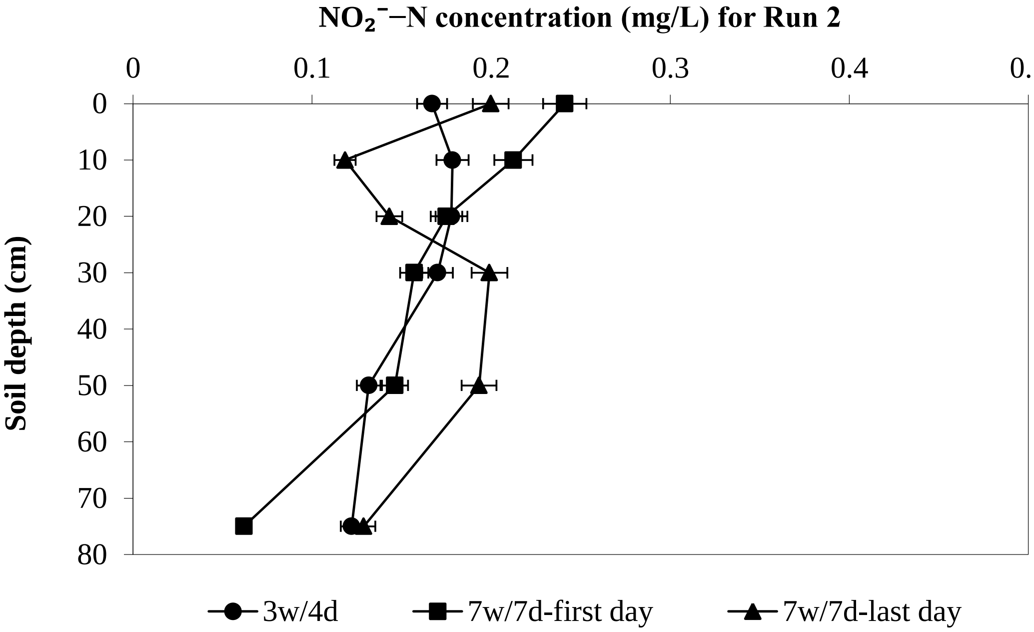

Figure 4.42 Changes of average NO_2^-–N concentration through the columns operated with RSTWW

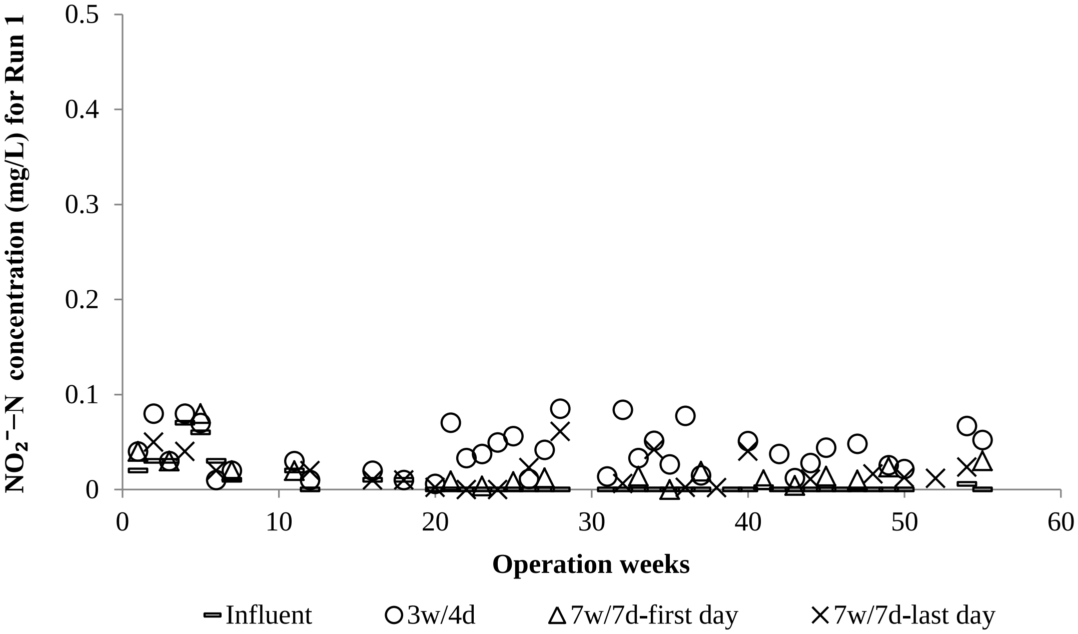

Figure 4.43 Changes of NO_2^-–N concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

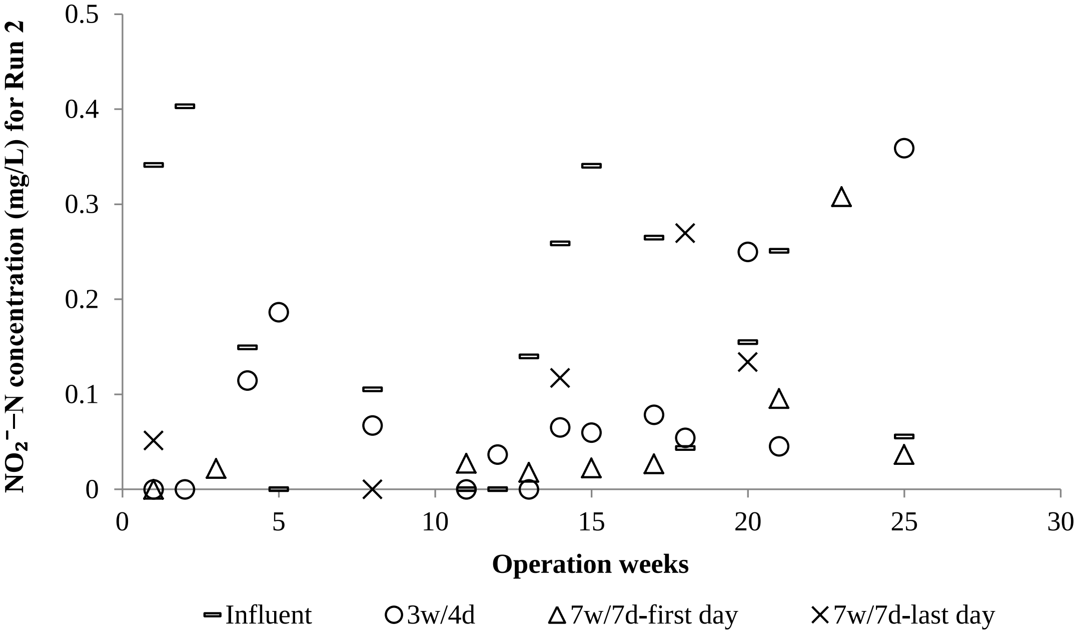

Figure 4.44 Changes of NO_2^-–N concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

Changes of average NO_3^-–N concentration through the columns operated with SSTWW and RSTWW are depicted in Figure 4.45 and Figure 4.46, respectively. It was observed that a slight increase up to 0.40 mg/L from the average NO_3^-–N concentrations occurred in the 7w/7d-last day cycle operation during Run 1 studies. However, the average NO_3^-–N concentrations were rapidly increased within the first 10 (to 1.56 mg/L) and 30 cm (to 3.86 mg/L) of the soil depth at the 7w/7d-first day and 3w/4d cycle operation, respectively. Thereafter, a rapid decrease was observed up to 0.17 and 0.40 mg/L for both the 7w/7d-first day and 3w/4d cycle operation, respectively. High DO concentrations in top layers of the soil resulted in an increase in the average NO_3^-–N concentrations within the first 10 and 30 cm of the soil depth at the 7w/7d-first day and 3w/4d cycle operation, respectively. As defined previously, oxygen concentrations in the soil increased more with shorter wetting and longer drying periods. As a result of this, the average NO_3^-–N concentrations increased more depending on high nitrification rate through high DO concentrations of the 3w/4d cycle operation. On the other hand, a decrease in both of them was observed, especially towards the last sampling ports. It is difficult to mention about the occurrence of a denitrification process since ammonium was not completely oxidized to nitrate and necessary negative redox values were not detected in the columns for denitrification to occur during the entire study. Hence, these reductions in NO_3^-–N concentrations could be attributed to other removal mechanisms such as adsorption via anion exchange as discussed by Rocca et al. (2007).

When two operating cycles were compared for the SSTWW, no major differences were observed at the end of the last sampling ports. However, more variable NO_3^-–N concentrations were observed at the end of the first days for each operation cycle, but as expected, the 7w/7d-last day cycle operation was more stable during Run 1 studies. The 3w/4d cycle operation demonstrated a significantly better performance than the 7w/7d cycle operation for nitrate removal. A rapid decrease was detected after 30 cm of soil depth at the 3w/4d cycle operation during Run 2 studies. In the first days of wetting periods, while the NO_3^-–N concentrations increased in the top layers of the soil by nitrification, nitrate was not detected in the lower depths where

Table 4.16 Variations of NO_3^-–N concentration with soil depth in the columns operated with SSTWW and RSTWW

	Nitrate-nitrogen concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	0.00	1.44	2.64	3.86	3.35	0.40	0.00	1.56	1.39	1.35	1.66	0.17	0.01	0.13	0.24	0.21	0.33	0.40
Minimum	0.00	0.11	0.15	0.10	0.02	0.03	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.02	0.00	0.00	0.03
Maximum	0.02	5.12	6.22	8.17	7.73	1.05	0.02	4.06	3.88	2.13	2.59	0.32	0.02	0.43	0.97	1.13	1.02	1.32
Standard deviation	0.01	1.20	1.87	2.37	1.85	0.31	0.01	1.35	1.07	0.64	0.78	0.08	0.01	0.13	0.25	0.30	0.33	0.58
10% percentile	0.00	0.37	0.37	0.46	0.79	0.07	0.00	0.20	0.41	0.60	0.74	0.08	0.00	0.01	0.08	0.01	0.01	0.03
50% percentile	0.00	1.15	2.84	4.04	3.31	0.25	0.00	1.35	1.04	1.26	1.92	0.16	0.00	0.07	0.16	0.09	0.16	0.04
90% percentile	0.02	2.92	5.02	6.92	5.56	0.79	0.01	3.56	2.81	2.08	2.38	0.25	0.02	0.33	0.46	0.47	0.73	1.13
	Nitrate-nitrogen concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	6.63	6.60	6.78	6.71	4.63	3.39	6.16	5.96	6.35	7.15	7.94	7.29	6.87	6.28	7.68	8.15	8.18	8.08
Minimum	4.69	4.66	4.40	4.11	0.91	0.63	5.09	4.25	5.00	5.97	6.51	1.87	4.69	3.26	3.79	5.33	6.41	6.34
Maximum	9.07	11.08	10.92	9.79	8.64	6.54	8.07	7.98	8.32	8.65	9.27	8.98	9.07	8.58	9.68	9.72	9.40	9.45
Standard deviation	1.54	2.22	1.99	1.83	2.55	1.99	1.26	1.36	1.32	1.15	1.09	2.70	1.93	2.73	2.64	1.94	1.36	1.58
10% percentile	5.01	5.06	4.69	4.42	1.28	0.66	5.20	4.69	5.00	5.98	6.84	4.79	4.86	4.01	5.21	6.32	6.66	6.76
50% percentile	6.65	5.47	6.44	6.56	4.81	3.59	5.39	5.65	6.21	7.22	7.58	8.23	7.08	7.00	8.63	8.78	8.80	8.44
90% percentile	8.35	9.42	9.01	8.86	8.23	5.18	7.89	7.56	7.83	8.54	9.22	8.84	8.80	8.26	9.39	9.48	9.33	9.25

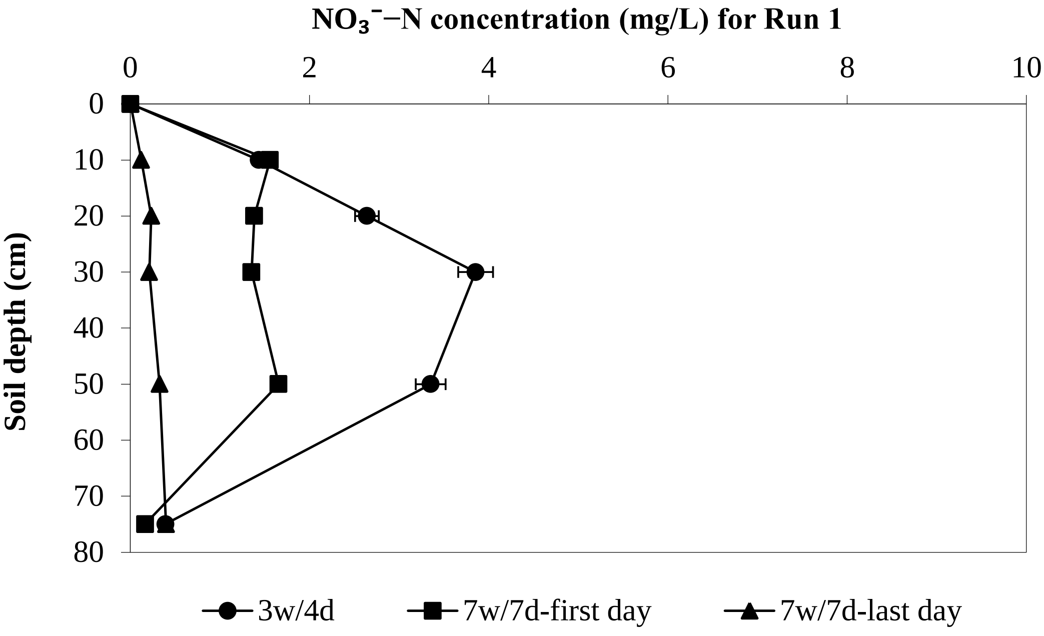

Figure 4.45 Changes of average NO_3^-–N concentration through the columns operated with SSTWW

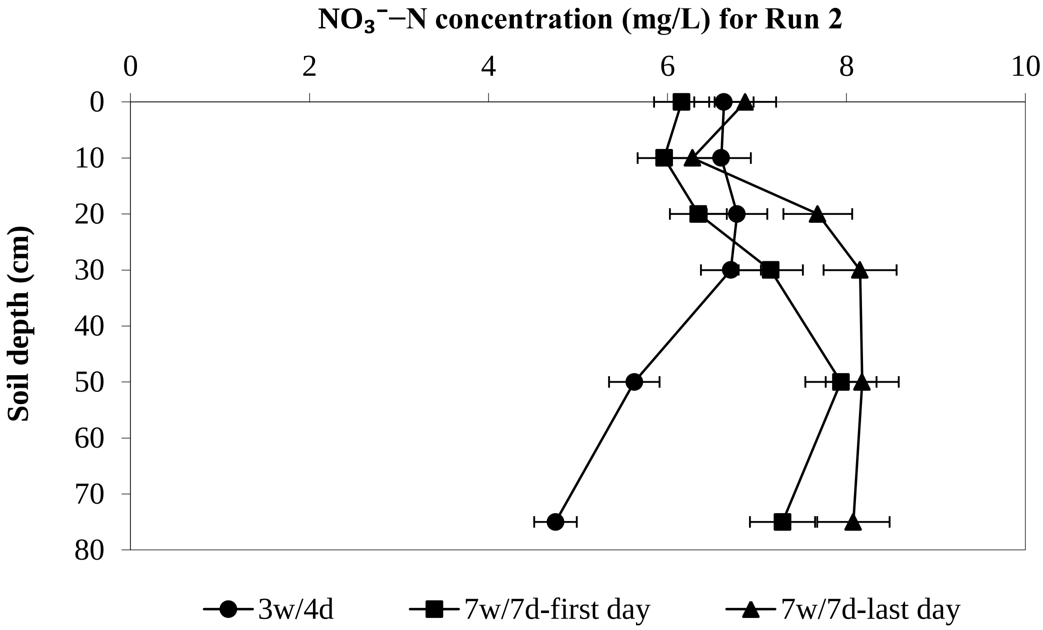

Figure 4.46 Changes of average NO_3^-–N concentration through the columns operated with RSTWW

there is not enough microorganism biomass. In addition, nitrate is known to be adsorbed via anion exchange mechanism on to the soil at the lower soil depths. Thereafter, this adsorbed nitrate was believed to be released by washing during the next wetting period.

Changes of NO_3^-–N concentration in the last sampling ports as a function of operation weeks are depicted in Figure 4.47 and 4.48 in the columns operated with SSTWW and RSTWW, respectively. Even though the influent total nitrogen were measured almost the same during both Run 1 and Run 2 studies, differences were observed in the concentrations between SSTWW and RSTWW. When two wastewaters were compered, higher NH_4^+–N concentrations were measured in the SSTWW and higher NO_2^-–N and NO_3^-–N concentrations were measured in the RSTWW. This situation was attributed to the fact that when the RSTWW samples were taken from the treatment plant, nitrification had already started.

4.1.16 Total Nitrogen Changes

Total–N concentrations were analyzed only in three sampling ports of each column due to limited total–N analysis kits. Variations of total–N concentration with soil depth in the columns operated with SSTWW and RSTWW in the three sampling ports of each column as well as the stock solution are given in Table 4.17. According to Table 4.17, total–N concentrations were measured in the range of 1.30–12.30 mg/L and 1.60–12.80 mg/L during Run 1 and Run 2 studies, respectively. Total–N concentrations were measured in almost the same range, but slightly differences in average concentrations were detected. Figure 4.49 and Figure 4.50 depict changes of average total–N concentration through the columns operated with SSTWW and RSTWW, respectively. Additionally, average total–N removal efficiencies through the columns operated with SSTWW and RSTWW are given in Figure 4.51 and Figure 4.52, respectively.

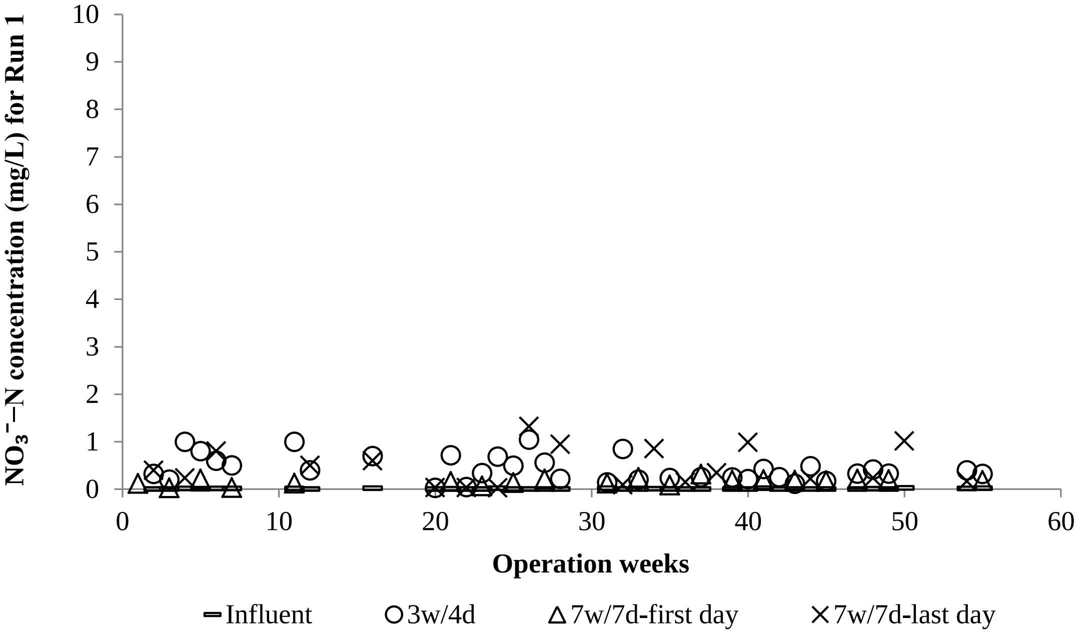

Figure 4.47 Changes of NO_3^-–N concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

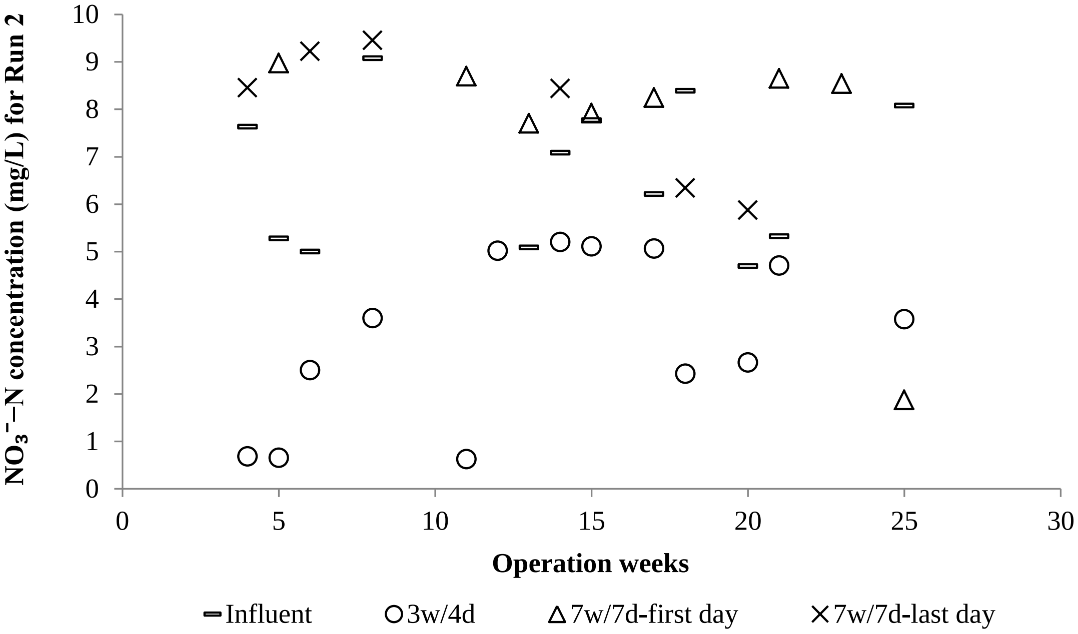

Figure 4.48 Changes of NO_3^-–N concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

While NH_4^+–N, NO_2^-–N and NO_3^-–N concentrations fluctuated through all columns operated with both SSTWW and RSTWW during Run 1 and Run 2 studies, they typically showed a uniform decreasing trend. Average total–N concentrations significantly decreased through the columns operated with both SSTWW and RSTWW. The results revealed that average total–N removal efficiencies increased along the columns operated with both SSTWW and RSTWW and demonstrated a gradual increase through the columns. While starting from about 12.0 mg/L, average total–N concentration decreased to about 2.6 mg/L through the columns operated with SSTWW, decreasing of average total–N concentration through the columns operated with RSTWW was observed from about 10.1 to 3.4 mg/L. The changes in average total–N concentrations and removal rates through the columns demonstrated a similar pattern during Run 1 and Run 2 studies.

Table 4.18 reports variations of total–N removal efficiencies with soil depth in the columns operated with SSTWW and RSTWW at the three sampling ports of each column. It was depicted in Table 4.18 that the average total–N removals in the last sampling ports were observed in the range of 43.80–89.26% and 25.81–83.02% during Run 1 and Run 2 studies, respectively. In the columns operated with SSTWW, the average removal reached to 78.6% in the entire column. In the columns operated with RSTWW, average total–N removal also increased along the soil profile and about 67.0% removal was reached in the entire column. These results are consistent with findings by Idelovitch et al. (2003) and Thawale et al. (2006). When total–N removal efficiencies in two wastewater types were compared, it could be seen that the performance of the columns operated with SSTWW was better than the performance of the columns operated with RSTWW. This finding can be attributed to the presence of more complex organic nitrogen compounds in the RSTWW.

As revealed in Figure 4.51 and Figure 4.52, a uniform increase was observed in the average total–N removal efficiencies through the columns operated with both SSTWW and RSTWW, whereas most of the removal occurred in the top layers of the columns. Biodegradation was considered to be the main mechanism in the

Table 4.17 Variations of total–N concentration with soil depth in the columns operated with SSTWW and RSTWW

	Total nitrogen concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	11.95	–	9.14	–	6.75	4.42	11.95	–	8.86	–	5.81	4.36	11.95	–	6.44	–	4.09	2.56
Minimum	11.60	–	7.10	–	4.40	1.30	11.60	–	6.10	–	3.30	2.20	11.70	–	3.50	–	2.10	1.40
Maximum	12.30	–	10.90	–	8.80	6.80	12.20	–	10.80	–	7.00	5.90	12.30	–	8.20	–	5.60	3.80
Standart deviation	0.17	–	1.12	–	1.31	1.46	0.20	–	1.46	–	1.00	1.18	0.15	–	1.13	–	1.03	0.70
10% percentile	11.70	–	7.50	–	5.10	2.40	11.65	–	7.30	–	4.65	2.55	11.80	–	5.70	–	3.02	1.84
50% percentile	12.00	–	9.50	–	6.80	4.40	12.00	–	8.80	–	6.05	4.65	11.90	–	6.40	–	4.00	2.40
90% percentile	12.10	–	10.20	–	8.40	6.10	12.15	–	10.70	–	6.80	5.65	12.10	–	7.62	–	5.36	3.46
	Total nitrogen concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	10.14	–	7.78	–	5.84	3.43	10.08	–	8.99	–	7.37	5.50	10.14	–	9.00	–	7.73	5.83
Minimum	7.50	–	4.20	–	2.20	1.60	7.50	–	5.80	–	4.80	3.50	8.60	–	7.20	–	6.40	4.80
Maximum	12.80	–	11.40	–	8.90	4.60	12.80	–	11.90	–	8.90	6.90	11.20	–	10.10	–	9.00	6.60
Standart deviation	1.43	–	1.63	–	2.00	1.01	1.66	–	1.75	–	1.19	1.01	1.05	–	1.13	–	0.89	0.67
10% percentile	8.32	–	5.86	–	2.86	1.86	7.82	–	7.40	–	6.40	4.30	8.78	–	7.50	–	6.82	5.04
50% percentile	10.30	–	8.10	–	6.60	3.80	10.30	–	9.10	–	7.40	5.60	10.60	–	9.30	–	7.60	5.90
90% percentile	11.60	–	8.84	–	7.64	4.44	11.68	–	10.86	–	8.50	6.58	11.08	–	10.04	–	8.70	6.48

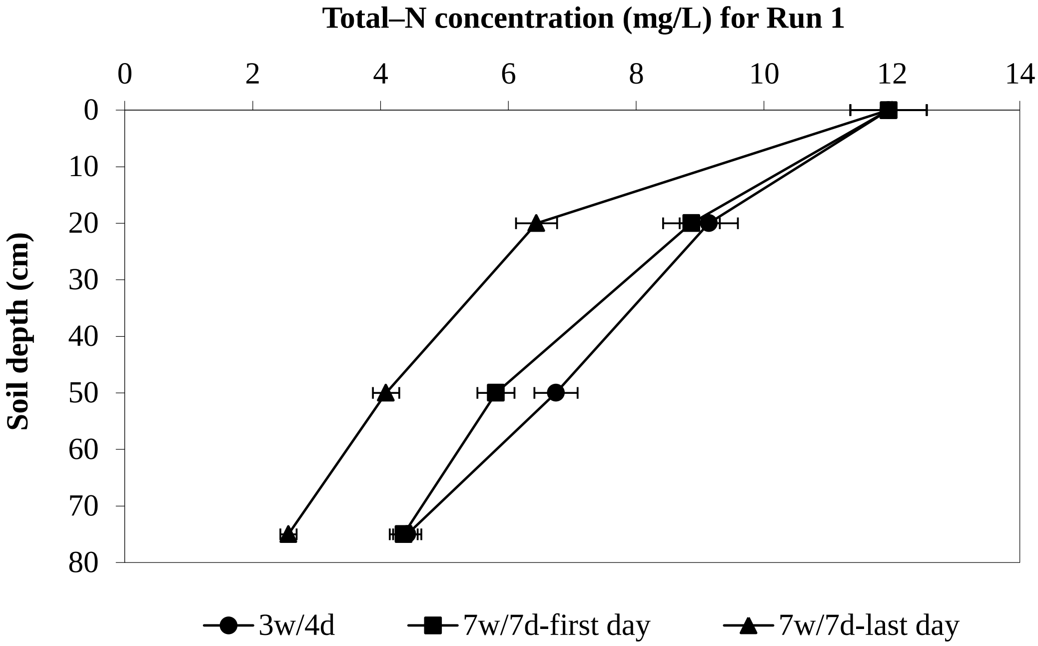

Figure 4.49 Changes of average total–N concentration through the columns operated with SSTWW

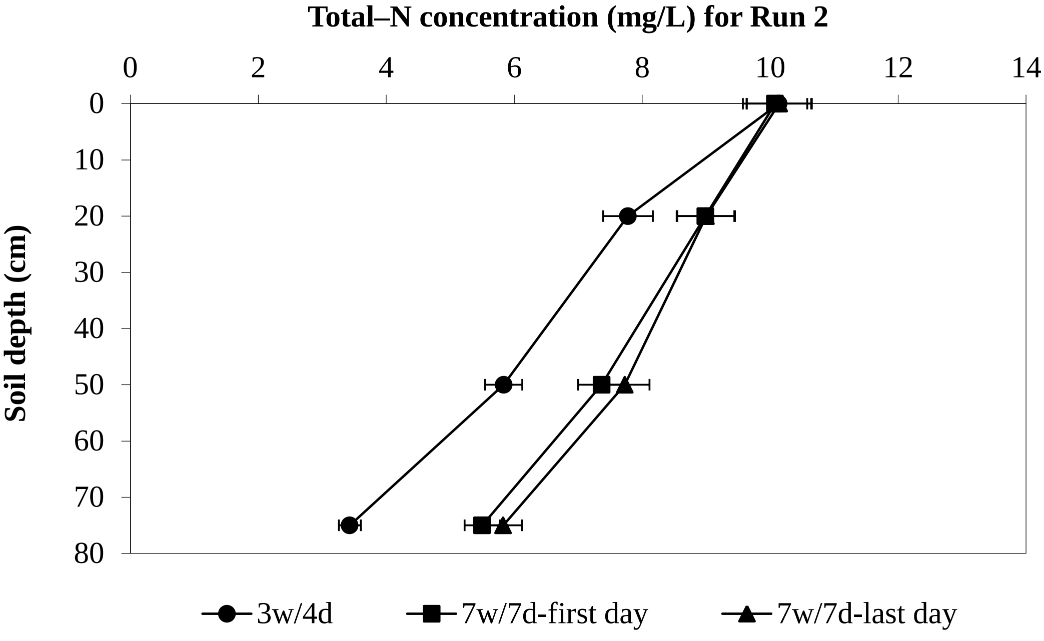

Figure 4.50 Changes of average total–N concentration through the columns operated with RSTWW

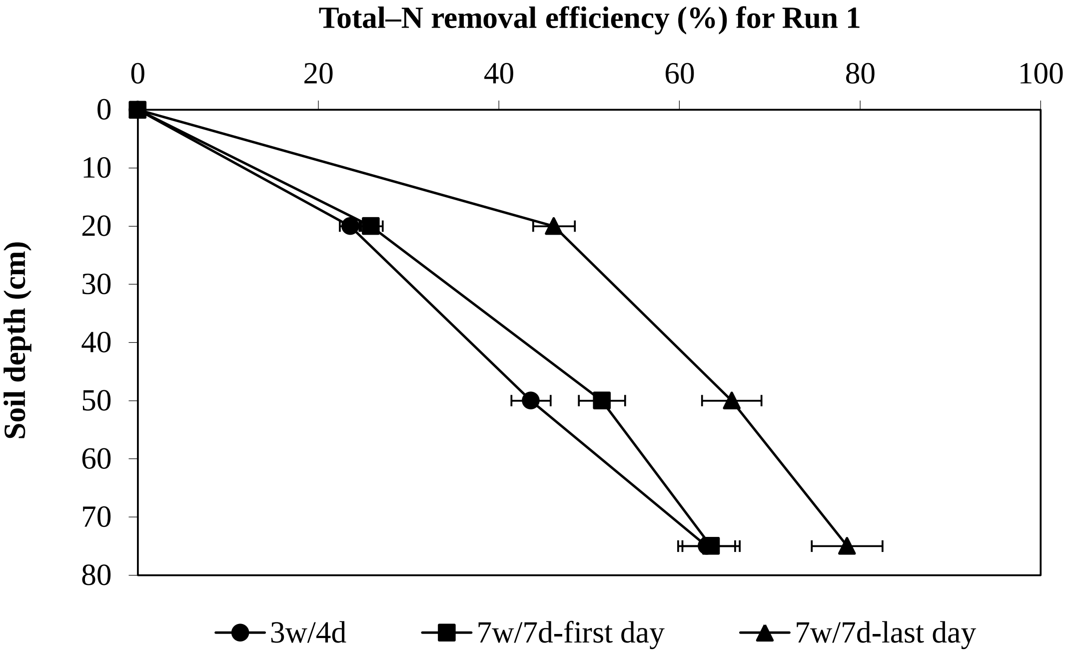

Figure 4.51 Average total–N removal efficiencies through the columns operated with SSTWW

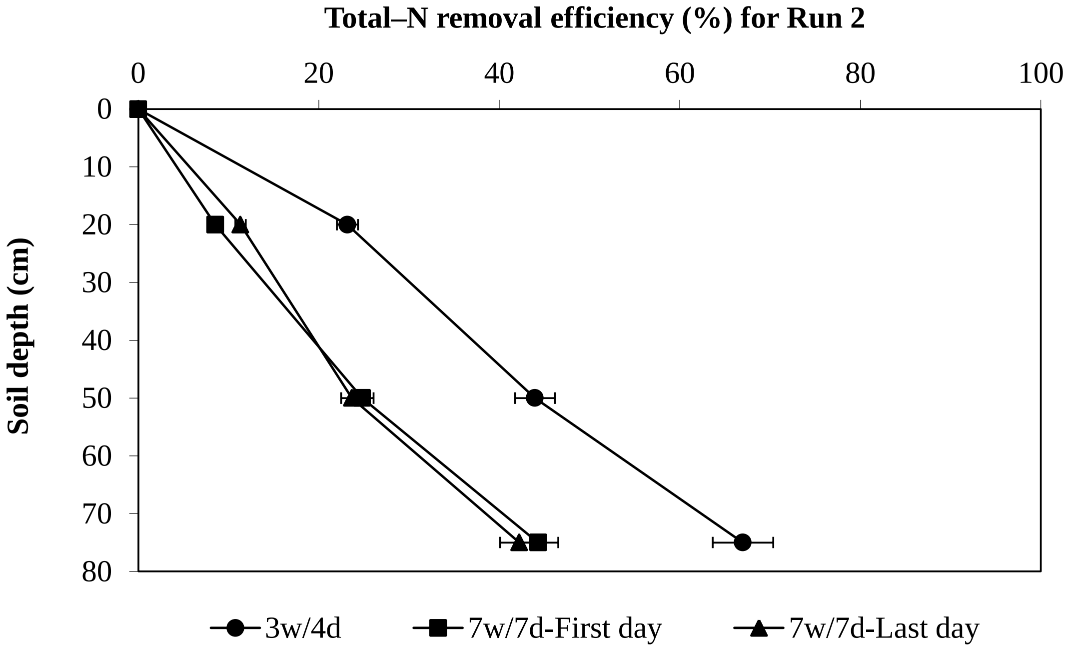

Figure 4.52 Average total–N removal efficiencies through the columns operated with RSTWW

removal of organic matters, yet it was clearly understood in Figure 4.51 and Figure 4.52 that this situation is not valid in the removal of total–N. As reported in previous studies total–N removal was mainly achieved by nitrification/denitrification processes, adsorption and filtration in SAT system (Gungor & Unlu, 2005; Idelovitch et al., 2003; Yun-zheng & Jian-long, 2006).

Metcalf & Eddy (1991) reported that DO concentration in wastewater must drop below 1 mg/L in order to initiate the denitrification process. Equation 4.4 depicts overall denitrification rate in wastewater (Metcalf & Eddy, 1991).

$$U'_{DN} = U_{DN} \times 1.09^{(T-20)} (1-DO) \qquad \text{Equation 4.4}$$

where U'_{DN} : overall denitrification rate

U_{DN} : specific denitrification rate

T : wastewater temperature, ºC

DO : dissolved oxygen in the wastewater, mg/L

As a result of Equation 4.4, denitrification did not occur during all Run 1 and Run 2 studies, since DO concentration never dropped below 1 mg/L. Additionally, ammonium was not completely oxidized to nitrate, and sufficiently low redox values were not detected for denitrification to start during the entire study. If residence time increases using longer wetting periods, DO concentration can drop below 1 mg/L required for denitrification. Consequently, findings indicated that the total–N removal mainly occurred by ammonium adsorption and filtration in this laboratory-scale SAT system.

It was observed that the two operational cycles demonstrated different total–N removal patterns during Run 1 and Run 2 studies. While the 3w/4d cycle operation performed better than the 7w/7d cycle operation for the RSTWW, the 7w/7d cycle operation performed better than the 3w/4d cycle operation for the SSTWW for the

Table 4.18 Variations of total–N removal efficiency with soil depth in the columns operated with SSTWW and RSTWW

	Total nitrogen removal efficiency (%) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	–	23.97	–	43.51	63.21	–	–	25.92	–	51.37	63.42	–	–	46.11	–	65.76	78.56
Minimum	–	–	8.40	–	24.79	43.80	–	–	10.00	–	41.88	49.14	–	–	30.51	–	52.54	68.60
Maximum	–	–	40.83	–	62.71	89.26	–	–	47.41	–	72.50	81.97	–	–	70.59	–	82.64	88.14
Standart deviation	–	–	9.28	–	11.22	12.48	–	–	11.59	–	8.55	10.06	–	–	9.38	–	8.73	5.89
10% percentile	–	–	14.00	–	30.14	47.80	–	–	11.93	–	42.86	52.69	–	–	36.50	–	55.20	70.68
50% percentile	–	–	21.31	–	42.86	63.93	–	–	25.15	–	49.79	61.24	–	–	45.30	–	66.67	79.83
90% percentile	–	–	36.99	–	57.13	80.07	–	–	39.41	–	61.57	78.83	–	–	51.94	–	75.10	84.75
	Total nitrogen removal efficiency (%) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	–	23.17	–	43.96	66.99	–	–	8.54	–	24.81	44.31	–	–	11.33	–	23.68	42.22
Minimum	–	–	2.20	–	16.48	49.44	–	–	1.27	–	10.13	25.81	–	–	5.10	–	15.12	34.69
Maximum	–	–	44.00	–	72.15	83.02	–	–	22.67	–	36.00	56.73	–	–	19.10	–	33.02	54.72
Standart deviation	–	–	13.17	–	18.96	9.19	–	–	7.19	–	10.24	11.98	–	–	5.44	–	5.96	6.80
10% percentile	–	–	8.76	–	19.76	54.54	–	–	1.80	–	10.50	27.79	–	–	5.44	–	16.96	36.12
50% percentile	–	–	24.11	–	42.20	65.79	–	–	7.03	–	28.85	48.62	–	–	10.47	–	24.11	40.00
90% percentile	–	–	42.70	–	69.23	77.71	–	–	16.22	–	33.12	54.69	–	–	17.55	–	30.06	50.28

removal of total–N. These differences can be illustrated by following the pathway of the each wastewater through the columns, since adsorption and filtration capacities may be affected by soil surface area during the percolation of wastewaters within columns.

Changes of total–N concentration in the last sampling ports as a function of operation weeks are depicted in Figure 4.53 and Figure 4.54 in the columns operated with SSTWW and RSTWW, respectively. Total–N concentrations through the columns operated with both SSTWW and RSTWW were always measured to be lower than influent concentrations. Although the initial total–N concentrations were measured in a wide range in the RSTWW, total–N removal efficiencies were observed to be relatively stable during both Run 1 and Run 2 studies and continued up to end of the both Run 1 and Run 2 studies without being affected by operation weeks.

4.1.17 Phosphate Phosphorus (PO_4^{-3}–P) Changes

Variations of PO_4^{-3}–P concentration with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column as well as the stock solution are depicted in Table 4.19. As reported in Table 4.19, the PO_4^{-3}–P concentrations were measured in the range of 0.00–2.40 mg/L and 0.00–3.33 mg/L during Run 1 and Run 2 studies, respectively. Although the maximum PO_4^{-3}–P concentration was obtained in the column operated with RSTWW, the average influent PO_4^{-3}–P concentration of RSTWW was lower than SSTWW. Figure 4.55 and Figure 4.56 depicts changes of the average PO_4^{-3}–P concentration through the columns operated with SSTWW and RSTWW, respectively.

Average PO_4^{-3}–P concentrations were significantly decreased through the columns operated with both SSTWW and RSTWW. Starting from about 1.9 and 0.8 mg/L average PO_4^{-3}–P concentration was almost completely removed through the columns operated with both SSTWW and RSTWW, respectively. Similar to the organic

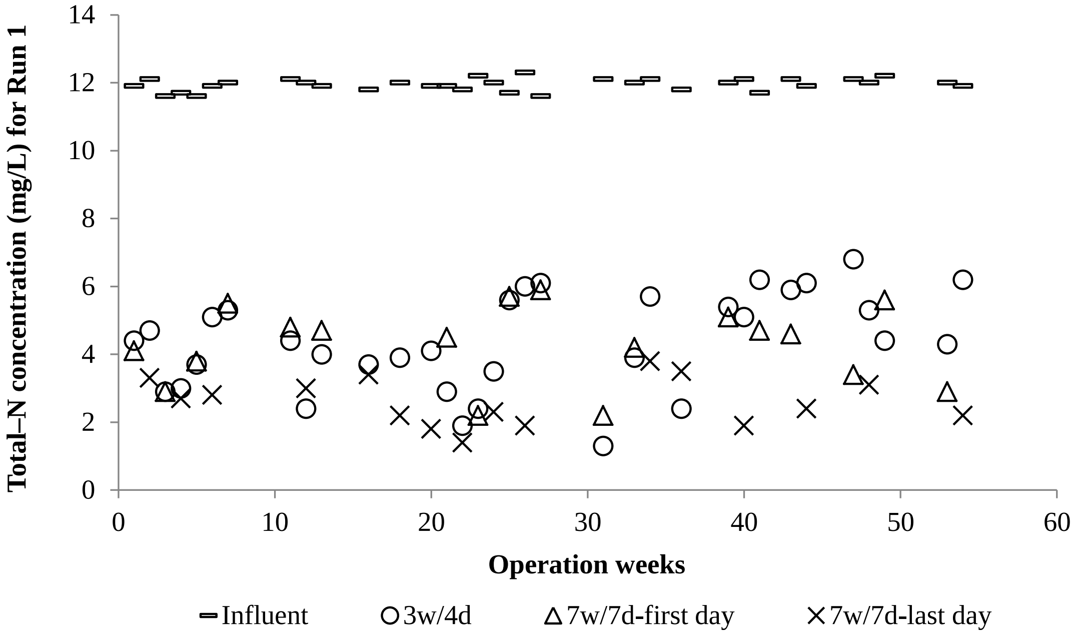

Figure 4.53 Changes of total–N concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

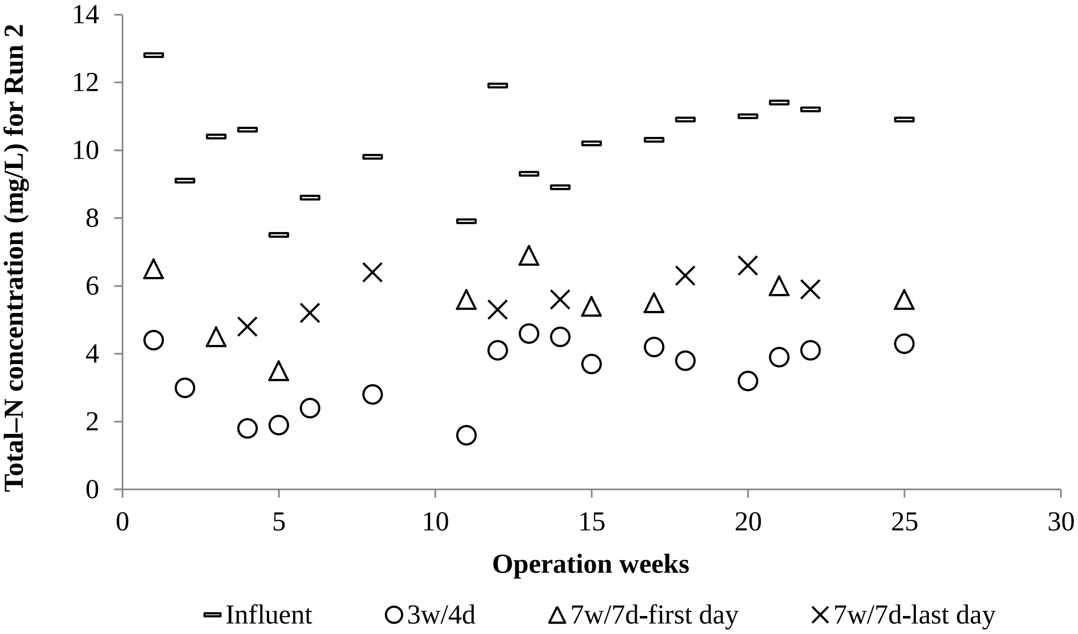

Figure 4.54 Changes of total–N concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

matter removal, the phosphate was significantly removed in the first 10 cm of the soil depth. Nevertheless, while the organic matter was removed by mostly biodegradation, the phosphate was removed by chemical precipitation and physical adsorption (Cha et al., 2006; Reemtsma et al., 2000). Consequently, phosphate primarily precipitated to the base of ponding and continued to be removed by precipitation in the soil pores and adsorbed on the soil surface.

Table 4.20 shows variations of PO_4^{-3}–P removal efficiencies with soil depth in the columns operated with SSTWW and RSTWW in the five sampling ports of each column. Additionally, average PO_4^{-3}–P removal efficiencies through the columns operated with SSTWW and RSTWW are given in Figure 4.57 and Figure 4.58, respectively.

The results demonstrated that average PO_4^{-3}–P removal efficiencies increased through the columns operated with both SSTWW and RSTWW and demonstrated a gradual increase thereafter. In the columns operated with SSTWW, the total average removal reached to 99.5% in the entire column. In the columns operated with RSTWW, PO_4^{-3}–P removal also increased along the soil profile and about 97.1% removal was reached in the entire column. These removal efficiencies are well supported by the findings reported by Cha et al. (2006), Idelovitch et al. (2003) and Zhang et al. (2007).

When PO_4^{-3}–P removal efficiencies in different wastewater types were compared, no notable differences were detected. Yet in the 7w/7d-last day cycle operation, PO_4^{-3}–P removal rapidly increased within the first 10 cm of the soil, since most of the phosphate was precipitated during 7 days ponding and then had a gradual increase thereafter. About average 74.4% removal was achieved in RSTWW experiments for 7w/7d-last day cycle operation within the top 10 cm.

When two operating cycles were compared for the each wastewater, it could be seen that 3w/4d cycle operation performed slightly better than the 7w/7d cycle operation in total removal for both SSTWW and RSTWW.

Table 4.19 Variations of PO_4^{-3}–P concentration with soil depth in the columns operated with SSTWW and RSTWW

	Phosphate-phosphorus concentrations (mg/L) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	1.82	1.11	0.97	0.80	0.71	0.01	1.89	1.18	1.06	0.93	0.68	0.12	1.84	1.28	1.12	0.96	0.56	0.16
Minimum	1.37	0.82	0.62	0.47	0.28	0.00	1.59	0.72	0.72	0.50	0.40	0.00	1.37	0.55	0.59	0.49	0.28	0.00
Maximum	2.40	1.79	1.53	1.29	1.17	0.04	2.17	1.80	1.77	1.65	1.16	0.40	2.40	2.16	1.93	1.71	0.92	0.40
Standard deviation	0.26	0.20	0.19	0.17	0.17	0.01	0.18	0.32	0.25	0.24	0.19	0.17	0.32	0.45	0.31	0.27	0.19	0.19
10% percentile	1.51	0.89	0.76	0.59	0.53	0.00	1.63	0.85	0.73	0.67	0.47	0.00	1.39	0.84	0.81	0.66	0.29	0.00
50% percentile	1.88	1.10	0.97	0.78	0.74	0.00	1.94	1.11	1.09	0.90	0.67	0.01	1.91	1.21	1.10	0.95	0.59	0.01
90% percentile	2.08	1.31	1.19	0.99	0.91	0.02	2.06	1.70	1.30	1.12	0.92	0.37	2.21	1.82	1.44	1.25	0.73	0.40
	Phosphate-phosphorus concentrations (mg/L) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	0.73	0.51	0.29	0.25	0.21	0.01	0.78	0.39	0.37	0.32	0.20	0.04	0.73	0.14	0.12	0.08	0.04	0.01
Minimum	0.08	0.14	0.00	0.04	0.03	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.18	0.04	0.00	0.00	0.00	0.00
Maximum	3.33	0.75	0.69	0.75	0.72	0.06	3.33	0.82	0.80	0.77	0.53	0.17	1.95	0.34	0.32	0.21	0.12	0.03
Standard deviation	0.87	0.27	0.26	0.29	0.25	0.03	1.09	0.40	0.38	0.34	0.21	0.07	0.62	0.17	0.17	0.09	0.05	0.02
10% percentile	0.17	0.25	0.03	0.04	0.04	0.00	0.13	0.03	0.03	0.02	0.00	0.00	0.32	0.04	0.01	0.01	0.00	0.00
50% percentile	0.47	0.58	0.14	0.11	0.07	0.00	0.25	0.37	0.34	0.10	0.08	0.00	0.56	0.05	0.05	0.05	0.01	0.00
90% percentile	1.59	0.72	0.62	0.74	0.64	0.06	1.73	0.77	0.73	0.72	0.45	0.13	1.29	0.28	0.26	0.17	0.09	0.02

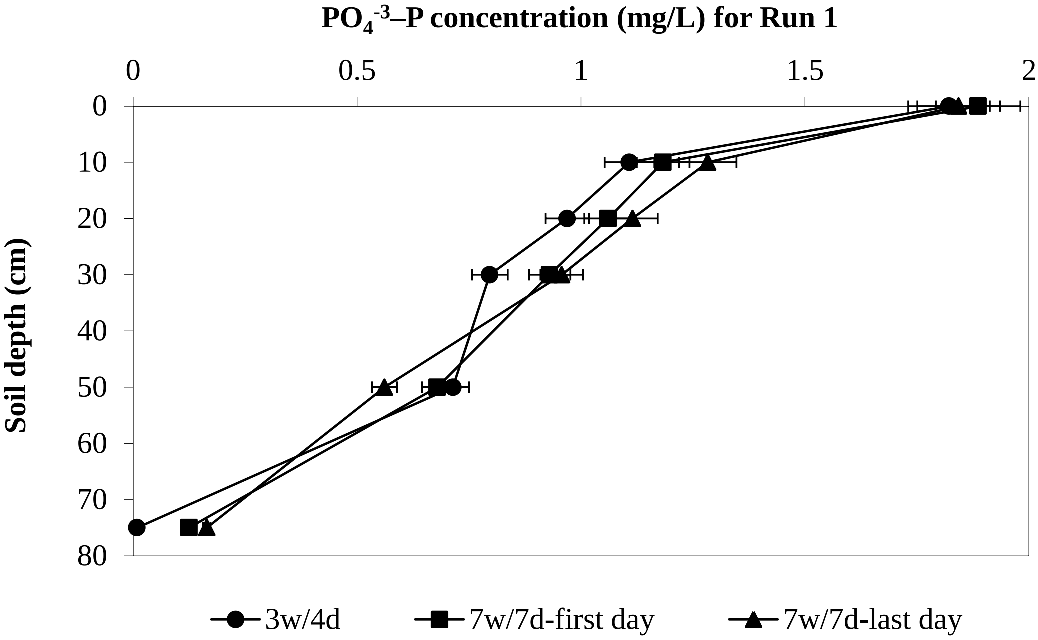

Figure 4.55 Changes of average PO_4^{-3}–P concentration through the columns operated with SSTWW

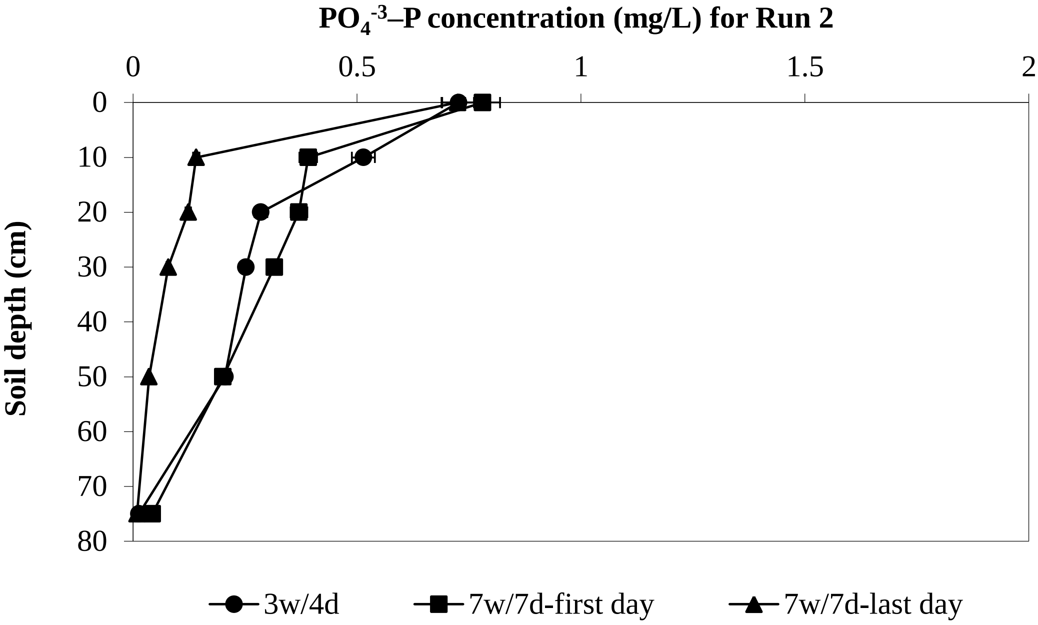

Figure 4.56 Changes of average PO_4^{-3}–P concentration through the columns operated with RSTWW

Changes of PO_4^{-3}–P concentration in the last sampling ports with operation weeks are depicted in Figure 4.59 and Figure 4.60 in the columns operated with SSTWW and RSTWW, respectively. PO_4^{-3}–P concentrations through the columns operated with both SSTWW and RSTWW were always measured to be lower than influent concentrations. The PO_4^{-3}–P removal efficiencies were observed relatively stable during both Run 1 and Run 2 studies and was continued up to end of the both Run 1 and Run 2 studies without being affected by operation weeks. Findings indicated that no phosphate accumulation by precipitation and exhausting adsorption capacity were experienced during 55 and 25 weeks operation in Run 1 and Run 2 studies, respectively.

4.1.18 Analysis of the Column Operated with Distilled Water after the Studies

The 7w/7d cycle column was also operated with distilled water for three cycles in order to determine the accumulated contaminants in the soil pores and on the soil surface after finishing Run 2 studies. Washing the column with distilled water started about one month later after Run 2 studies was ceased, and was also operated as 7 days wetting 7 days drying, again. Table 4.21 depicts the effluent values of analyzed parameters for each sampling port in the columns operated with distilled water after the studies.

While the salinity, EC and TDS values were increased through the column, DO and ORP values were decreased during three cycles, as expected. When both operations with distilled water before and after the studies are compared, it is clearly seen that the salinity, EC and TDS values were tremendously higher initially and decreased rapidly as time passed. Salinity, EC and TDS values were extremely higher in RSTWW than their corresponding values coming from the soil matrix (Table 4.2 and Table 4.21). High dissolved solids cause to high salinity, EC and TDS as they all depend on each other. High dissolved solids in the RSTWW were accumulated in the soil pores and on the soil surface, and then released during three cycles of washing operation. The salinity, EC and TDS values obtained from

Table 4.20 Variations of PO_4^{-3}–P removal efficiency with soil depth in the columns operated with SSTWW and RSTWW

	Phosphate-phosphorus removal efficiency (%) in the columns operated with sythetic wastewater (Run 1)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	38.71	46.28	55.89	60.38	99.49	–	37.58	43.56	50.32	63.88	93.70	–	34.21	42.63	50.59	71.18	92.00
Minimum	–	18.15	26.35	39.42	42.27	97.57	–	10.00	9.46	15.73	40.89	78.95	–	10.31	19.59	28.84	52.10	80.00
Maximum	–	58.05	68.11	73.04	82.63	100.00	–	58.66	63.44	76.19	79.95	100.00	–	72.39	70.56	75.36	86.18	100.00
Standart deviation	–	9.75	10.23	9.29	9.40	0.73	–	14.17	13.00	13.15	9.84	8.53	–	19.39	12.86	11.90	8.65	9.25
10% percentile	–	25.95	31.71	42.93	49.96	98.71	–	18.20	31.50	38.65	54.00	81.50	–	13.01	24.54	36.12	63.25	80.95
50% percentile	–	38.61	46.69	56.42	59.67	99.92	–	41.07	43.57	51.28	63.90	99.18	–	32.48	43.98	50.10	70.63	99.47
90% percentile	–	51.11	58.18	67.32	72.48	100.00	–	54.89	60.24	65.01	75.64	100.00	–	56.16	55.34	62.10	83.64	100.00
	Phosphate-phosphorus removal efficiency (%) in the columns operated with real wastewater (Run 2)																	
	3w/4d						**7w/7d-first day**						**7w/7d-last day**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Average	–	30.25	47.66	54.46	62.51	97.09	–	56.03	58.00	63.77	75.86	94.81	–	74.43	75.78	81.26	93.56	95.06
Minimum	–	12.37	4.08	24.26	24.53	75.48	–	7.59	9.78	22.45	54.17	83.91	–	35.20	39.06	59.24	79.19	85.17
Maximum	–	45.41	100.00	97.83	96.79	100.00	–	100.00	100.00	100.00	100.00	100.00	–	97.85	100.00	100.00	100.00	100.00
Standart deviation	–	13.86	33.38	29.51	26.95	8.12	–	41.85	40.43	25.85	18.83	7.44	–	34.18	32.34	16.89	8.71	8.56
10% percentile	–	17.12	11.18	24.69	26.64	93.76	–	17.99	20.00	37.95	59.13	86.39	–	46.21	48.91	65.53	83.01	88.14
50% percentile	–	31.60	39.65	43.47	64.22	100.00	–	38.99	44.89	58.79	67.49	100.00	–	90.23	88.29	82.89	97.68	100.00
90% percentile	–	42.29	95.49	86.71	93.10	100.00	–	100.00	100.00	91.19	100.00	100.00	–	96.33	97.66	95.67	100.00	100.00

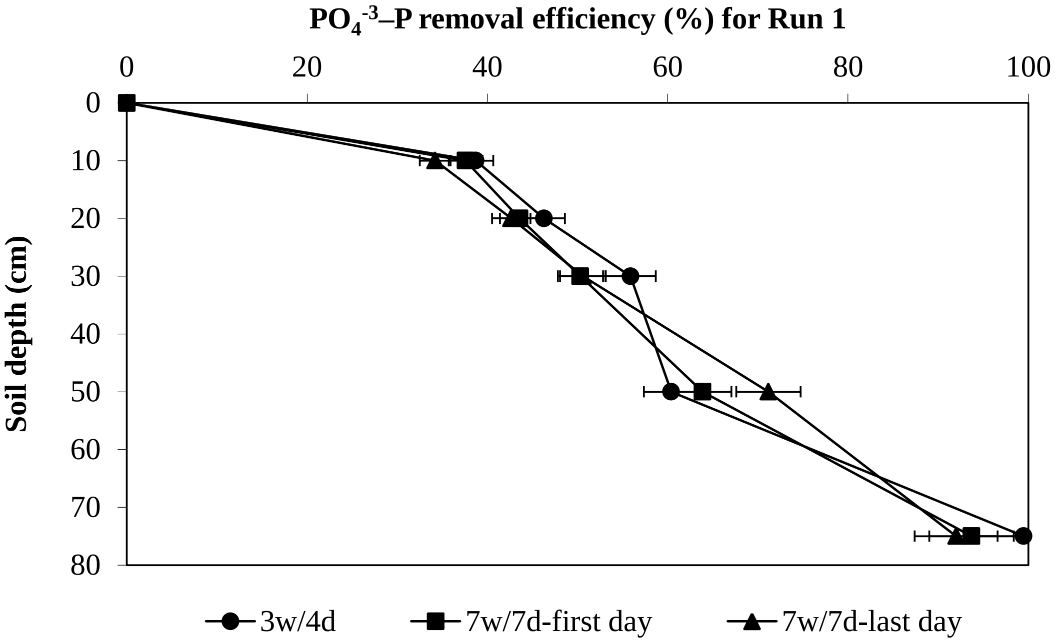

Figure 4.57 Average PO_4^{-3}–P removal efficiencies through the columns operated with SSTWW

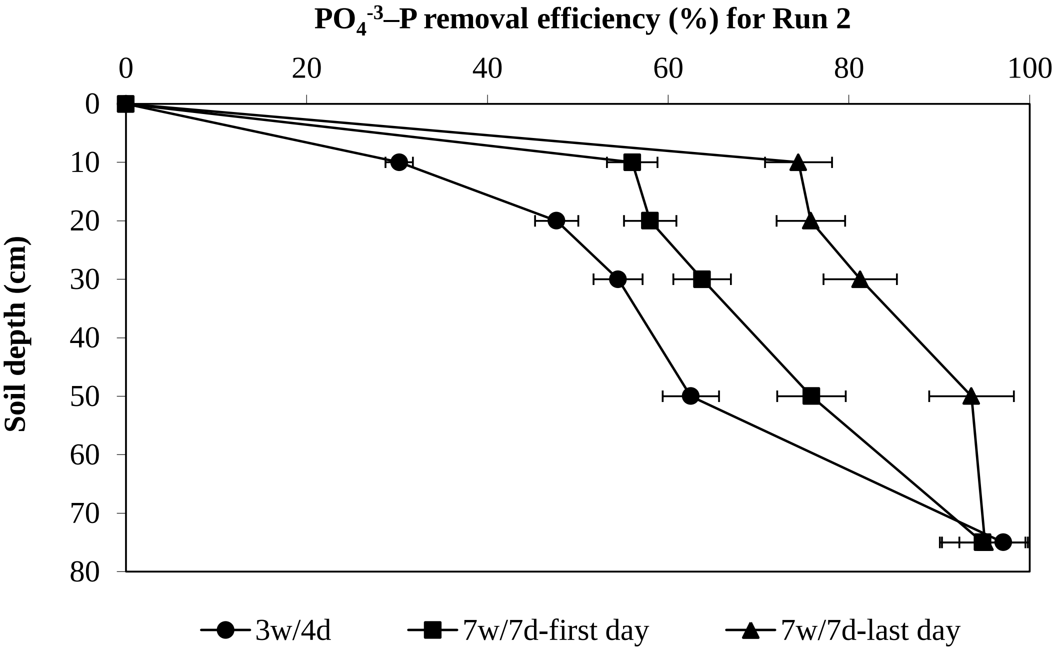

Figure 4.58 Average PO_4^{-3}–P removal efficiencies through the columns operated with RSTWW

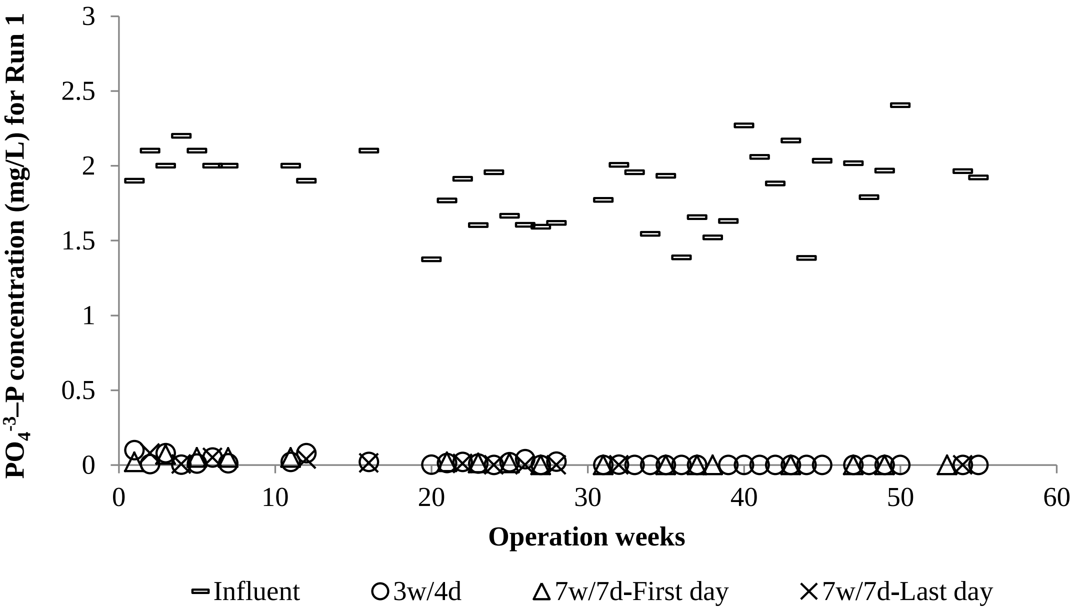

Figure 4.59 Changes of PO$_4^{-3}$–P concentration in the last sampling ports with operation weeks in the columns operated with SSTWW

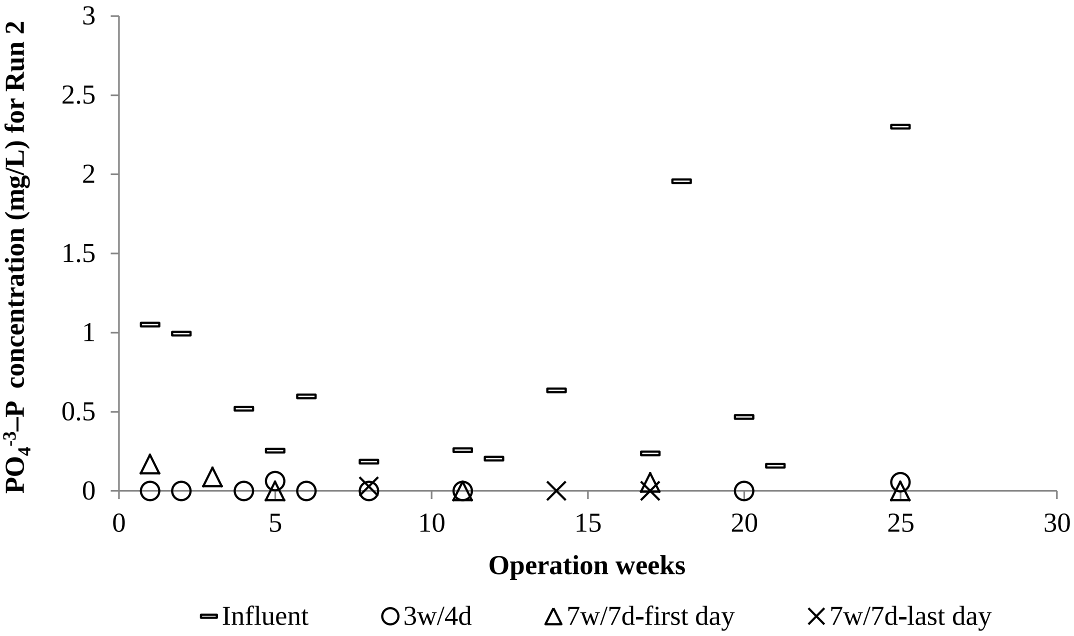

Figure 4.60 Changes of PO$_4^{-3}$–P concentration in the last sampling ports with operation weeks in the columns operated with RSTWW

washing operations before and after the studies approached to each other at the end of the three cycles.

TOC and COD concentrations reflected that organic matter increased through the column similar to the column operated with distilled water before the studies. After finishing three cycles of washing period, TOC and COD concentrations were decreased until almost the same levels as obtained from the soil matrix prior to the studies.

While the NH_4^+–N, NO_3^-–N, total–N and PO_4^{-3}–P concentrations increased through the column during three cycles of washing period, nitrite was not detected. NO_3^-–N concentrations decreased in the last sampling port with reference to prior sampling port during all washing period similar to the columns operated with SSTWW and RSTWW. Ammonium and nitrate adsorbed during the studies were released during three cycles washing period. Accumulated phosphate by chemical precipitation and physical adsorption was released during three cycles washing period, too.

The concentration of the all contaminants decreased relatively through the three cycles washing period. Although all contaminants removed by various mechanisms were released during three cycles of washing period, all contaminant concentrations at the end of the three cycles washing period were measured to be lower than the column operated with distilled water before the studies. These findings indicated that SAT systems could effectively be used in long term without any reduction in removal performance.

4.2 Analysis of the Columns Operated with Synthetic Heavy Metals

Run 3 studies were carried out in order to determine the behavior of heavy metals through the SAT system. Copper, lead and zinc were selected for experimental studies. For this purpose, four columns were operated with 3w/4d cycle to test the

Table 4.21 Effluent values of analyzed parameters for each sampling port in the column operated with distilled water after the studies

	Cycle 1						**Cycle 2**						**Cycle 3**					
Soil depth (cm)	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**	**Influent**	**10**	**20**	**30**	**50**	**75**
Temperature (℃)	-	23.68	23.67	23.33	23.70	23.71	-	25.98	24.96	24.94	24.93	24.88	-	24.62	24.85	24.62	24.74	24.59
pH	-	8.18	8.11	8.08	7.85	7.91	-	7.84	8.08	8.14	7.95	8.03	-	7.96	7.99	8.05	7.99	7.86
Salinity (PSU)	-	0.16	0.17	0.20	0.48	0.66	-	0.04	0.05	0.07	0.13	0.15	-	0.01	0.01	0.03	0.04	0.05
EC (µS/cm)	-	336.00	384.00	421.00	976.00	1252.00	-	88.00	112.00	148.00	266.00	322.00	-	34.00	38.00	63.00	80.00	106.00
TDS (mg/L)	-	168.00	192.00	211.00	488.00	627.00	-	44.00	56.00	74.00	133.00	161.00	-	17.00	19.00	31.00	39.00	53.00
ORP (mV)	-	260.00	252.00	243.10	216.30	197.00	-	193.00	181.60	160.90	158.70	157.60	-	221.00	206.00	185.00	179.00	163.00
DO (mg/L)	-	8.26	7.92	7.84	7.16	7.00	-	6.97	6.88	6.68	6.31	6.26	-	7.16	7.03	6.95	6.77	6.54
TOC (mg/L)	-	24.80	25.31	26.85	28.04	34.63	-	14.25	15.56	15.85	16.27	23.49	-	7.12	8.33	9.01	11.84	13.12
COD (mg/L)	-	50.61	54.81	60.49	63.33	74.52	-	31.77	33.13	35.81	39.65	49.16	-	16.94	18.45	20.29	25.13	29.81
Ammonium-N (mg/L)	-	0.10	0.11	0.14	0.28	1.24	-	0.35	0.43	0.49	0.57	0.73	-	0.05	0.06	0.08	0.13	0.54
Nitrite-N (mg/L)	-	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00	-	0.00	0.00	0.00	0.00	0.00
Nitrate-N (mg/L)	-	0.42	0.98	1.59	4.02	2.41	-	0.16	0.32	0.92	1.54	0.59	-	0.06	0.10	0.28	0.90	0.38
Total-N (mg/L)	-	-	4.90	-	5.50	6.70	-	-	2.10	-	3.10	3.40	-	-	0.70	-	1.70	3.00
Phosphate-P (mg/L)	-	0.00	0.17	0.21	0.20	0.33	-	0.04	0.06	0.15	0.18	0.28	-	0.00	0.06	0.08	0.16	0.19

removal of some selected parameters. One column was operated for four weeks with deionized water in order to determine the background metal contamination originating from the soil and average results are given in Figure 4.61 and Table 4.22. The other three columns were operated with single synthetic heavy metal solutions of copper, lead and zinc. Each column was operated for 21 weeks with 3w/4d cycle and samples were taken at the end of the first wetting day.

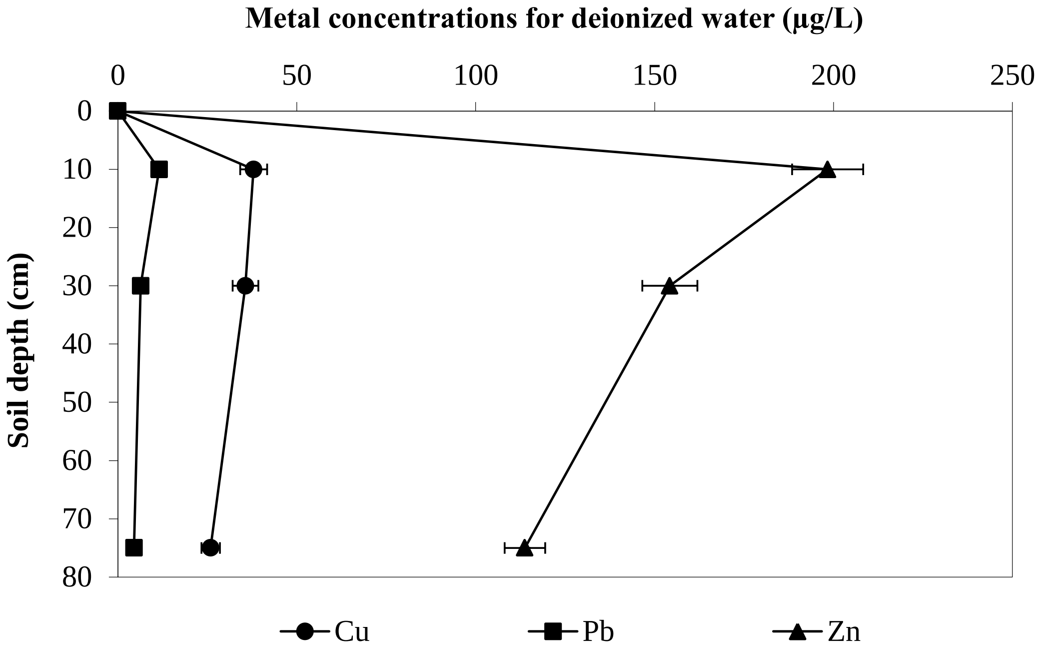

Figure 4.61 Changes of average metal concentration in the column operated with deionized water

The average concentrations of selected single metals rapidly increased within the first 10 cm of the soil and then had a gradual decrease thereafter through the columns operated with both deionized water and synthetic single metal solutions. Figure 4.62 depicts changes of average Cu, Pb and Zn concentrations through the columns operated with single heavy metal solutions. It was clearly seen that the two graphics (Figure 4.61 and Figure 4.62) revealed a similar pattern through the columns. Table 4.23 reports variations of single metal concentrations with soil depth. As reported in Table 4.23, the heavy metal concentrations demonstrated a wide range (especially zinc), since concentrations of soluble metal from the soil were variable depending on pH and contact surface area between soil and water.

Table 4.22 Average metal concentrations in the column operated with deionized water

Soil depth (cm) Parameters	**10**	**30**	**75**
Cu (µg/L)	37.93	35.64	25.90
Pb (µg/L)	9.01	6.37	4.50
Zn (µg/L)	163.87	156.75	113.73

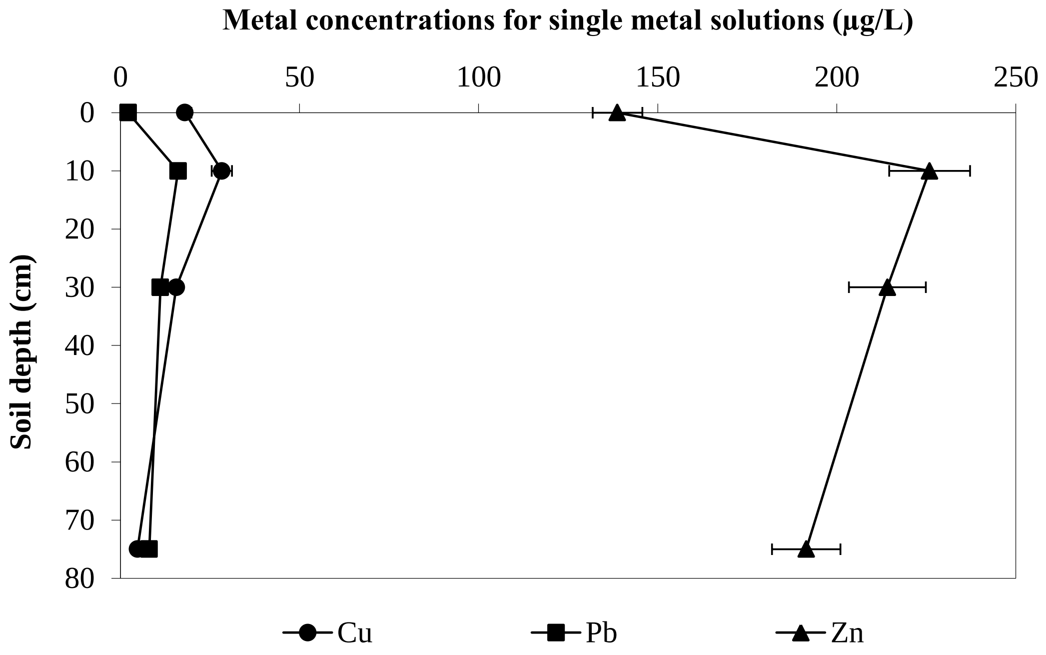

Figure 4.62 Changes of average Cu, Pb and Zn concentrations through the columns operated with single metal solutions

Copper, lead and zinc concentrations in the soil were reported as 28.6, 14.3 and 55 mg/kg in Table 3.4, respectively. These concentrations are generally lower than metal concentrations in urban soils reported by Marjanovic et al. (2009) and almost same metal concentrations in agricultural soil reported by Mico et al. (2006).

While single heavy metal solutions were prepared, deionized water was used in order to dilute to concentrate metal solutions. When deionized water comes into contact with atmospheric carbon dioxide, carbonic acid reduces the pH of water to as little as 5.5 through dissolving of carbon dioxide in the water (Sandhyarani, 2011). As a result of this, all influent metal solutions and deionized water used in this study were slightly acidic. Due to the fact that solubility of metals in water increases with decreasing pH, concentrations of copper, lead and zinc metals used in this study were also increased in the first 10 cm of soil by releasing of metals in the soil matrix in the columns operated with both deionized water and synthetic single heavy metal solutions. Figure 4.63 depicts changes of average pH values through the columns operated with deionized water and single heavy metal solutions.

The solubility products (K_{sp}) of Cu^{+2}, Pb^{+2} and Zn^{+2} with OH^- anions were given in Equations 4.5, 4.6 and 4.7.

$$Cu(OH)_2 \leftrightarrows Cu^{+2} + OH^- \Longrightarrow K_{sp} = 4.8x10^{-20} \qquad \text{Equation 4.5}$$

$$Pb(OH)_2 \leftrightarrows Pb^{+2} + OH^- \Longrightarrow K_{sp} = 1.43x10^{-20} \qquad \text{Equation 4.6}$$

$$Zn(OH)_2 \leftrightarrows Zn^{+2} + OH^- \Longrightarrow K_{sp} = 3x10^{-17} \qquad \text{Equation 4.7}$$

According to these solubility product values and the average metal concentrations in the solution (Table 4.23), the pH values that metals start to precipitate (as hydroxides) are calculated to be 7.62, 8.07 and 8.57 for Cu^{+2}, Pb^{+2} and Zn^{+2}, respectively. Owing to the fact that most pH values through the columns were measured to be below these values, metals stayed in the solution and did not precipitate through the columns. The reason for the rapid increase in the feed solution’s pH was related to contact with soil. The weakly alkaline soil present in the columns (Table 3.2) created a rapid increase in solution pH in the top layer of the columns (Figures 4.63) but this increase was not sufficient to reach the pH level necessary to start metal precipitation. Hence, pH values in liquid samples were always measured to be in the range of a weakly alkaline solution through columns during all Run 3 studies. Only at the last sampling port, pH levels were slightly above 7.62 for Cu^{+2} ions, which might have precipitated at the end of the column.

Table 4.23 Variations of single metal concentrations with soil depth

	Cu (μg/L)				Pb (μg/L)				Zn (μg/L)			
Soil depth (cm)	**Influent**	**10**	**30**	**75**	**Influent**	**10**	**30**	**75**	**Influent**	**10**	**30**	**75**
Average	18.00	28.32	15.59	4.74	2.16	16.09	11.15	8.03	138.77	225.91	214.15	191.49
Minimum	15.31	6.86	4.95	0.00	1.37	1.06	1.68	0.91	105.20	97.86	56.64	15.38
Maximum	21.58	43.40	25.41	10.13	3.61	29.46	24.10	32.20	163.90	455.20	418.66	415.00
Standard deviation	3.23	9.94	7.49	3.39	1.26	9.25	5.59	10.55	30.24	106.46	122.96	124.10
10% percentile	15.67	22.21	6.29	0.16	1.39	4.52	3.24	1.06	113.60	113.16	84.94	60.53
50% percentile	17.11	26.34	15.87	4.74	1.49	19.27	10.85	3.13	147.20	192.30	167.68	171.95
90% percentile	20.69	39.26	24.57	9.08	3.19	27.98	17.19	26.82	160.56	357.14	398.97	389.57

The decrease in metal concentrations in the first 10 cm of the soil can mainly be attributed to adsorption, carbonate precipitation and filtration. Heavy metals are adsorbed to the soil particles by either cation exchange or chemisorption (A.S. Sheoran & V. Sheoran, 2006). As a result of this, Cu^{+2}, Pb^{+2} and Zn^{+2} were adsorbed via cation exchange with mostly Ca^{+2} that originated from 6.0% $CaCO_3$ in soil matrix (Table 3.2) during Run 3 studies. Previous studies reported that the other cations (i.e., Mg^{+2}, Mn^{+2}, Na^{+}, Fe^{+3}, etc.) in soil matrix were also important in cation exchange (A.S. Sheoran & V. Sheoran, 2006; Hawari. & Mulligan, 2006; Lin et al., 2004; Woodberry et al., 2007). Furthermore, high bicarbonate concentrations of the wastewater facilitate carbonate precipitation of the heavy metal ion. Carbonate precipitation is a particularly effective removal mechanism for lead. Equation 4.8 depicts heavy metal precipitation with carbonate (Lin, 1995).

$$M^{2+}\left\{\begin{matrix} SO_4 \\ Cl_2 \end{matrix}\right. + Na_2CO_3 \rightarrow MCO_3 \downarrow + Na_2\left\{\begin{matrix} SO_4 \\ Cl_2 \end{matrix}\right.$$

Equation 4.8

where M represents the metal ion. Noller (1994) reported that lead and zinc could also be removed by filtration.

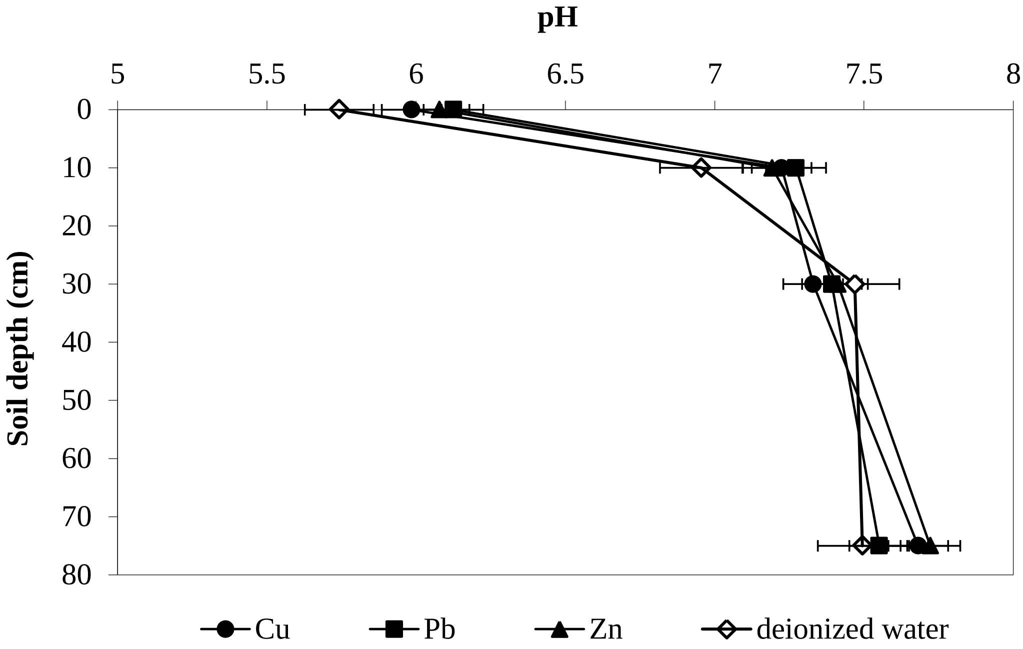

Figure 4.63 Changes of average pH through the columns operated with deionized water and single heavy metal solutions

Heavy metal concentrations generally decreased through the columns after 10 cm of the soil. While the average concentration of copper decreased from 18.0 to 4.7 μg/L (removed by 74%), a similar decrease was not observed in lead and zinc concentrations. The reason of this phenomenon is primarily related to lower pH levels of water and lower influent metal concentrations. The metal concentrations in the soil matrix were higher than the prepared synthetic metal solutions as the synthetic heavy metal concentrations were prepared based on the effluent metal concentrations of Cigli WWTP. If the column studies with selected metal ions were conducted with RSTWW, the pH of the influent would have been comparably more alkaline than the heavy metal solutions prepared by deionized water. Thus, the increase in metal concentrations in the top few centimeters of the columns would not have been observed in RSTWW. Even so, this study indicated that if SAT system would be used in order to remove organic matter and nutrient in RSTWW, SAT system and the soil would not be affected from heavy metal in wastewater since the heavy metal concentrations of the soil are much higher than the associated concentrations in the secondary treated wastewater. Hence, SAT operation in the current study will not negatively influence the soil quality from heavy metal point of view. On the contrary, heavy metal removal from RSTWW could occur by adsorption, cation exchange and filtration if appropriate pH levels are maintained in the effluent wastewater.

CHAPTER FIVE
CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The performance of a SAT system was investigated using a laboratory-scale experimental setup in different wastewater types. Although the soil columns of 120 cm were used in the all experimental studies, effective soil depth was 75 cm. All experimental studies were carried out using silt loam soil. Two different wastewater and two different wetting/drying cycles were used in order to determine of effect on SAT system performance. In order to determine the fate of dissolved solids, organic matters and nutrients, Run1 and Run 2 studies were carried out using SSTWW and RSTWW, respectively. In addition, the change of some selected heavy metals through the soil columns were studied during Run 3 studies.

During Run 1 and Run 2 studies, infiltration rates were periodically measured in both operational cycles. Average infiltration rate of the column operated as 3w/4d was higher than the 7w/7d column. Average infiltration rate during 3w/4d cycles and 7w/7d cycles were measured to be 34.4 and 28.3 cm/day respectively. Lower infiltration rates occurred at the end of the wetting periods owing to the fact that the soil became more saturated whereas higher infiltration rates occurred at the beginning of the wetting period. Additionally, infiltration rates for each operation cycle decreased through the end of the study because the soil became more compacted and clogged in time. For Run 1 cases, the infiltration rate for column operated as 3w/4d was measured between 28 and 45 cm/day whereas the infiltration rate for column operated as 7w/7d was in the range of 23-37 cm/day. Average hydraulic residence times during 3w/4d cycles and 7w/7d cycles were measured to be 2.18 and 2.65 day, respectively.

Since there is a relationship between salinity, EC and TDS, these parameters demonstrated a similar pattern through the columns operated with both SSTWW and RSTWW. However, while the salinity, EC and TDS values decreased through the columns operated with RSTWW, they increased through the columns operated with SSTWW as a result of dissolved materials originating from the soil media. Additionally, the salinity, EC and TDS values were considerably lower in SSTWW than in RSTWW because of seawater intrusion into the sewerage system. Dissolved solids were removed in the range of 16-26% in the RSTWW during this study. Consequently, if SAT system is to be applied in a field scale, certain level of dissolved solids removal could be achieved during the application.

DO and ORP values mostly decreased through the columns operated with both SSTWW and RSTWW. While the average DO and ORP dropped until about 4.3mg/L and 99.7 mV, respectively in the columns operated with SSTWW, they were detected to be higher in the columns operated with RSTWW. In essence, no anoxic or anaerobic conditions were observed during all experimental studies. As a result of this, denitrification required for nitrogen removal did not occur. If residence time was to increase using a longer wetting period, DO concentration could have dropped to anoxic levels.

TOC and COD concentrations decreased through the columns operated with both SSTWW and RSTWW. In the columns, organic matter removal rapidly increased within the first 10 cm of the soil and then had a gradual increase thereafter. It was observed that organic carbon removal essentially occurred within the first 10 cm of soil surface where more microbial biomass were present. The declining removal efficiencies along the columns were considered to be a general function of declining oxygen availability. Biochemically, the top 10 cm of the columns were more exposed to atmospheric oxygen that favored sharp removal of organic matter. As a result, most of the total microorganism growth was observed in the top 10 cm of the columns.

An average 55.4% TOC removal was achieved during Run 1 studies within the top 10 cm where exposure to atmospheric oxygen was more likely. The total average removal reached to 68.2% in the entire column during Run 1 studies. In the columns operated with RSTWW, TOC removal also increased along the soil profile where about 33.7% removal was achieved in the top 10 cm and 51.1% removal was reached in the entire column during Run 2 studies.

In the columns operated with SSTWW, an average of 51.6% COD removal was achieved in the top 10 cm and an average of 61.4% in the last sampling ports of the columns. Nevertheless, in the columns operated with RSTWW, average 32.5% COD removal efficiency was achieved in the top 10 cm and an average of 58.3% in the last sampling ports of the columns.

When organic matter removal efficiencies in different wastewater types were compared, it could be seen that the performance of the columns operated with SSTWW was better than the performance of the columns operated with RSTWW. In essence, easily biodegradable portion of organic matter was removed by microorganisms in the first 10 cm where oxygen levels peaked. Complex organic compounds that are likely to be found in RSTWW could thus be removed when longer residence times were achieved through the columns. On the other hand, when two operating cycles were compared for the each wastewater, it could be seen that 3w/4d cycle operation performed slightly better than the 7w/7d cycle operation for SSTWW and 7w/7d cycle operation is better than 3w/4d cycle operation for the RSTWW due to the fact that the longer residence times are required in order to remove complex organic compounds that are likely to be found in RSTWW by biodegradation. Findings indicated that biodegradation was the basic removal mechanisms for organic matter removal in this study. The results further demonstrated the fact that this SAT system could be used for long term removal of organic matter as the system maintained its removal capacity for a period of 55 weeks without any decrease in removal performance.

When the removal of nutrients in a SAT system is considered, a more complex case is observed. Removal of ammonium was achieved by a number of removal mechanisms including nitrification and adsorption. Owing to existence of oxygen through the columns, ammonium was oxidized to nitrate by microorganisms. In addition, because of the considerable cation exchange capacity of the soil used in experiments, the cation exchange was significantly responsible for the removal of ammonium in this study. When two operating cycles were compared for the each wastewater, it could be seen that 3w/4d cycle operation performed slightly better than the 7w/7d cycle operation for SSTWW and 7w/7d cycle operation is better than 3w/4d cycle operation for the RSTWW, similar to the performance of organic matter removal. The ammonium was rapidly oxidized to nitrite and then immediately to nitrate due to high dissolved oxygen concentrations through the columns. As a result of this, nitrite was mostly removed during the studies. Since nitrate is the last product of nitrification process, nitrate concentrations in the wastewater increased with decreasing ammonium concentrations. However, a slight decrease in the nitrate concentration was observed particularly at the end of the last sampling port (75 cm). In addition, it was detected that when nitrate concentrations were decreased, chloride concentrations increased. This observation was most likely attributed to ion exchange.

Nitrogen was removed by adsorption and filtration in this study as the conditions of denitrification did not occur due to short residence time in the columns. The average total–N removal efficiencies increased along the columns operated with both SSTWW and RSTWW and demonstrated a gradual increase through the columns. In the columns operated with SSTWW, the average removal reached to 78.6% in the entire column. In the columns operated with RSTWW, average total–N removal also increased along the soil profile and about 67.0% removal was reached in the entire column. When total–N removal efficiencies in two wastewater types were compared, it could be seen that the performance of the columns operated with SSTWW was better than the performance of the columns operated with RSTWW as in the case of organic matter removal performance.

Similar to the organic matter removal, the phosphate was significantly removed in first 10 cm of the soil depth. Nevertheless, while the organic matter was removed by mostly biodegradation, the phosphate was mostly removed by physicochemical processes such as precipitation. This finding can be illustrated by the fact that phosphate primarily precipitated to base of ponding and continued to be reduced by precipitation in the soil pores and adsorption on the soil surface. The results demonstrated that phosphate removal efficiencies increased through the columns operated with both SSTWW and RSTWW. In the columns operated with SSTWW, the total average removal reached to 99.5% in the entire column. In the columns operated with RSTWW, phosphate removal also increased along the soil profile and about 97.1% removal was reached in the entire column. When phosphate removal efficiencies in different wastewater types were compared, it could not be seen a notable differences. In addition, when two operating cycles were compared for the each wastewater, it could be seen that 3w/4d cycle operation performed slightly better than the 7w/7d cycle operation in total removal for both SSTWW and RSTWW. Findings indicated that phosphate accumulation by precipitation did not create any exhaustion in the adsorption capacity of the soil even at the end of the 55 weeks of operation.

In Run 3 studies, the single solutions of copper, lead and zinc were used in order to research changes of some selected heavy metals through the soil columns. Although the copper was removed up to 74% by mostly cation exchange and precipitation, no major removal values were obtained in lead and zinc concentrations. Reasons of this are; firstly, lower pH in synthetic metal solutions caused resolution of metals from the soil, and secondly considerably lower influent metal concentrations than the soil concentrations has resulted in resolution of the metals from the soil to the liquid matrix.

Finally, a SAT system that is based on infiltration of treated wastewater into soil is being considered to be one of the most important land treatment techniques that utilize the soil ecosystem to polish secondary treated wastewaters. Aerobic microbial activity within the top portions of the soil columns was the main removal mechanism in a SAT system. High removal efficiencies were achieved within the top layers where oxygen levels were the highest. Filtration, adsorption, ion exchange and precipitation were other effective mechanisms for polishing secondary treated wastewater in SAT system. When the experimental studies obtained in this study are concerned, SAT system could be considered to serve as an effective mean of polishing for secondary treated wastewaters and used in long term without any decreasing to removal performance. It also has the added benefit of recharging groundwater resources that are under stress due to anthropogenic and natural causes.

Although groundwater recharge with treated wastewater is currently prohibited in Turkey according to “Water Pollution Control Regulation”, SAT system can be used in the future as an economic way of wastewater treatment. Furthermore, increasing scarcity in water resources might force the law makers change the currently effective legislation and allow the use of secondary treated wastewaters for agricultural irrigation of non-edible products and artificial recharge of declining groundwater levels. In particular, this artificial recharge application of treated wastewater might help reduce the negative consequences of saltwater intrusion in coastal aquifer systems.

5.2 Recommendations for Future Research

Some of the recommendations for the future studies using the same laboratory-scale SAT system could be given as follows:

- The performance of the system can be investigated using different soil types.
- Wastewaters that have gone through different treatment levels can be used in order to determine the influence of influent wastewater quality on the performance of system.
- Longer wetting periods or longer column depths can be experimented in order to ensure of denitrification conditions to facilitate higher nitrogen removal.
- More detailed studies could be conducted to demonstrate the fate of heavy metals and their removal capacities with different soil types.

- Removal of endocrine disrupting chemicals (EDC) can be investigated under different operational conditions.

- Various plants can be grown up on soil surface in order to increase the contaminants removal (i.e., nitrate, metals, etc.) by uptake.

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