A MATHEMATICAL MODELING STUDY ON THE FEASIBILITY OF DISPOSING PARTIALLY TREATED DOMESTIC WASTEWATER USING SOIL PILE SYSTEMS

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Hatice Altınoklar

ABSTRACT

A MATHEMATICAL MODELING STUDY ON THE FEASIBILITY OF DISPOSING PARTIALLY TREATED DOMESTIC WASTEWATER USING SOIL PILE SYSTEMS

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The soil pile system (SPS) is a wastewater infiltration system used for secondary and tertiary treatment of wastewater. The purpose of this study is to perform a feasibility study to assess the applicability of SPS for treatment and safe disposal of domestic wastewaters, using a simplistic steady-state flow analytical modeling and a numerical transient unsaturated flow and transport modeling approaches. It is also aimed to develop guidelines for the design and operation of field scale SPS using the results of modeling studies.

The analytical modeling approach (AMA) was used to assess total coliform and chlorine attenuation efficiency in a SPS with clay loam soil. Analytical modeling results showed that SPS can treat wastewater in terms of total coliform and chlorine. Thus, in the light of findings of analytical modeling study, a pilot scale field study was conducted for the identifying the design and operational characteristics of a field scale system. Numerical modeling approach was used to evaluate the impact on contaminant removal of transient nature of wastewater infiltration and redistribution through clay loam soil pile. The results of numerical and analytical models were compared to assess the effect of flow regime on contaminant removal efficiencies. Results show that there is no significant difference between removal efficiencies achieved by numerical and analytical models. Whereupon, analytical model was used to assess behavior of SPS with different soil types, namely silt loam, loam, and sandy loam soils.

Model results indicated that SPS can be effective reducing chlorine and total coliform concentrations of wastewater below discharge standards. Results also indicated that SPS is highly sensitive to soil thickness, infiltration rate, soil bulk density and most importantly decay rate coefficients and the performance of SPS is dependent on the design, construction, operation characteristics and soil-environmental conditions of the system.

Keywords: domestic wastewater infiltration, total coliform, chlorine, soil pile system, analytical and numerical modeling

ÖZ

KISMEN ARITILMIŞ EVSEL ATIKSUYUN TOPRAK YIĞIN SİSTEMİ KULLANILARAK BERTARAF FİZİBİLİTESİ ÜZERİNE MATEMATİKSEL MODELLEME ÇALIŞMASI

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Toprak yığın sistemi, ikincil ve üçüncül atıksu arıtımında kullanılan bir atıksu infiltrasyon sistemidir. Bu çalışmanın amacı, basitleştirilmiş sabit akış analitik model ve değişken doymamış sayısal akış ve taşınım modeli yaklaşımları kullanarak toprak yığın sisteminin atıksu arıtımı ve bertarafında uygulanabilirliğinin değerlendirilmesidir. Aynı zamanda model sonuçlarını kullanarak, saha ölçekli toprak yığın sisteminin tasarım ve işletilmesi için kılavuz geliştirilmesidir.

Analitik model yaklaşımı killi topraktan oluşan toprak yığın sisteminde toplam koliform ve klor giderim hızlarını değerlendirmek için kullanılmıştır. Analitik model sonuçları, toprak yığın sisteminin toplam koliform ve klor giderimi açısından atıksuyun arıtımında uygulanabilir olduğunu göstermiştir. Analitik model çalışmasının bulguları ışığında, pilot ölçekli toprak yığın sisteminin tasarım ve işletim özelliklerinin belirlenmesi yoluna gidilmiştir. Sayısal model yaklaşımı, atıksu infiltrasyonu ve dağılımının killi topraktan oluşmuş toprak yığını içerisindeki değişkenlik özelliğinin, kirlilik giderimi üzerindeki etkisini değerlendirmek için kullanılmıştır. Akış rejiminin kirlilik giderim hızları üzerindeki etkisini değerlendirmek için sayısal ve analitik model sonuçları karşılaştırılmıştır. Sonuçlar, sayısal ve analitik model ile elde edilen giderim hızları arasında çok önemli bir fark olmadığını göstermiştir. Bunun üzerine, siltli tın, tın ve kumlu tın gibi farklı toprak tiplerinden oluşan toprak yığın sistemlerinin davranışlarını değerlendirmek için analitik modelleme yaklaşımı kullanılmıştır.

Model sonuçları, toprak yığın sisteminin atıksudaki toplam koliform ve klor konsantrasyonlarını, deşarj standartlarının altına indirmede etkili olabileceğini göstermiştir. Sonuçlar aynı zamanda toprak yığın sisteminin toprak kalınlığına, infiltrasyon hızına, toprak hacim ağırlığına ve en önemlisi giderim hız sabitine çok duyarlı olduğunu ve toprak yığın sisteminin performansının; toprak yığın sistemi tasarımı, inşaatı, işletim koşulları ve toprak-çevre koşullarına bağlı olduğunu göstermiştir.

Anahtar Kelimeler: evsel atıksu infiltrasyonu, koliform, klorin, toprak yığın sistemi, analitik ve sayısal modelleme

To my dear family….

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A	Cross-sectional area
AMS	Analytical Modeling Study
AWWA	American Water Works Association
BOD_5	5 day Biological Oxygen Demand
BTC	Baku Tiblisi Ceyhan
C	Effluent Concentration
C_0	Chemical Concentration in the Influent Wastewater Infiltrating Soil Pile
COD	Chemical Oxygen Demand
D	Dispersion Coefficient
DBPs	Disinfection By-products
DOC	Dissolved Organic Carbon
EC	Electrical Conductivity
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organization
h	Soil Water Pressure Head
k_b	First-order Decay Constant
K(h)	Hydraulic Conductivity Function
k_r	The Relative Permeability as a Function of Volumetric Water

	Content
K_s	Saturated Hydraulic Conductivity
L	Thickness of the Soil Pile
LDPE	Low Density Polyethylene
METU	Middle East Technical University
PWWTPs	Package Wastewater Treatment Plants
PVC	Poli Vinyl Chlorid
R	Retardation Factor
R^2	Regression Coefficient
Q	Volumetric Flow Rate
q_w	Net Infiltration Rate through the Soil Pile
R	Removal (Attenuation) Efficiency
S	Space and Time Dependent Volumetric Source/Sink Term
s	Adsorbed Concentration
SAT	Soil Aquifer Treatment
S_e	Reduced Water Content (Effective Fluid Saturation)
SMRC	Soil Moisture Retention Curve
SPS	Soil Pile System
SWISs	Subsurface Wastewater Infiltration Systems
t	Time
TPH	Total Petroleum Hydrocarbons
TOX	Total Organic Halide

THMs	Trihalomethanes
TSS	Total Suspended Solid
WC-DIF	Water Content Difference between Observed and Fitted Water Content
WC-FIT	Fitted Water Content
WC-OBS	Observed Water Content
X	Soil Depth Taken Positive Downwards
VOCs	Volatile Organic Compounds
z	Vertical Distance
θ	Soil Moisture Content
$\Delta h / \Delta l$	Hydraulic Gradient
$\theta(h)$	Soil Moisture Retention Function
θ_r	Residual Water Content
θ_s	Saturated Water Content
α , n, m	Empirical Constants Determining the Shape of the hydraulic Functions
ϕ	Soil Porosity
ε	Pore Size Distribution Parameter
v	Pore Water Velocity
μ	First-order Decay Coefficient
ρ	Soil Bulk Density
$q_0(t)$	Net Fluid Flux
$q_l(t)$	Imposed Net Drainage Flux

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Many natural soils and soil materials are well suited to the task of treating wastewater. Physical, chemical, and biological processes in soils work to remove nutrients, organic matter, disease-causing organisms, and odors from wastewater, to deliver clean water to the environment and for human use. The wastewater is treated as it passes through the soil by filtration, adsorption, ion exchange, precipitation, microbial action, and plant uptake. Success in wastewater treatment in turn depends on appropriate properties of the soil and site, and a good match between the system design and the opportunities and limitations of the site. A detailed assessment of a proposed site and soil resources is essential for design of a functioning wastewater treatment system, and its continued operation in the long term. Where soil and site conditions are favorable for treating wastewater through soil, a high degree of pollutant removal can be achieved by allowing partially-treated sewage effluent to infiltrate into the soil. The soil then acts as a natural filter and can remove essentially all suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms. Significant reductions in nitrogen, phosphorus, and heavy metals concentrations can also be achieved. In addition to treating wastewater, soil treatment systems provide an economic return from the reuse of wastewater (UNEP, 1997).

In the past several years, interest in land treatment of domestic wastewaters has increased. This increase arises from a widespread desire to conserve water by recycling. Another reason of increase in application of land treatment for domestic wastewater and different types of wastes from industrial practices is its remarkable advantages such as less energy requirement, reduced long term liabilities and low initial and operational costs compared to other alternatives (U.S. EPA, 1983). Also, it is thought that land disposal of wastewater would minimize water pollution problems attributed to the presence of large amounts of chemical constituents that can cause significant water quality deterioration in water-based disposal system. It is widely accepted that land application of domestic wastewaters is potentially an ecologically sound practice.

1.2 OVERVIEW OF SOIL PILE SYSTEM

Soil Pile System (SPS) is a small scale and moderately engineered version of soil based natural wastewater treatment systems such as soil aquifer treatment (SAT) and land treatment systems. A SPS can be defined as a wastewater infiltration system, which is a technology for secondary and tertiary treatment of wastewater and receives the effluent of partially treated wastewater and purifies it through biological, physical, and chemical reactions as it passes through the unsaturated soil. The SPS consists of the following components: a wastewater infiltration system, a soil treatment zone, a drainage system coupled with a surrounding lined drainage ditch, an impermeable bottom layer, and finally a lined treated wastewater collection pond. In SPS the wastewater is applied to re-packed natural soils uniformly across the soil surface. The wastewater is treated as it percolates through the soil matrix. Soil thickness, infiltration rate, soil bulk density and most importantly decay rate coefficients are very significant parameters for the design and operation of the SPS. Since first-order decay rates are controlled by soil environmental conditions such as soil temperature, water content, and pH, soil environmental conditions are also very important factors for contaminant attenuation in SPS. Soil type is also important for the removal of contaminants with SPS. Since wastewater passes too rapidly through the soil pile, coarse-textured soils are not ideal for SPS. There has not being very many reported applications on domestic wastewater infiltration through soil pile system. SPS is widely used in environmental engineering area for treatment of contaminated soils.

Biopiles are facilities that use the bioremediation process to economically cleanup of hydrocarbon-contaminated soils containing gasoline, diesel, and jet fuels. Under optimal soil conditions (non-compacted, sandy loam is ideal), indigenous microorganisms use dissolved organic compounds as a food source and convert them to carbon dioxide and water. There are two different types of systems – temporary and permanent. In the temporary system, the biopile is built on top of a clean soil layer over a liner and base. In the permanent system, the clean soil layer is replaced by a concrete pad. Temporary facility construction costs are less than permanent concrete facilities.

Physical structure of the biopiles is very similar to SPS. Biopile systems consist of an aeration system to provide oxygen to the microbes, an irrigation/nutrient injection system to provide nutrients and moisture after pile construction, and a leachate collection system for controlling excess moisture in the pile. A liner, berm, and cover protect the soil piles from storm events and prevent the spread of contaminants. The principle of the process is to activate soil microorganisms by supplying nutrients and oxygen to contaminated soil. The soils are dug up, transported and placed on a waterproof platform equipped with infrastructures which allow for forced aeration of the soil, capture and treatment of the leached water, and filtration of the contaminated air (peat and/or activated charcoal filters). Membranes cover the soil, thus isolating it from precipitation, reducing the spread of volatile organic compounds (VOCs) and minimizing heat loss (NFESC, 1996). Figure 1.1 shows conceptual drawing of the soil pile method of the bioremediation of the contaminated soil.

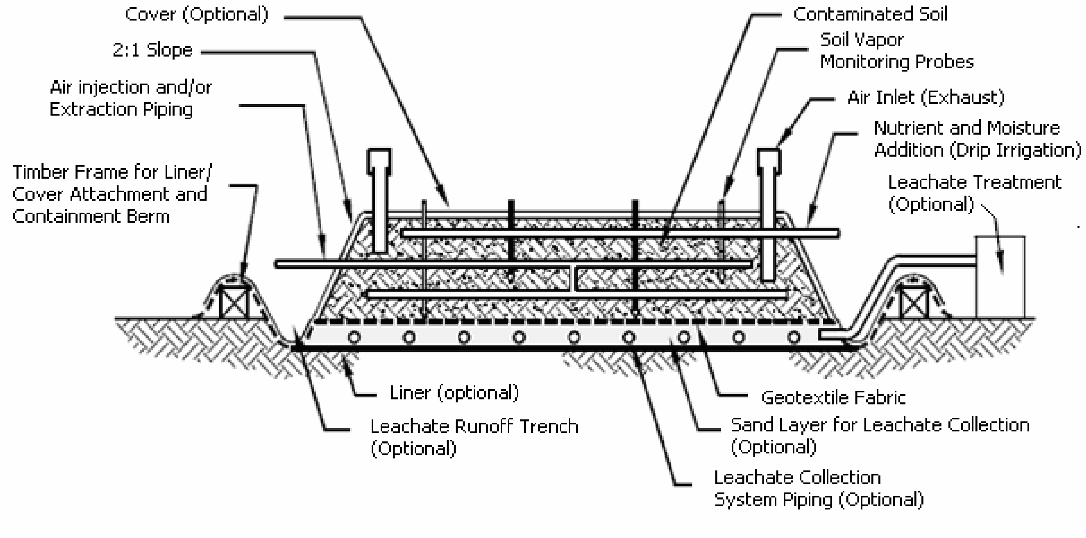

Figure 1.1 Conceptual drawing of the soil pile method

**Source: U.S. Environmental Protection Agency, Solid Waste and Emergency Response, 2004, How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers. (EPA 510-R-04-002).*

Soil environmental parameters play very important role for biopiles as it is also the case for SPS. Oxygen, water, nutrients, pH, temperature, and microbial population is essential components of the biopile systems. So soil characterization prior to remediation is required to maximize bioremediation efficiency. This characterization provides baseline values for total petroleum hydrocarbons (TPH), the indigenous population of microbes (including hydrocarbon degraders), nutrient levels, pH, porosity, and moisture content (NFESC, 1996).

Soil pile treatment of wastewater has the potential to achieve high purification efficiency. There are lots of studies on virus, nitrate and organic removal using wastewater infiltration systems especially Soil Aquifer Treatment (SAT) systems, which relies on unsaturated soil and the aquifer media for contaminant removal (Güngör, 2001; Quanrud et al., 2003; Cha et al., 2004; NCSWS, 2001; Icekson –Tel et al., 2003).

1.3 SCOPE AND OBJECTIVES

Baku Tiblisi Ceyhan Pipeline Company (BTC Co.) – Turkey Branch has developed camps at various locations along the pipeline to support the construction activities and to provide suitable living quarters for the workers. In the camps, package wastewater treatment plants have been installed to treat the produced wastewater to meet the discharge standards prescribed by regulations. Due to non-compliance of the discharge standards at some camp sites, it was anticipated that infiltration of partially treated wastewater through soil pile systems, constructed from soils available at the site, can be applicable to treatment and subsequent disposal of domestic wastewater.

The scope of this study includes performing simplistic analytical and numerical unsaturated flow and transport modeling study for infiltration of partially treated wastewater through soil pile systems, such systems are usually constructed for tertiary treatment of wastewater effluent prior to discharge. In order to meet the discharge standards in terms of effluent quality of chlorine and total coliform analytical and numerical model simulations were performed using available literature and site specific data. Coliform and Limited amount of measured effluent data were used for model calibration with respect to total coliform attenuation.

In a preceding study (Unlu, 2004) a simplistic analytical modeling approach was used to assess chlorine and total coliform attenuation in a SPS with clay loam soil. Analytical model has been developed based on available site data and literature information to assess contaminant attenuation efficiencies achievable by soil pile systems during steady infiltration of partially treated domestic wastewater produced at BTC Co. construction camp sites. Considering the lack of relevant information and the analytical nature of the developed model, the findings of analytical modeling study need to be taken with some caution. For example, steady-state assumption for water flow introduce some uncertainty in the model results; and achieving steady-state water flow conditions through soil pile may take very long time especially for thicker and finer textured, such as clay loam soil piles, which may pose operational problems due to low infiltration capability of soil pile, in turn reduce treatment capacity (infiltration volume) per day. Therefore, the transient nature of water infiltration and redistribution through soil piles need to be considered and its effects need to be investigated. For this purpose, use of numerical unsaturated flow and transport modeling approach was adopted.

Soil Moisture Characteristic Curves (SMRC) and hydraulic conductivity (Ks) of site soil were measured to run the numerical model. Results of numerical and analytical model were compared for clay loam soil pile in which transient flow conditions expected to be the most effective. A comparison of steady-state analytical and transient numerical model simulations considered to be necessary to identify the impact of wastewater flow regime through soil on total coliform and chlorine removal efficiencies.

In order to calibrate the model, a pilot scale SPS study was conducted for tertiary treatment of domestic wastewater using site soil and wastewater. Calibration was performed using data obtained from pilot study to determine site-specific coliform removal coefficients. Finally, calibrated analytical model was used to develop guidelines for design and operation of field scale SPS for different soil types.

The specific objectives of this study are:

1. to assess the performance of soil pile system with respect to chlorine and total coliform removal using analytical and numerical modeling approaches;
2. to compare the numerical and simplistic analytical modeling approaches, for the evaluation of the effect of flow regime on removal efficiencies of total coliform and chlorine; and
3. to develop guidelines for the design and operation of field scale soil pile systems having different soil types.

1.4 REMOVAL MECHANISMS OF COLIFORM AND CHLORINE IN SOIL

Wastewater analysis performed by BTC Company showed that chlorine and coliform most of the time exceeds project discharge standards. To meet the project discharge standards in terms of chlorine and total coliform, tertiary treatment of wastewater effluent using SPS was considered. Total coliform and chlorine effluent parameters were used as influent data during SPS application. Chlorine and total coliform were used to assess applicability of SPS for tertiary treatment of domestic wastewater due to data availability for calibration purposes. So, possible total coliform and chlorine removal processes occurred in soil has been discussed in this section.

1.4.1 Coliform Removal

Members of two bacteria groups, coliforms and fecal streptococci, are used as indicators of possible sewage contamination because they are commonly found in human and animal feces. Although they are generally not harmful themselves, they indicate the possible presence of pathogenic (disease-causing) bacteria, viruses, and protozoans that also live in human and animal digestive systems. The most commonly tested fecal bacteria indicators, which is used as an indicator organisms of wastewater treatment efficiency, are total coliforms, fecal coliforms, Escherichia coli, fecal streptococci, and enterococci (EPA 841-B-97-003, 1997). In this study, total coliform was used to assess movement of bacterial pollutants through soil pile system.

Soil wastewater infiltration systems readily remove biological particles (e.g., coliform, bacteria, protozoa, viruses). Coliform is removed by straining, adsorption, and biological processes in soil environment. Basic mechanisms responsible for pathogen removal are filtration and inactivation (i.e., die-off). Particle filtration involves both transport and attachment processes (Bales et al. 1993; Fontes et al. 1991). Straining occurs when the diameter of the pathogen is large relative to soil pore size. Consequently, straining is negligible for viruses, but is important for larger bacteria and protozoa (Lawrence A. Baker and Paul Westerhoff). The reduction in the density of the coliform bacteria above the restricting soil layers can probably be attributed to dilution, filtration, and die-off as the bacteria move through the natural soil systems (Reneau, Pettry, Shanholtz, Graham, and Weston, 1977).

Soil type and composition, pH, moisture content and virus strain all interact to affect the adsorptive capacity and virus die-off rate in soil (Goyal and Gerba 1979, Powelson et al. 1993). Clays have a much higher surface area than sand and adsorb more viruses (Schaub and Sorber 1977; Jin 1997).

Fine sands have been reported to remove pathogens faster, over a shorter distance, than coarse sand (0.56 mm) (Farooq and Al-Youssef 1993). Virus removal is also better in saturated soils than in unsaturated soils, possibly because flow velocities are lower and the liquid film thickness is smaller under unsaturated conditions (Powelson and Gerba 1994; Lance and Gerba 1984a, b). Organic matter readily sorbs to soil surfaces, decreasing pathogen attachment potential (Jin 1997; Jansons et al. 1989, Pieper et al. 1997; Johnson and Logan 1996). The presence of microbial biofilms, and the associated predation of pathogens, generally improves overall pathogen removal (Schaub et al. 1982; Hurst et al. 1980; Powelson et al. 1993; Weiss et al. 1995).

1.4.2 Chlorine Removal

Partially treated domestic wastewater produced in the construction camp sites is disinfected for the inactivation/destruction of pathogenic organisms. Chlorine, which is the most widely used disinfectant for municipal wastewater is used in the effluent of the PWWTPs. Chlorine is applied to the wastewater in the hypochlorite solutions.

Chlorine is removed by chemical reaction between chlorine and organic matter in soil and wastewater and natural attenuation. Chlorine oxidizes certain types of organic matter in wastewater, creating more hazardous compounds. Disinfection by-products (DBPs) can also be formed during infiltration of chlorine-disinfected wastewater. Although much is known about disinfection processes and factors that influence by-product formation, less is known about their fate in the environment. Initial studies on groundwater recharge by direct injection of reclaimed municipal wastewater found that although total organic carbon (TOC) and Trihalomethanes (THMs) decreased, the Total organic halide (TOX) showed no retardation or sorption in the aquifer (Roberts et al, 1982). Using secondary and tertiary treated wastewater for aquifer recharge, a decrease of 50 percent of Dissolved organic carbon (DOC) and 40 percent of TOX was accomplished by shallow (6 m) soil aquifer treatment, while the THMs volatilized in the recharge ponds prior to infiltration (Amy et al, 1993). Most removal occurred within the top meter of the surface. Soil aquifer treatment at the same site using greater depths (24 m) reduced DOC by 92 percent and TOX by 85 percent (Wilson et al, 1995). Soil column studies with secondary effluent showed DOC removal of 56 percent for sandy loam, 48 percent for sand and 44 percent for silty sand (Quanrud et al, 1996a). While 48 percent of the DOC was removed with most removal near the surface, absorbable organic halide removal, assumed to be sorption, was only 17 percent, (Quanrud et al, 1996b).

In conclusion, SPS with shallower depths compared to SAT seems to be less efficient to remove DBPs. So, in application of SPS, it should be attend using chlorine.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

This chapter presents a literature survey, which was conducted to provide the available information about wastewater infiltration systems and compile values of kinetic parameters associated with the rates of pollutant (coliform and chlorine) decay reactions that may occur during wastewater infiltration through soil. Literature survey also presents modeling and experimental studies, which can be helpful to characterize the wastewater infiltration systems. In the literature, there are theoretical and experimental studies on soil pile system especially for hazardous waste treatment. Specific studies on domestic wastewater infiltration through soil pile system are somewhat rare. In most respects, Land Treatment, SAT, subsurface wastewater infiltration systems (SWISs) behave very similar to soil pile systems considered here. Thus, a literature survey on domestic wastewater infiltration through soil pile system was performed especially on related land treatment, SAT, and SWISs.

2.2 WASTEWATER INFILTRATION INTO SOIL

Wastewater treatment for onsite and small community applications commonly relies on infiltration and percolation of effluent through soil to achieve purification prior to discharge to land or recharge to groundwater. Application of land treatment for domestic wastewater and different types of wastes from industrial practices is widespread due to the its remarkable advantages such as less energy requirement, reduced long-term liabilities and low initial and operational costs compared to other alternatives (U.S. EPA, 1983). More than 25% of the U.S. population and 37% of all new development is served by on-site and small-scale wastewater systems. These porous media–based systems have high purification performance resulting from the complex interactions of hydraulic and purification processes (Siegrist et al., 2001; McCray et al., 2000; Ausland, 1998; Schwagger and Boller, 1997). Figure 2.1 shows hydraulic and purification processes in a wastewater soil absorption system.

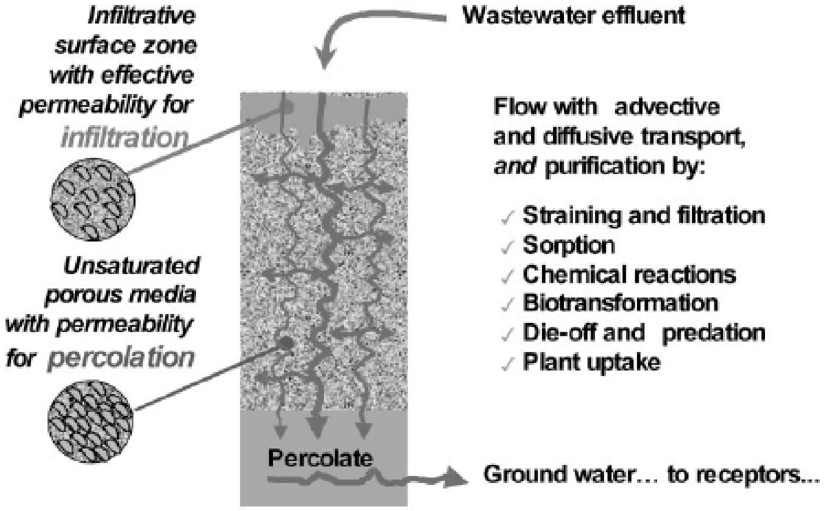

Figure 2.1 Illustration of hydraulic and purification processes operative in a wastewater soil absorption system (S. Van Cuyk et al. 2001)

When domestic wastewater is applied to a wastewater infiltration unit, the soil in that unit acts as the treatment medium. Multiple applications are possible, and the same bed may be used for years without requiring soil replacement. SWISs, SAT, and Land Treatment are different applications of wastewater infiltration systems used in soil-based wastewater treatment area.

SWISs are the most commonly used systems for the treatment and disposal of onsite wastewater. Infiltrative surfaces are located in permeable, unsaturated natural soil or imported fill material so wastewater can infiltrate and percolate through the underlying soil to the groundwater. As the wastewater infiltrates and percolates through the soil, it is treated through a variety of physical, chemical, and biochemical processes and reactions.

SWISs provide both dispersion and treatment of the applied wastewater. Wastewater is transported from the infiltration system through three zones. Two of these zones, the infiltration zone and vadose zone, act as fixed-film bioreactors. The infiltration zone, which is only a few centimeters thick, is the most biologically active zone and is often referred to as the "biomat." Carbonaceous material in the wastewater is quickly degraded in this zone, and nitrification occurs immediately below this zone if sufficient oxygen is present. Free or combined forms of oxygen in the soil must satisfy the oxygen demand generated by the microorganisms degrading the materials. If sufficient oxygen is not present, the metabolic processes of the microorganisms can be reduced or halted and both treatment and infiltration of the wastewater will be adversely affected (Otis, 1985). The vadose (unsaturated) zone provides a significant pathway for oxygen diffusion to reaerate the infiltration zone (Otis, 1997, Siegrist et al., 1986). Also, it is the zone where most sorption reactions occur because the negative moisture potential in the unsaturated zone causes percolating water to flow into the finer pores of the soil, resulting in greater contact with the soil surfaces. Finally, much of the phosphorus and pathogen removal occurs in this zone (Robertson and Harman, 1999; Robertson et al., 1998; Rose et al., 1999; Yates and Yates, 1988).

SWISs are passive, effective, and inexpensive treatment systems because the assimilative capacity of many soils can transform and recycle most pollutants found in domestic and commercial wastewaters. SWISs are the treatment method of choice in rural, unsewered areas. Where point discharges to surface waters are not permitted, SWISs offer an alternative if groundwater is not closely interconnected with surface water. Soil characteristics, lot size, and the proximity of sensitive water resources affect the use of SWISs. Results from numerous studies have shown that SWISs achieve high removal efficiencies for most wastewater pollutants of concern. Biochemical oxygen demand, suspended solids, fecal indicators, and surfactants are effectively removed within 0.6 to 1.5 m of unsaturated, aerobic soil.

The fate of viruses and toxic organic compounds has not been well documented (Tomson et al., 1984). Field and laboratory studies suggest that the soil is quite effective in removing viruses, but some types of viruses apparently are able to leach from SWISs to the groundwater. Fine-textured soils, low hydraulic loadings, aerobic subsoils, and high temperatures favor destruction of viruses and toxic organics. Chlorides also leach readily to groundwater because they, too, are highly soluble and are nonreactive in soil. (EPA, Onsite Wastewater Treatment Systems Manual, EPA/625/R-00/008, 2002)

Treatment of wastewater by the high rate land infiltration system is known as SAT. SAT is a proven technique for the improvement of wastewater quality. The quality of wastewater produced after SAT is suitable for unrestricted irrigation. The cost of treatment by SAT is considerably less than that of conventional methods (Viswanathan et al., 1999). SAT is one prominent water reuse technology employing the unsaturated and saturated zones of an aquifer to improve the water quality of a wastewater effluent (Cha et al., 2004). Where soil and groundwater conditions are favorable for artificial recharge of groundwater through infiltration basins, a high degree of upgrading can be achieved by allowing partially-treated sewage effluent to infiltrate into the soil and move down to the groundwater. The unsaturated or "vadose" zone then acts as a natural filter and can remove essentially all suspended solids, biodegradable materials, bacteria, viruses, and other microorganisms. Significant reductions in nitrogen, phosphorus, and heavy metals concentrations can also be achieved (Kim et al., 2002).

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

The major removal mechanisms in SAT systems include the followings: filtration, biological degradation, physical degradation, physical adsorption, ion exchange and precipitation (Kopchynski, 1996). Fox et al. (1998) stated that filtration, chemical precipitation/dissolution, organic biodegradation, nitrification, denitrification, disinfection, ion exchange, and adsorption/desorption are the major purification processes occurring in the SAT systems.

SAT consists of a number of processes that collectively improve water quality during the percolation of treated wastewater through unsaturated soil and subsequent storage/transport in the underlying aquifer (Quanrud et al., 2002). Yates and Gerba (1998) reviewed several studies that examined the fate of viruses during soil passage within the context of SAT. These studies indicated that significant reduction in numbers of virus particles occurs during the passage of wastewater through the soil and that removal is controlled by a number of factors. Most important are the type of soil, infiltration rate, type of virus, and the degree of soil saturation. Viruses are generally removed less by sandy soils, and removal rates are inversely related to percolation rate (Quanrud et al., 2002).

Yates et al. (1998) indicated that important factors affecting viral survival include temperature, soil moisture content, adsorption to soil particles, pH, solar radiation, and soil type. Hurst et al. (1980) reported that temperature and soil moisture levels appeared to be the most important factors affecting viral inactivation in soil (Choi et al., 2004).

Wang et al., 1981) performed laboratory experiments on four different soils, using 100 cm long columns, to determine the extent of virus movement when wastewater percolated through the soils at various hydraulic flow rates. The effectiveness of virus removal from wastewater varied greatly among the different soil types but appeared to be largely related to hydraulic flow rates. The rate of virus removal in the upper 17 cm of the soil column was found to be significantly greater than in the lower depths of the soil column. This study suggests that the flow rate of water through the soil may be the most important factor in predicting the potential of virus movement into the groundwater. Furthermore, the length of the soil column is critical in obtaining useful data to predict virus movement into groundwater.

Van Cuyk et al. (2004) conducted a research to quantify the removal of virus and bacteria through the use of microbial surrogates and conservative tracers during controlled experiments with three-dimensional pilot-scale soil treatment systems in the laboratory and during the testing of full-scale systems under field conditions. The results of this study suggested that 99–99.9% removal of virus and near complete removal of fecal coliform bacteria during unsaturated flow through 60 to 90 cm of sandy medium may be obtained. Results also suggested that the fate of fecal coliform bacteria may be indicative of that of viruses in soil media near the infiltrative surface receiving wastewater effluent. Concentrations of fecal coliform in percolating soil solution may be conservatively estimated from analysis of extracted soil solids.

Gerba et al. (1975) concluded in their study on the fate of wastewater bacteria and viruses in soil that 2 to 3 months was sufficient for reduction of pathogenic bacteria to negligible numbers once they had been applied to the soil. Most fecal coliform bacteria and coliphage viruses were removed within the first 30 cm of travel in unsaturated soils beneath adsorption trenches, with occasional migration of up to 120 cm, before removal (Addo, 2004).

2.3 KINETIC PARAMETERS

A literature search was conducted to compile values of kinetic parameters associated with the rates and orders of chlorine and total coliform decay reactions that may occur during wastewater infiltration through soil. During literature search, relevant data were compiled for the decay of virus and chlorine.

Among several applications of urban wastewater reuse, use of reclaimed wastewater to sustain flows has become attractive in the urban area. Since these rivers are used for recreational purposes and for restoring aquatic eco-system, the adequate control of residual chlorine is essential. The kinetics of chlorine disappearance in drinking water distribution networks was commonly modeled by first order kinetics (Lyndon et al., 1998). Funamuzi et al. (2004) developed a mathematical model for describing reactions between residual chlorine and organic matter in a reclaimed wastewater and for examining the temperature effect on decline rate of chlorine. In their laboratory scale experiments performed to estimate reaction rate constants and to confirm the model, the estimated first-order self decay rate constant of chlorine was found to range from 0.024 to 0.12 d^{-1}.

Castro and Neves (2003) presented a study on mathematical modeling of chlorine decay along the water supply system. This work is based on the study of part of a real distribution system, in the municipality of Lousada and is supported by the version 2.0 of the EPANET simulator so as to illustrate the process of calibrating and using the water quality model. They determined that the value of first-order chlorine kinetic constant is 0.343 d^{-1}.

Table 2.1 lists some first-order chlorine decay constants obtained from literature and show that the value has been observed to vary between 0.024 and 0.12 d^{-1} for reclaimed wastewater.

Table 2.1 First-order chlorine decay constants from literature

Decay rate (d^{-1})	**Application**	**Refs.**
0.024 – 0.12	Reclaimed wastewater	Finumazi et al. (2004)
0.343	Water supply system	Castro et al. (2003)

It was reported in the literature that important factors affecting microbial survival in soils were temperature, soil moisture content, adsorption to soil particle, soil pH, solar radiation and soil type (Hurst et al., 1980; Yates et al., 1988, and Seymour and Appleton, 2001). Microorganism survival and transport in soils and aquifers are controlled by a number of factors: climate (e.g., temperature, rainfall), type of soil or aquifer material (e.g., texture, pH, water holding capacity, cation exchange capacity), pore fluid properties (e.g., chemistry, saturation, and type of pathogen) (Gerba and Bitton, 1984).

Bacterial retention in porous media has been attributed to several mechanisms including straining or filtration at pore constrictions, sedimentation in the pores, diffusion in pores not contributing actively to the transport of water, and adsorption (Yates and Yates, 1988; Corapcioglu and Haridas, 1984). Andelman et al. (1994) indicated that there are many different processes that can remove pathogens from the recharge water as it flows through the vadose zone. Large pathogens such as parasites and some bacteria can be filtered by narrow soil pores. Viruses can be retained by soil solid phases and inactivated by reactions occurring in the soil. Bouwer (1984) stated that while small bacteria are adsorbed onto soil particles, larger bacteria are rather immobilized in soils by physical straining and filtration.

Choi et al. (2004) conducted field studies to investigate viral contamination and survival in soil when tertiary wastewater effluent was used with subsurface drip and furrow irrigation systems in semi arid regions. They found that virus inactivation rates follow first-order reaction kinetics with values of decay rate coefficients calculated from experimental data ranging from 0.03 to 0.85 d^{-1}.

Benjamin K. Addo (2004) conducted a study to quantify the impact of natural die-off on bacterial removal within the Marshland Upwelling System (MUS). In this study bacterial retardation rates were determined in laboratory repacked sandy loam soil columns, and the effectiveness of the MUS were evaluated in removing fecal pathogens from settled, raw wastewater. Varying salinities and temperatures were used to investigate the inactivation rates for fecal coliforms. In studying the impact of natural die-off conditions on bacterial survival, laboratory experiments performed at two distinct temperatures (20^oC and 25^oC) indicated that the higher temperature was more detrimental to fecal coliform survival. This study indicated that fecal coliform decay rate constants ranged from 0.57 to 1.03 d^{-1} (Addo, B.K., 2002).

Reddy et al. (1981) conducted a review of bacterial survival in soil systems and found average die-off rate constants of fecal coliforms to be 1.14 d^{-1}.

Actual field-scale mortality rates of 0.18-0.81 d^{-1} and 0.17– 0.44 d^{-1} were determined for fecal and allochthonous bacteria, respectively in natural aquatic ecosystems with freshwater conditions (Menon et al., 2003). First-order decay coliform constants in soil compiled from literature are summarized in Table 2.2.

Table 2.2 First-order coliform decay constants in soil from literature

k_b (d^{-1})	**Refs.**
0.03 – 0.85	Choi et al. (2004)
0.57– 0.65 (20°C) 0.70 –1.03 (25°C)	Benjamin K. Addo (2004)
1.14	Reddy et al. (1981)
0.18-0.81 for fecal bacteria 0.17– 0.44 for allochthonous bacteria	Menon et al. (2003)

Other documented die-off rate constants for bacteria in groundwater are reported in Table 2.3.

Table 2.3 Fecal coliform and Escherichia coli decay coefficients in groundwater determined from laboratory studies

Microorganism	**k_b (d^{-1})**	**Refs.**
Escherichia Coli	0.32	[a]Keswick et al., 1982
	0.92	[a]Reddy et al., 1981
	0.36	[a]McFeters and Stuart, 1974
	0.16	[a]Bitton et al., 1983
Fecal Coliform	1.53	[a]Reddy et al., 1981
	0.50 – 4.57	Auer and Niehaus, 1992

[a] adapted from Gerba and Bitton (1984)

CHAPTER 3

MATERIALS AND METHODS

3.1 WASTEWATER AND SITE SOIL CHARACTERISTICS

The wastewater used in this study is domestic wastewater produced at the PT1 and PT4 construction camp sites of the BTC Project. In the camp sites, domestic wastewater produced because of the living activities of the workers has been treated using package wastewater treatment plants (PWWTPs). These PWWTPs were designed according to conventional activated sludge process. Wastewater effluent analysis which has been made on a weekly basis showed that some quality parameters in the effluent of the PWWTPs are above the prescribed project discharge standards. Project wastewater discharge standards and values of some quality parameters (pH, Biological Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), Total suspended solid (TSS), Chlorine, Oil&Grease, Total Coliform and Fecal Coliform) for treated wastewaters produced at PT1 and PT4 construction camp sites are provided by BTC Co. (Table 3.1 & 3.2). Table 3.1 and 3.2 also give statistics (the mean, median, standard deviation and the range, minimum and maximum) of the quality parameters for both camp sites.

Table 3.1 Project wastewater discharge standards and measured water quality parameters for treated wastewater produced at the PT1 site.

Parameter	**pH**	**BOD_5 mg/L**	**COD mg/L**	**TSS mg/L**	**Chlorine mg/L**	**Oil& Grease mg/L**	**Total coliform unit/100 mL**	**Fecal coliform unit/100 mL**
Project discharge standards	**6-9**	**25**	**125**	**35**	**0.2**	**10**	**400**	**20**
Water quality parameters For partially treated wastewater	7.42	220	358	95.58	0	0	0	0
	8.10	60	138	4	0	19.4	0	0
	8.51	40	132	12.4	0	6	4800	0
	8.68	100	130	46.42	64.61	15	4800	0
	7.77	98	178	44.21	145.55	18	0	0
	8.27	140	204	61.66	102.95	20	4800	0
	7.93	88	184	108.75	92.30	16	4800	0
	8.10	150	226		0		4800	0
Mean	8.10	112	193.75	53.29	50.68	13.49	3000	0
Median	8.10	99	181	46.42	32.31	16	4800	0
Standard deviation	0.4	56.94	75.07	39.08	58.47	7.58	2484.24	0
Range	7.42-8.68	40-220	130- 358	4-108.75	0-145.55	0-20	0-4800	0

Table 3.2 Project wastewater discharge standards and measured water quality parameters for treated wastewater produced at the PT4 site.

Parameter	**pH**	**BOD$_5$ mg/L**	**COD mg/L**	**TSS mg/L**	**Chlorine mg/L**	**Oil&Grease mg/L**	**Total coliform unit/100 mL**	**Fecal coliform unit/100 mL**
Project discharge standards	**6-9**	**25**	**125**	**35**	**0.2**	**10**	**400**	**20**
Water quality parameters for partially treated wastewater	8.68	16.80	184.73	64.26	0.20	31.63	4.50	0.00
	8.18	87.10	273.08	194.61	0.01	52.54	2400.00	920.00
	8.33	19.50	232.77	64.20	0.10	12.29	1.80	0.00
	8.18	46.50	225.14	24.80	0.01	21.75	240.00	49.00
	8.32	55.00	194.40	94.80	0.20	22.40	7.80	0.00
	8.23	22.56	254.80	92.00	0.20	307.45	27.00	0.00
	8.18	28.30	80.00	48.70	0.60	72.10	33.00	0.00
	8.23	55.40	193.80	98.40	0.02	12.80	2400.00	
	8.53	48.80	145.44	76.00	0.02	39.60	2400.00	0.00
	8.27	52.70	141.80	52.00	0.01	21.60	2400.00	
	8.45	44.50	138.17	79.60	0.05	33.00	2400.00	
	8.15	47.50	140.00	48.00				
	8.59	17.00	384.12	97.00	0.08	96.00	2400.00	
	8.34	74.00	158.40	173.80	0.04	25.07	2400.00	
	8.42	134.00	277.20	226.20	0.02	31.00	2400.00	
	8.35	80.50	245.52	157.33	0.00	36.50	2400.00	
	8.23	77.20	316.80	97.00	0.02	53.00	2400.00	
	8.16	8.50	79.20	54.33	30.13	2.20	4.50	
	8.23	33.60	110.88	87.00	0.02	15.60	4.00	

Table 3.2 Continued

Parameter	**pH**	**BOD_5 mg/L**	**COD mg/L**	**TSS mg/L**	**Chlorine mg/L**	**Oil&Grease mg/L**	**Total coliform unit/100 mL**	**Fecal coliform unit/100 mL**
Water quality parameters for partially treated wastewater	8.14	18.60	47.52	51.80	0.05	3.26	540.00	
	8.35	5.90	43.56	83.60	0.20	18.20	13.00	
	8.15	55.20	95.04	53.00	0.00	24.80	6.80	
	8.32	1.70	35.64	35.80	0.20	19.40	4.50	
	8.26	1.50	43.56	42.50	0.10	11.20	2.00	
	8.12	1.90	99.00	46.80	0.10	25.00	0.00	
Mean	8.30	41.37	165.62	85.74	1.35	41.18	1037.04	121.13
Median	8.26	44.50	145.44	76.00	0.05	24.90	136.50	0.00
Standard deviation	0.146	32.418	93.377	51.153	6.132	60.603	1182.125	323.249
Range	8.12-8.68	1.50-134	35.64-384.12	24.8-226.20	0.00-30.13	2.20-307.45	0.00-2400.00	0.00-920.00

As seen from Table 3.1 and 3.2;

- measured values of BOD_5, COD, TSS, Chlorine, Oil& Grease, and Total coliform most of the time exceed prescribed project discharge standards at PT1 site.

- a similar situation is valid for PT4 camp, measured values of BOD, COD, TSS, Oil& Grease, and Total Coliform values exceed prescribed project discharge standards.

To meet the project discharge standards in terms of chlorine and total coliform tertiary treatment of wastewater effluent using SPS was considered. Total coliform and chlorine effluent parameters were used as influent data during SPS application.

It was reported by BTC Company that soils of both camps (PT1 and PT4) have a clay loam texture and low salinity. The PT1 camp site soils have low pH measured in saturation extract and high organic matter content, whereas at PT4 camp site soil pH is slightly alkaline and organic matter content is low. Table 3.3 gives qualitative information of site soil characteristics.

Table 3.3 Site Soil Characteristics

Soil parameter	**PT1**	**PT4**
Soil Texture	Clay loam	Clay loam
Soil salinity	Low	Low
Organic matter content of soil	High	Low
pH	Low	High

3.2 LABORATORY MEASUREMENTS OF SOIL HYDRAULIC PARAMETERS

Soil hydraulic properties are needed as input data to describe and simulate flow of water and transport solutes in the soil profile. For unsaturated soils, the most important hydraulic characteristics are the soil moisture retention curve (SMRC) and hydraulic conductivity (K_s). This chapter presents laboratory measurements, which was performed to determine the hydraulic parameters of the site soil taken from site PT4.

3.2.1 Soil Moisture Retention Curve (SMRC)

The knowledge of soil hydraulic properties is indispensable to solve many soil and water management problems related to agriculture, ecology, and environmental issues. These properties are needed to describe and predict water and solute transport. One of the main soil hydraulic properties is the SMRC, which expresses the relationship between the pressure head and the water content of the soil. It can be considered as a soil's fingerprint, since the shape of the curve is related to various physical and chemical soil properties, which are unique for each soil.

As a part of modeling study of water movement through soil pile, SMRC was measured in the Contaminant Hydrology Lab of Environmental Engineering Department of Middle East Technical University (METU). In order to determine the water retention parameters, the experimental soil moisture retention data were fitted to the empirical model of van Genuchten (van Genuchten, M. Th.,1980) using a non-linear least square program RETC (van Genuchten et al, 1991).

A set of pressure cell apparatus was used to observe SMRC, which represents the amount of water remaining in the soil under equilibrium pressure conditions. The set up of pressure cell apparatus is shown in Figure 3.1.

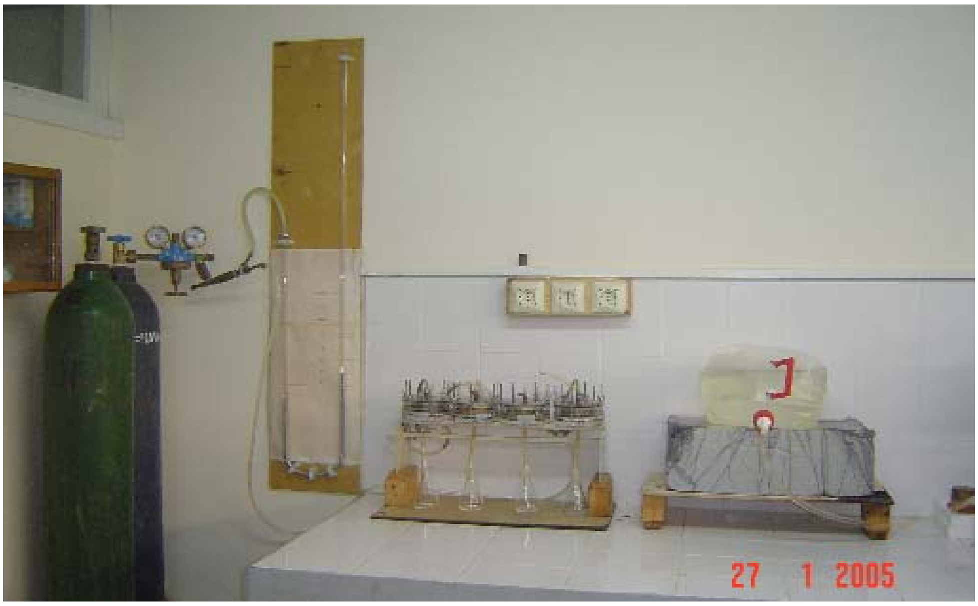

Figure 3.1 SMRC test set-up

The soil samples were packed in the cylinders having a diameter of 10 cm and height of 3 cm at densities of 1.150, 1.341, 1.374 gr/cm^3 and was allowed to saturate with water from the bottom. After the soil samples were saturated, air pressures of 50, 100, 150, 200, 250, 300, 350, and 400 cm-water was consecutively applied to the saturated soil samples. Volume of water drained soil sample at each pressure step was recorded and soil moisture contents were calculated. Table 3.4 shows test results.

Table 3.4 SMRC test results

CYLINDER NO	Water used for saturation mL	Bulk soil volume cm^3	Pressure cm	Volume of water drained mL	Cumulative volume of water drained mL	Soil moisture content θ
A1	75.413	179.439	0	0.000	0.000	0.420
			50	7.500	7.500	0.378
			100	3.000	10.500	0.362
			150	7.500	18.000	0.320
			200	3.500	21.500	0.300
			250	2.900	24.400	0.284
			300	2.000	26.400	0.273
			350	1.250	27.650	0.266
			400	1.750	29.400	0.256
A2	71.764	172.903	0	0.000	0.000	0.415
			50	6.500	6.500	0.377
			100	3.000	9.500	0.360
			150	3.000	12.500	0.343
			200	3.500	16.000	0.323
			250	2.900	18.900	0.306
			300	2.100	21.000	0.294
			350	1.000	22.000	0.288
			400	1.750	23.750	0.278
A3	69.693	173.307	0	0.000	0.000	0.402
			50	6.000	6.000	0.368
			100	3.500	9.500	0.347
			150	2.500	12.000	0.333
			200	3.500	15.500	0.313
			250	2.500	18.000	0.298
			300	2.750	20.750	0.282
			350	2.750	23.500	0.267
			400	1.500	25.000	0.258

3.2.2 Saturated Hydraulic Conductivity

A constant head permeameter was used to measure saturated hydraulic conductivities of soil samples taken from PT4 site. Hydraulic conductivity was measured in the Soil Mechanics Lab of Civil Engineering Department of METU. The apparatus used to measure saturated hydraulic conductivity is shown in Figure 3.2. The soil samples were packed in the cylinders having a diameter of 3.56 cm and height of 7.1 cm at two different soil packing densities.

Figure 3.2 Saturated hydraulic conductivity test set up

The saturated hydraulic conductivities can be found using following equation.

$$\frac{Q}{A} = K_s \left(\frac{\Delta h}{\Delta l} \right)$$

(3.1)

where,

Q: volumetric flow rate
A: cross-sectional area
$\Delta h / \Delta l$ = hydraulic gradient
K_s: hydraulic conductivity

Hydraulic conductivities of soils were found as 4.6×10^{-5} and 3.7×10^{-6} cm/s for 1.279 and 1.325 g/cm^3 soil bulk densities, respectively.

3.2.3 Unsaturated Flow Parameters

Nonlinear least-squares parameter optimization method was used for estimating the unknown coefficients in the θ(h), soil moisture retention, and K(h), hydraulic conductivity, functions. For this purpose RETC program was used. These hydraulic properties are key parameters in any quantitative description of water flow into and through the unsaturated soils. The program uses the parametric models of van Genuchten (van Genuchten, M. Th., 1980) to represent the soil water retention curve, and the theoretical pore-size distribution models of Mualem (1976) and Burdine (1953) to predict the unsaturated hydraulic conductivity function from observed soil water retention data.

The functional forms of the hydraulic properties used in the RETC are as follows:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha * |h|)^n\right]^m} \tag{3.2}$$

$$m = (1 - \frac{1}{n}) \tag{3.3}$$

$$K(S_e) = K_s \sqrt{S_e}\left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{3.4}$$

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{3.5}$$

Where;

- θ: Volumetric water content
- θ_r: Residual water content
- θ_s: Saturated water content
- α, n, m: empirical constants determining the shape of the hydraulic functions
- h: soil water pressure head
- S_e: reduced water content (effective fluid saturation)
- K_s: saturated hydraulic conductivity

The series of water contents and water pressures of Table 3.4 are used to estimate the coefficients in the van Genuchten model equations; i.e., equations (3.2) and (3.4). For each soil sample, the water content and water pressure values are input to the RETC program, which then determines the coefficients. In order to run the RETC program, initial values of the coefficients based on the texture of the soil sample are needed. The initial value of saturated water content, θ_s, is fixed at the measured saturated water content of the sample, and is not allowed to vary during the iterations of RETC run. The saturated water content is determined by calculating the porosity of the sample, based on the bulk density and assuming a particle density of 2.65 g/cm^3, and assuming the entire pore space to be full of water. With θ_s fixed, only the values of residual water content, θ_r, α , and n are determined by the program. Initial values for these three coefficients for each soil textural class are provided by Rawls et al. (1982).

3.3 FIELD STUDIES

In the light of findings and recommendations of previous Analytical Modeling Study (AMS) (Unlu, 2004), a pilot scale soil pile system was constructed at the PT1 construction camp site for feasibility study of tertiary treatment of wastewater effluent prior to discharge to the land. The results obtained from operation of a pilot scale soil pile system were used to determine site specific kinetic data. The results of both numerical and analytical modeling studies were used together with the results of pilot scale soil pile system to calibrate these models and provide guidelines for improved design and operation of site specific field scale soil pile system.

3.3.1 Construction of Pilot Scale Soil Pile System

To verify findings of modeling study of SPS, design and operation of a pilot scale SPS is necessary. One of the major objectives of pilot scale SPS is to collect data to accurately estimate contaminant attenuation rate coefficients and to verify the proposed design and operation characteristics of soil pile and thus improve the site specific design and operation of field scale SPS. Proposed pilot SPS was defined in Section 5.4.3.1. BTC Co. constructed pilot plants at the PT1 camp site. Figure 3.3 shows construction stages of pilot plant. The soil pile area was excavated to a height of 80 cm. The plastic sheet was covered on the area of the bottom side of the SPS (15 x 15 m). The trench was excavated width of 1 m and height of approximately 2.2 m. Firstly pipe with a diameter of 10 cm was placed in the trench to a slope 1% through 30 cm x 100 cm gravel. The one end of the pipe left exposed. The remaining depth of the trench was backfilled with topsoil. After the leveling of the area by backfilling of trench with topsoil, the geotextile material (10 m x 10 m) was placed on area. And gravel to nearly height of 30 cm was laid on geotextile material to prevent the pipes clogged. The surface of this gravel was covered with plastic sheets to prevent system from rainfall again. As the last stage the remaining depth was backfilled with topsoil. The each drainage pipe has 2 mm size of holes which are circular shape. The holes are perforated uniformly along the pipe to meet infiltration rate. Nearly 40 Network of Perforated Pipes has been laid from end to end of area to distribute wastewater uniformly across the soil surface. Due to the low temperature conditions experienced at PT1 station, the perforated pipe was placed to a depth 80cm below surface level.

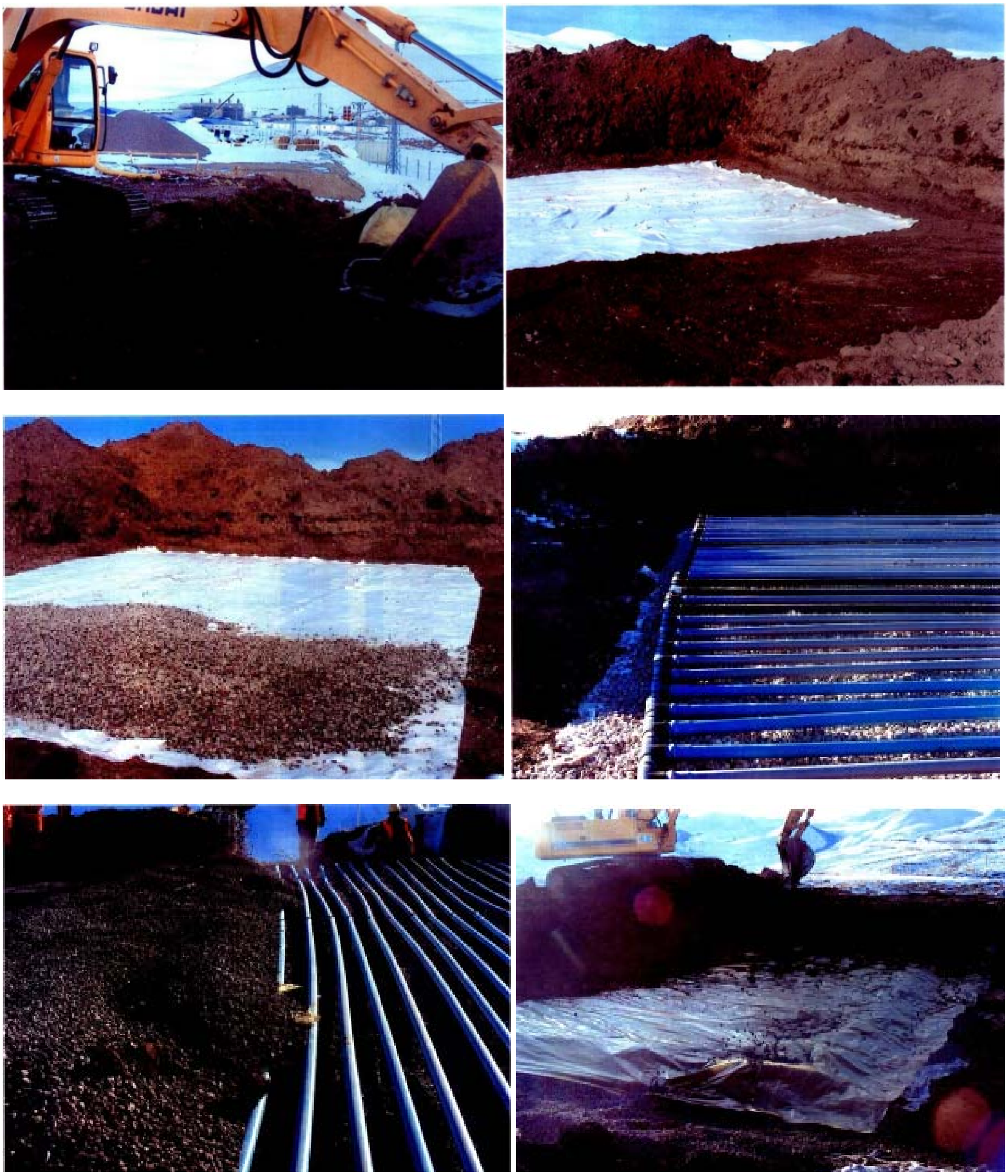

Figure 3.3 Construction stages of pilot plant of SPS

3.3.2 Effluent Sampling

Due to the operational problem related to the sample collection system of soil pile pilot plant, effluent samples could not be taken effectively from pilot plant by BTC Co.. So, soil water sampler was used for taking sample from the pilot plant. The model 1900 soil water sampler of Soil Moisture Equipment Corp. was used to collect wastewater sample from the soil pile pilot plants. This soil moisture sampler is a large-volume sampler designed for near-surface installation at depths ranging from 0.15 to 1.8 m. The unit consist of a 4.8 cm outside diameter PVC tube, a porous ceramic cup with a 2 bar (200 kPa) air-entry value, and a santoprene stopper. Neoprene tubing that is attached to a 0.0064 cm diameter access tube is used as an access port for sample extraction evacuation. Clamping rings slip over the folded Neoprene tubing to seal the sampler. An extraction kit is used for sample retrieval and a vacuum pump is used to evacuate the sampler. The 1900 K3 1,000 ml extraction kit was used for routine operation.

The model 0230 series soil augers were used for coring a hole to accept the samplers. The soil was then sifted through mesh screen to free it of pebbles and rocks. This provides a reasonably uniform backfill soil for filling in around the soil water sampler. The primary concern in installation of Soil water sampler is that the porous ceramic cup of the sampler be in tight, intimate contact with the soil so that soil water can move readily from the pores of the soil through the pores in the ceramic cup and into the soil water sampler. After the hole was cored, sifted soil was mixed with water to make a slurry which has a consistency of cement mortar. The slurry was made using silica flour, which was then used to establish good contact between the ceramic cup and the soil. The silica was mixed with water to produce slurry. This slurry was then poured down to the bottom of the cored hole to insure good soil contact with the porous ceramic cup. Immediately after the slurry had been poured, the soil water sampler was inserted down in to the hole so that the porous ceramic cup is completely embedded in the soil slurry (Figure 3.4). The remaining area around the sampler was backfilled with sifted soil which is free of pebbles and rocks. The soil was tamped firmly to prevent surface water from running down the cored hole.

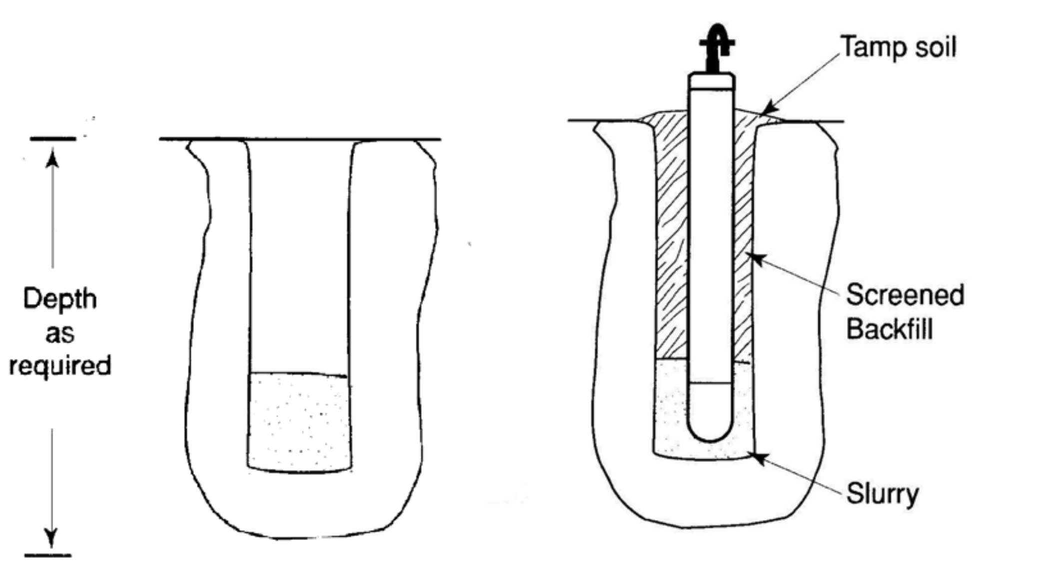

Figure 3.4 Installation of porous ceramic cup.

After the soil water sampler has been installed in the field, extraction kit and vacuum test hand pump were used for collecting a soil water sample (Figure 3.5).

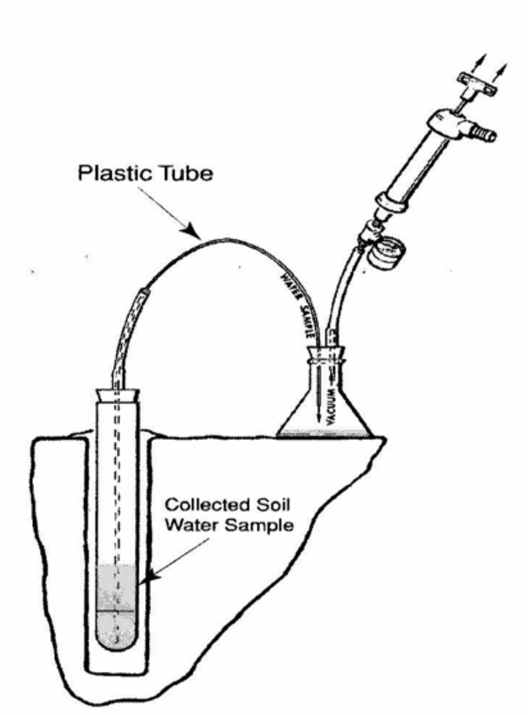

Figure 3.5 Collecting a soil water sample.

The vacuum provided by vacuum hand pump in the sampler causes the moisture to move from the soil, through the porous ceramic cup and into the sampler.

Three samples were collected from the depths of 50, 100, and 150 cm of SPS. Total coliform was measured in the samples taken from the SPS pilot plant using Membrane Filtration method. Total coliform concentrations were found 1700/100 mL, 0/100 mL and 0/100 mL at the depths of 50, 100, and 150 cm, respectively.

CHAPTER 4

MODELING APPROACHES

4.1 CONCEPTUAL MODEL DESCRIPTION

Soil pile was physically conceptualized as an engineered system constructed over a suitable area by packing surface soils so as to have a uniform thickness, density and porosity throughout the pile. Wastewater is applied across the surface of the pile uniformly using surface or below surface irrigation systems to achieve steady-state infiltration and uniform unsaturated moisture content distribution. In the soil pile, wastewater was assumed to infiltrate into soil predominantly in the vertical direction by gravity flow with negligible horizontal pressure gradient and collected at the bottom by an underlying blanket drainage system. During infiltration, it was assumed that coliform and chlorine are subject to usually assumed first-order decay reaction. Basically, removal process and thus treatment was regarded as a race between migration and degradation. If degradation rate exceeds the migration rate, contaminants will be removed in the soil before they can reach the drainage system. Conceptually, the system consists of following components:

- a wastewater infiltration system;
- a soil treatment zone ; and
- a drainage and effluent collection system;

Figure 4.1 shows a conceptualized schematic profile of a soil pile system.

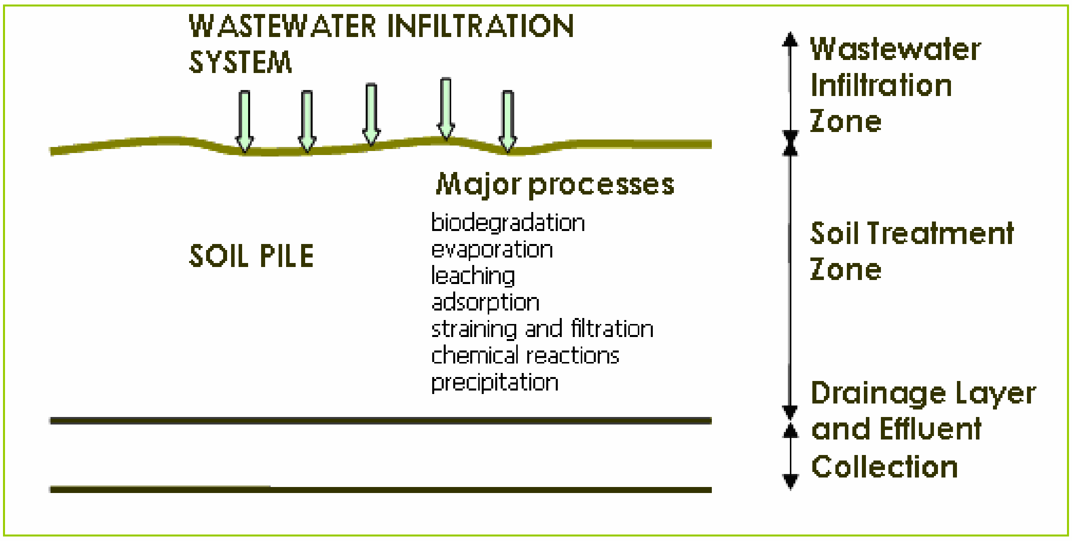

Figure 4.1 Conceptualized schematic profile of a soil pile system

4.2 ANALYTICAL SOIL PILE MODEL

A simplistic analytical modeling approach has been developed based on available site and literature data to assess contaminant attenuation efficiencies achievable during steady infiltration of treated wastewater through soil pile (Unlu, 2004). The governing equations and associated boundary conditions of the developed model were built based on the described conceptual model. The following sections describe the analytical model and the solutions of model equations.

4.2.1 Unsaturated Water Flow

For the analyses of unsaturated water flow through soil pile, the approach of Unlu et al. (1992) was adopted. The actual flow behavior in the soil pile can be quite complicated when one considers the effects of three-dimensional nature of water flow and transient boundary conditions associated with the soil pile. Such conditions require a three-dimensional numerical unsaturated flow modeling approach. However, in the present analyses flow calculations can be simplified, because simulation of average flow conditions is of concern. As wastewater distributed uniformly across the surface of soil pile, the flow through the pile can be assumed to be predominantly in the vertical direction. Horizontal flow, resulting from boundary effects and possible packing heterogeneities of soil pile, accounts for a small portion of the total flow and can be neglected. Hence, under these circumstances a unit gradient approach can be implemented to simplify the flow calculations. This approach has been proven to work reasonably well even for moderately heterogeneous soils under steady flow conditions (Yeh, 1989). The major simplification of this approach is that the pressure head in the soil pile is constant and so is the moisture content.

Darcy’s equation for unit gradient case may be written as

$$q_w = -k_r K_s \tag{4.1}$$

where,

q_w : net infiltration rate through the soil pile [LT^{-1}]

k_r : the relative permeability as a function of volumetric water content

K_s : the saturated hydraulic conductivity of soil [LT^{-1}]

The relative permeability as a function of volumetric water content, θ_w, can be described by the Brooks-Corey model (Brooks and Corey, 1964) as

$$k_r = \left[\frac{(\theta_w - \theta_r)}{(\phi - \theta_r)}\right]^{\varepsilon} \tag{4.2}$$

where,

ϕ: soil porosity

θ_r: residual water content

ε: pore size distribution parameter

k_r: the relative permeability as a function of volumetric water content

Due to the availability of a large data base on the statistical properties of van Genuchten model parameters (Carsel and Parrish, 1988) the Brooks-Corey exponent, ε, can be related to the van Genuchten parameter, n, following Lenhard et al. (1989) as

$$\varepsilon = 3 + \frac{2}{(n-1)(1-0.5^{n/n-1})} \tag{4.3}$$

Using equations (4.1) and (4.2) the volumetric water content can be obtained from

$$\theta_{\mathrm{w}} = (\phi - \theta_r)\left[\frac{q_w}{K_s}\right]^{1/\varepsilon} + \theta_r \tag{4.4}$$

And pore water velocity, v, can be calculated as

$$v = \frac{q_w}{\theta_w} \tag{4.5}$$

In the foregoing analysis, it is assumed that $q_w \le K_s$. Data required for soil pile unsaturated flow model for soil pile are q_w, the net infiltration rate through the soil pile [LT^{-1}]; K_s, the saturated hydraulic conductivity of soil [LT^{-1}]; ϕ, soil porosity; θ_r, residual water content; and the van Genuchten soil parameter, n.

4.2.2 Chemical Transport

The governing partial differential equation describing one-dimensional transport of a chemical subject to first-order decay reaction in the unsaturated soil pile under steady-state water flow conditions is taken as

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} - v\frac{\partial C}{\partial z} - \mu C \tag{4.6}$$

where,

C: chemical concentration [ML^{-3}]
D: dispersion Coefficient [L^{2}T^{-1}]
v: pore-water velocity [LT^{-1}]
μ: first-order decay coefficient
z: vertical distance [L]
t: time [T]

The relevant initial and boundary conditions for Equation (4.6) to obtain concentrations for chemical transport are:

$$
\begin{aligned}
&C(z,0) = 0 \\
&C(0,t) = C_0 \\
&\frac{\partial C}{\partial z}(L,t) = 0
\end{aligned}
\tag{4.7}
$$

where,

C_0: chemical concentration in the influent wastewater infiltrating soil pile [M/L^3]

L: thickness of the soil pile

The solution of Equation (4.6) subject to Equation (4.7) is given by van Genuchten and Alves (1882) as:

$$C(z,t) = \frac{C_0 B_1(z,t)}{B_2(z)} \tag{4.8}$$

where,

$$\begin{aligned} B_1(z,t) = {} & \frac{1}{2}\exp\left[\frac{(v-u)z}{2D}\right]erfc\left[\frac{z-ut}{2\sqrt{Dt}}\right] + \frac{1}{2}\exp\left[\frac{(v+u)z}{2D}\right]erfc\left[\frac{z+ut}{2\sqrt{Dt}}\right] \\ & + \frac{(u-v)}{2(u+v)}\exp\left[\frac{(v+u)z-2uL}{2D}\right]erfc\left[\frac{(2L-z)-ut}{2\sqrt{Dt}}\right] \\ & + \frac{(u+v)}{2(u-v)}\exp\left[\frac{(v-u)z+2uL}{}2D\right]erfc\left[\frac{(2L-z)+ut}{2\sqrt{Dt}}\right] \\ & - \frac{v^2}{\mu D}\exp\left[\frac{vL}{D}-\mu t\right]erfc\left[\frac{(2L-z)+vt}{2\sqrt{Dt}}\right] \end{aligned} \qquad (4.9a)$$

$$B_2(z) = 1 + \left(\frac{u-v}{u+v}\right)\exp\left[\frac{(-uL)}{D}\right] \qquad (4.9b)$$

$$u = v\left(\sqrt{1+\frac{4\mu D}{v^2}}\right) \qquad (4.9c)$$

Data requirement for the chemical transport model for soil pile are C_0, the chemical concentration in the influent wastewater entering soil pile [M/L^3]; L, the thickness of the soil pile; D, dispersion coefficient [L^{2}T^{-1}]; v, pore water velocity [LT^{-1}] calculated by Equation (4.5); and μ, first-order decay coefficient.

4.3 NUMERICAL SOIL PILE MODEL

Transient unsaturated flow is modeled using a finite-element numerical computer code (WORM) developed by van Genuchten (1987). The following sections describe the flow and transport equations and associated initial and boundary conditions of the numerical model.

4.3.1 Unsaturated Water Flow

The differential equation describing water flow in unsaturated soils is used in the model. For one-dimensional flow in a rigid medium, and neglecting air flow dynamics, this equation is as follows,

$$C(\frac{\partial h}{\partial t}) = \frac{\partial}{\partial x}(K\frac{\partial h}{\partial x} - K) \pm S \qquad (4.10)$$

where,

h: soil water pressure head (with dimension L)
K: Hydraulic conductivity as a function of h (LT^{-1})
C: Specific soil water capacity (L^{-1})
x: soil depth taken positive downwards (L)
t: Time (T)
S: Space and time dependent volumetric source/sink term (T^{-1})

4.3.2 Chemical Transport

The governing equation for chemical transport during transient unsaturated flow is taken as:

$$\frac{\partial(\partial c+\rho s)}{\partial t}=\frac{\partial}{\partial x}(\theta\ D\frac{\partial c}{\partial x}-q\ c)-\theta\ \mu\ c \qquad (4.11)$$

Where,

c: solution concentration (ML^{-3})
ρ: soil bulk density (LT^{-1})
s: adsorbed concentration (M^0)
θ: volumetric water content (M^0)
q: volumetric flux density (LT^{-1})
μ: first order decay coefficient (T^{-1})
D: dispersion coefficient (L^2T^{-1}) which represents the effects of both molecular diffusion and mechanical dispersion.

D is defined by;

$$D=D_0\tau+\gamma|v| \qquad (4.12)$$

D_0= molecular diffusion coefficient (L^2T^{-1})
τ = tortuosity factor (L^0)
γ = dispersivity (L)
v = q/θ, average pore water velocity (LT^{-1})

Equation (4.11) neglects chemical precipitation/dissolution reactions.

The adsorbed concentration s is related to the solution concentration means linear equilibrium isotherm:

$$s = k\,c \tag{4.13}$$

where, k is an empirical constant. Substituting (4.13) into (4.11) gives:

$$\frac{\partial \theta R s}{\partial t} = \frac{\partial}{\partial x}(\theta\, D \frac{\partial c}{\partial x} - q\, c) - \theta\, \mu\, c \tag{4.14}$$

In which the retardation factor R is defined by;

$$R = 1 + \frac{\rho k}{\theta} \tag{4.15}$$

Water content, θ is taken to be unique function of the pressure head h and can thus be obtained from solutions of Eq (4.10). Te volumetric flux also follows immediately from (4.10) by making use of Darcy's Law, i.e.,

$$q = -K\frac{\partial h}{\partial x} + K \tag{4.16}$$

4.3.3 Initial and Boundary Conditions of the Flow Equation

The following boundary conditions can be imposed at the soil surface (x=0)

$$\left.(-K\frac{\partial h}{\partial x} + K)\right|_{x=0} = q_0(t) \tag{4.17}$$

where $q_0(t)$ is the net fluid flux, respectively.

Similar conditions can be applied to the lower boundary of the soil profile (x=l), i.e.,

$$(-K\frac{\partial h}{\partial x}+K)\bigg|_{x=l} = q_l(t) \tag{4.18}$$

where $q_l(t)$ is the imposed net drainage flux. For a free draining profile as in the SPS the following condition can be applied.

$$\frac{\partial h}{\partial x}(L,t)=0 \tag{4.19}$$

which is equivalent to the condition that q_l equals the hydraulic conductivity at $x=l$.

Finally, any arbitrary initial condition in terms of the pressure head of the water can be invoked.

4.3.4 Initial and Boundary Conditions of the Transport Equation

The solute transport equation (Eq. 4.11) is solved subject to the following mixed or third type boundary condition at the soil surface.

$$(-\theta\frac{\partial c}{\partial x}+qc)\bigg|_{x=0} = \begin{matrix} q_0(t)\, c_0(t) & if\ q_0(t)>0 \\ 0 & if\ q_0(t)<0 \end{matrix} \tag{4.20}$$

Where $q_0(t)$ is the fluid flux density at the soil surface, and $c_0(t)$ is the concentration of the infiltrating water. Note that the solute flux is zero during periods of evaporation ($q_0 < 0$).

A zero gradient boundary condition at $x = l$ may be used when a free draining profile is considered:

$$(\frac{\partial c}{\partial x})\bigg|_{x=l} = 0 \tag{4.21}$$

Again, any arbitrary depth-dependent concentration distribution initial condition can be applied as initial condition.

4.3.5 Model Input Data Requirement

The soil water characteristics and hydraulic conductivity functions are essential to the application of soil water flow theory and solute transport. Experimental methods for determining hydraulic properties of soil often are time consuming and tedious (Carsel and Parrish, 1998). Thus Carsel and Parrish (1998) used simplified approaches for estimating the hydraulic properties of soils. In their study, a method, which has been demonstrated by Rawls and Brakensiek (1985), was used for computing saturated hydraulic conductivity from soil-saturated water content, sand content and clay content.

For modeling water movement through soil pile, some soil physical and hydraulic properties, such as porosity, pore size distribution parameter, residual water content and saturated hydraulic conductivity, are need. Laboratory measured value of saturated hydraulic conductivity is almost the same as the literature data compiled by Carsel and Parrish (1988). All measured values of soil hydraulic properties were used in both analytical and numerical models for simulations. Typical (base case) values of input parameters are presented in Table 4.1.

Table 4.1 Base case values of input parameters used in the analytical and numerical soil pile models

Parameters	**Symbol**	**Unit**	**Value**
Infiltration rate	q_w	m/day	0.05
Saturated hydraulic conductivity	K_s	m/day	0.1
Soil porosity	Ø	m^3/ m^3	0.4
Residual water content (θ_w)	θ_w	m^3/ m^3	0.1
van Genuchten psd[a] parameter	n	unitless	1.31
Dispersion coefficient	D	$m^2/$ day	0.01
Soil thickness	m	m	1.0
First-order decay rate coefficient	μ	d^{-1}	(0.069 - 0.85)[b] (0.024 – 0.12)[c]
Influent concentration	C_o	Unit/100 mL – mg/L	(4800 – 150)[d]

[a] *Pore size distribution*

[b] *Lower and upper range decay rate values, respectively for total coliform*

[c] *Lower and upper range decay rate values, respectively for chlorine*

[d] *Influent concentration values and units for total coliform and chlorine, respectively.*

Carsel and Parrish (1998) provide a large statistical data base for soil moisture parameters required for the assessment of water flow and chemical transport in unsaturated porous media. Statistics of soil parameter values for clay loam, silt loam, loam and sandy loam obtained from Carsel and Parrish (1998) are presented in the Table 4.2, 4.3, 4.4, 4.5 and 4.6.

Table 4.2 Descriptive statistics for hydraulic conductivity, K_S (Carsel and Parrish, 1988)

Soil Type	**Hydraulic conductivity K_S, cm**			
	Mean	**Standard deviation**	**Coefficient of variation (%)**	**Sample size**
Clay loam	0.26	0.70	267.2	114
Loam	1.04	1.82	174.6	735
Silt loam	0.45	1.23	275.1	1093
Sandy loam	4.42	5.63	208.6	1183

Table 4.3 Descriptive statistics for van Genuchten [1976] water retention parameter, α (Carsel and Parrish, 1988)

Soil type	**α, cm^{-1}**			
	Mean	**Standard deviation**	**Coefficient of variation (%)**	**Sample size**
Clay loam	0.019	0.015	77.9	363
Loam	0.036	0.021	57.1	735
Silt loam	0.020	0.012	64.7	1093
Sandy loam	0.075	0.037	49.4	1183

Table 4.4 Descriptive statistics for van Genuchten [1976] water retention model parameter, n (Carsel and Parrish, 1988)

Soil type	**n**			
	Mean	**Standard deviation**	**Coefficient of variation (%)**	**Sample size**
Clay loam	1.31	0.09	7.2	364
Loam	1.56	0.11	7.3	735
Silt loam	1.41	0.12	8.5	1093
Sandy loam	1.89	0.17	9.2	1183

Table 4.5 Descriptive statistics for saturated water content, θ_s (Carsel and Parrish, 1988)

Soil type	**Saturated water content, θ_s**			
	Mean	**Standard deviation**	**Coefficient of variation (%)**	**Sample size**
Clay loam	0.41	0.09	22.4	364
Loam	0.43	0.10	22.1	735
Silt loam	0.45	0.08	18.7	1093
Sandy loam	0.41	0.09	21.0	1183

Table 4.6 Descriptive statistics for residual water content, θ_r (Carsel and Parrish, 1988)

Soil Type	**Residual water content, θ_r**			
	Mean	**Standard deviation**	**Coefficient of variation (%)**	**Sample size**
Clay loam	0.095	0.010	10.1	363
Loam	0.078	0.013	16.5	735
Silt loam	0.067	0.015	21.6	1093
Sandy loam	0.065	0.017	26.6	1183

CHAPTER 5

RESULTS AND DISSCUSIONS

5.1 SOIL HYDRAULIC PARAMETERS

The soil-moisture characteristic θ(h) and hydraulic conductivity K(h) functions are two basic hydraulic properties of unsaturated soils. Saturated hydraulic conductivity and soil moisture retention characteristics for clay loam soil coming from PT4 camp site were measured in the laboratory as a part of modeling study. Soil moisture retention data were obtained through pressure plate apparatus and saturated hydraulic conductivity were measured through constant head permeameter. These laboratory measurements were described in detail in section 3.2. The experimental soil moisture retention data and saturated hydraulic conductivity were fitted to the empirical θ(h) and K_s models of van Genuchten to determine the empirical parameters of water retention and hydraulic conductivity functions.

Van Genuchten parameters, α and n, obtained through non-linear regression analysis using measured θ(h) and K_s data are presented in Table 5.1, 5.2 and 5.3. The functional forms of the hydraulic properties used in the RETC were presented in section 3.3.

α, n, and m values obtained through non-linear regression analysis are same for soil samples of 1.150 and 1.341 g/cm^3 bulk densities. As seen from the Tables 5.1, 5.2, and 5.3 when soil bulk density was set as 1.374 g/cm^3, α value increased, n and m values decreased.

Figure 5.1, 5.2 and 5.3 show the corresponding soil moisture retention curves for the soil samples having the bulk densities of 1.150, 1.341, 1.374 gr/cm^3, respectively. The retention models fit the measured data very well. The non-linear regression analysis performed between the predicted and measured soil moisture content has a very high R^2 value of 0.99 for both soil samples having the bulk densities of 1.150 and 1.341 g/cm^3 and 0.981 for the soil sample having the bulk density of 1.374 g/cm^3. These curves also show that SMRCs are sensitive to the changes in bulk densities, and in turn changes in soil porosity.

Table 5.1 Results of nonlinear least squares analysis for soil sample of 1.150 g/cm^3 bulk density

<table>
<tr><th colspan="6">OBSERVED AND FITTED DATA</th></tr>
<tr><th>NO</th><th>H</th><th>WC-OBS</th><th>WC-FIT</th><th colspan="2">WC-DIF</th></tr>
<tr><td>1</td><td>1</td><td>0.420</td><td>0.420</td><td colspan="2">0</td></tr>
<tr><td>2</td><td>50</td><td>0.378</td><td>0.393</td><td colspan="2">-0.015</td></tr>
<tr><td>3</td><td>100</td><td>0.362</td><td>0.357</td><td colspan="2">0.005</td></tr>
<tr><td>4</td><td>150</td><td>0.320</td><td>0.327</td><td colspan="2">-0.007</td></tr>
<tr><td>5</td><td>200</td><td>0.300</td><td>0.304</td><td colspan="2">-0.004</td></tr>
<tr><td>6</td><td>250</td><td>0.284</td><td>0.285</td><td colspan="2">-0.001</td></tr>
<tr><td>7</td><td>300</td><td>0.273</td><td>0.270</td><td colspan="2">0.003</td></tr>
<tr><td>8</td><td>350</td><td>0.266</td><td>0.258</td><td colspan="2">0.008</td></tr>
<tr><td>9</td><td>400</td><td>0.256</td><td>0.248</td><td colspan="2">0.008</td></tr>
<tr><td>10</td><td>15300</td><td>0.095</td><td>0.116</td><td colspan="2">-0.021</td></tr>
<tr><td colspan="6">95% CONFIDENCE LIMITS</td></tr>
<tr><th>VARIABLE</th><th>VALUE</th><th>S.E.COEFF.</th><th>T-VALUE</th><th>LOWER</th><th>UPPER</th></tr>
<tr><td>α</td><td>0.0063</td><td>0.0008</td><td>7.9</td><td>0.0045</td><td>0.0081</td></tr>
<tr><td>n</td><td>1.6167</td><td>0.08723</td><td>18.53</td><td>1.4156</td><td>1.8179</td></tr>
<tr><td>m</td><td>0.3815</td><td>-</td><td>-</td><td>0.2936</td><td>0.4499</td></tr>
</table>

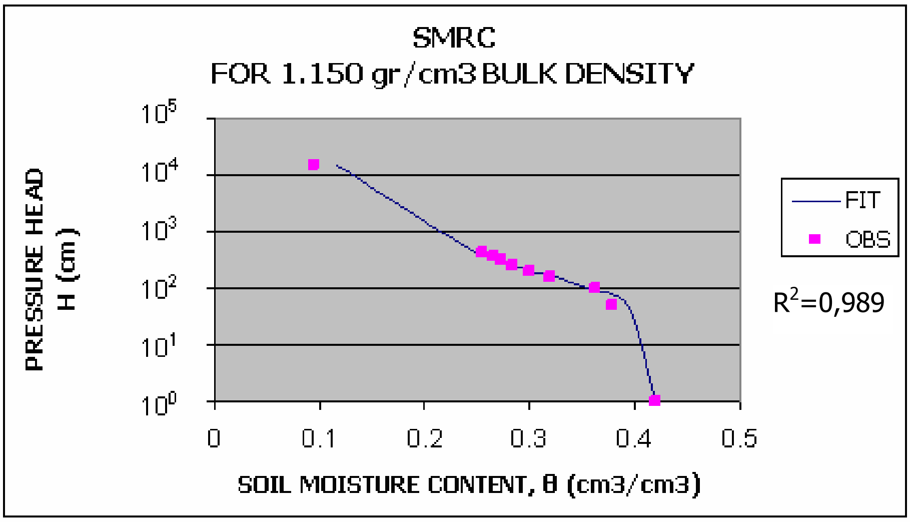

Figure 5.1 Measured and fitted Soil Moisture Retention Curve for soil sample of 1.150 gr/cm^3 bulk density

Table 5.2 Results of nonlinear least squares analysis for soil sample of 1.341 g/cm^3 bulk density

OBSERVED AND FITTED DATA				
NO	H	WC-OBS	WC-FIT	WC-DIF
1	1	0.402	0.4	0.002
2	50	0.368	0.384	-0.016
3	100	0.347	0.358	-0.011
4	150	0.333	0.333	-0.000
5	200	0.313	0.312	0.001
6	250	0.298	0.294	0.005
7	300	0.282	0.278	0.004
8	350	0.267	0.266	0.001
9	400	0.258	0.255	0.003
10	15300	0.095	0.113	-0.018

95% CONFIDENCE LIMITS					
VARIABLE	VALUE	SZ.E.COEFF.	T-VALUE	LOWER	UPPER
α	0.0063	0.0008	7.9	0.0045	0.0081
n	1.6167	0.0872	18.53	1.4156	1.8179
m	0.3815	-	-	0.2936	0.4499

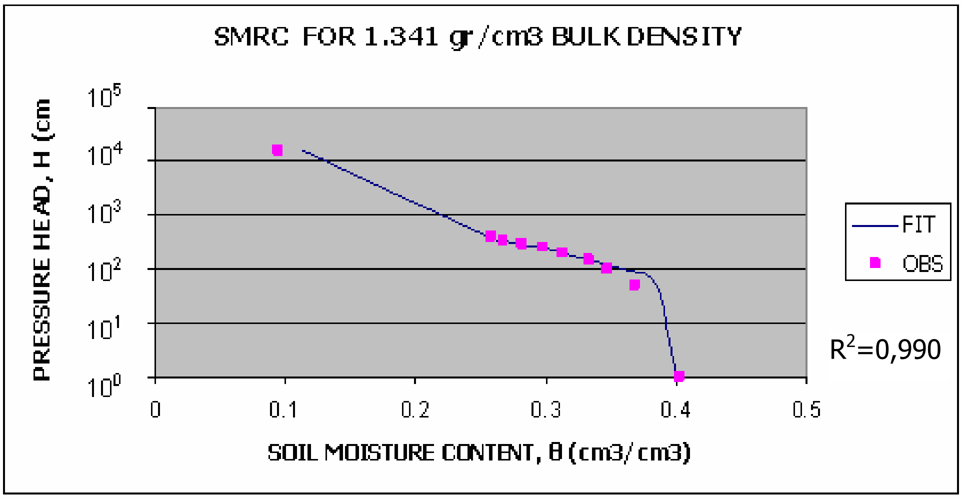

Figure 5.2 Measured and fitted Soil Moisture Retention Curve for soil sample of 1.341 gr/cm^3 bulk density

Table 5.3 Results of nonlinear least squares analysis for soil sample of 1.374 g/cm^3 bulk density

OBSERVED AND FITTED DATA				
NO	**H**	**WC-OBS**	**WC-FIT**	**WC-DIF**
1	1	0.420	0.420	0
2	50	0.377	0.399	-0.022
3	100	0.360	0.371	-0.011
4	150	0.343	0.345	-0.002
5	200	0.323	0.324	-0.001
6	250	0.306	0.306	0.0003
7	300	0.294	0.291	0.003
8	350	0.288	0.279	0.010
9	400	0.278	0.268	0.010
10	15300	0.095	0.121	-0.026

95% CONFIDENCE LIMITS					
VARIABLE	**VALUE**	**SZ.E.COEFF.**	**T-VALUE**	**LOWER**	**UPPER**
α	0.0072	0.0013	5.5	0.0042	0.0102
n	1.5375	0.0955	16.11	1.3174	1.7576
m	0.3496	-	-	0.2409	0.4310

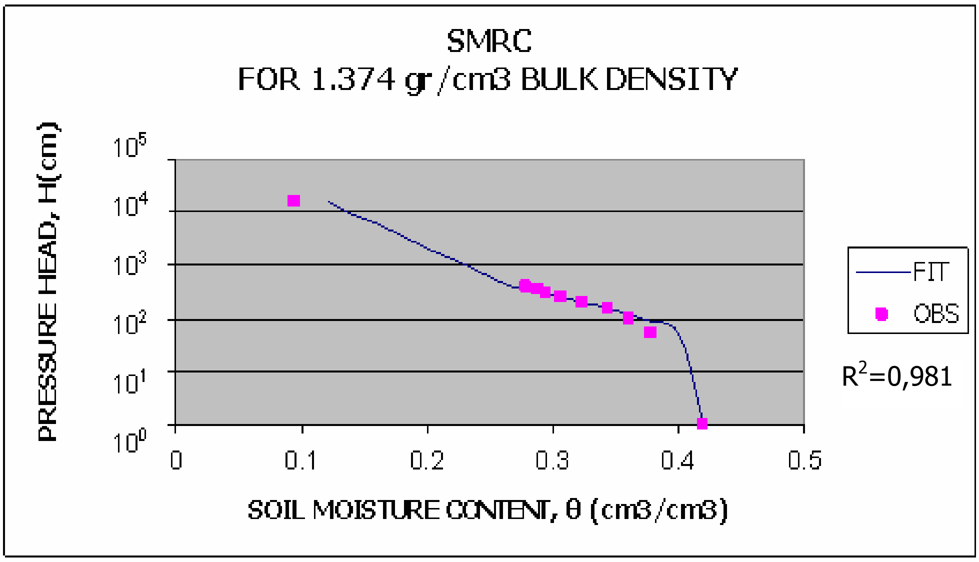

Figure 5.3 Measured and fitted Soil Moisture Retention Curve for soil sample of 1.374 gr/cm^3 bulk density

5.2 MODEL APPLICATION

A simplistic analytical and a numerical unsaturated flow and transport modeling approaches were used to assess total coliform and chlorine attenuation during steady-state infiltration of partially treated wastewater and transport of total coliform and chlorine through soil pile systems. Simulations of clay loam (actual site soil texture) soil pile were performed to assess contaminant attenuation efficiencies for SPS during steady infiltration of partially treated domestic wastewater produced at the BTC Co. construction site. Steady-state assumption for wastewater flow through soil pile may introduce some uncertainty in the model predictions. Time to reach steady-state in the soil pile may take long time especially for fine-textured soils with large pile thickness. Therefore, transient nature of wastewater infiltration and redistribution through soil pile must be investigated. A coupled numerical transient unsaturated flow and transport modeling approach can well serve for this purpose. Numerical model simulations of the same clay loam soil were performed to assess the transient nature of water infiltration and redistribution through soil piles. Results of numerical and analytical model were compared for SPS with clay loam soil which is the most conservative case for comparing numerical and analytical model results.

Following to comparison of analytical and numerical modeling results, analytical modeling approach was used to develop guidelines for the design and operation of SPS consisting of different soil textures. Soil texture is important factor affecting wastewater infiltration and contaminant removal in soil. Table 5.4 presents land treatment applications and corresponding soil textures (USEPA, 1992). Fine-textured soils which have a lot of clay and/or silt often have slow water infiltration, because the space that the soil occupies is relatively dense. Low infiltration rate provides low concentration at the bottom of the system, reflecting long detention time in the soil pile. Coarse-textured soils (such as sands or sandy loams) have rapid infiltration rates. This causes short detention time of pollutant in the soil environment. In this study, silt loam, loam and sandy loam soils were selected to see impact of soil texture on total coliform and chlorine removal efficiencies in SPS.

Table 5.4 Land treatment applications versus soil textures

Land treatment application	**Soil textures**
Slow rate	Sandy loam to clay loam
Rapid infiltration	Sand and sandy loam
Subsurface infiltration	Sand to clayey loam
Overland flow	Silty loam and clayey loam

**Source: USEPA, Wastewater Treatment/Disposal for Small Communities. Cincinnati, Ohio, 1992. (EPA Report No: EPA-625/R-92-005)*

Using the analytical and numerical models, a total of 260 runs were performed to simulate effluent concentrations for total coliform and chlorine at the bottom of the clay loam soil pile as a function of time. These simulations represent different soil types (clay loam, loam, sandy loam and silt loam), soil pile configuration, packing and infiltration conditions, reflecting the sensitivity of soil pile system to various parameters. Results of model simulations were used to calculate the contaminant attenuation efficiencies from the simulated concentrations of effluent collected at the bottom of the soil pile by the drainage system. Removal (attenuation) efficiency, R, was calculated by using following equation:

$$R = 1 - \frac{C}{C_0} \tag{5.1}$$

where, R is removal efficiency (%), C is the simulated effluent concentration and C_0 is the influent concentration.

5.2.1 Sensitivity Analysis

Sensitivity analysis was done to evaluate the sensitivity of soil pile system response to the variation of input parameter. Sensitivity analysis was performed by changing soil thickness, infiltration rate, saturated hydraulic conductivity and soil porosity data one by one while keeping the base case values for the others. Mean value of saturated hydraulic conductivity given in Table 4.2 was taken as a base case value and sensitivity analysis value was taken by increasing (or decreasing) base case value of hydraulic conductivity by %50. Half value of mean saturated hydraulic conductivity was taken as a base case value of infiltration rate and values for sensitivity analysis was calculated by increasing (or decreasing) base case parameter of infiltration rate by %50. 100, 150, and 200 m soil thicknesses were used to analyze the soil pile system in terms of soil thickness. Mean value of soil porosity given in Table 4.5 was taken as a base case value and values for sensitivity analysis of soil porosity was calculated by increasing (or decreasing) base case value by standard deviation. Values of sensitivity analysis for clay loam were given in Table 5.8.

5.2.2 Analytical Model Application for Clay Loam Soil

A simplistic analytical modeling approach was used to assess contamination attenuation efficiencies achievable by soil pile systems during steady infiltration of partially treated domestic wastewater produced at BTC Co.

construction camp sites. In total 52 simulation runs for clay loam soil were carried out to simulate fate and transport of total coliform and chlorine using analytical modeling. Textural proportions of clay loam soil are given in the Appendix A. Simulation runs are performed to demonstrate the model sensitivity to input parameters. Both contaminant data and soil hydraulic parameters are compiled from the literature (Finamuzi et al., 2004; Choi et al., 2004; Carsel and Parrish, 1988). Values of input parameters for base case and sensitivity simulation runs used in the analytical model for clay loam soil are presented in Table 4.1 and 5.5, respectively.

Table 5.5 Simulation runs of sensitivity analysis for clay loam soil

Cases for model runs	**Unit**	**Values**		
Soil thickness, L	cm	100	150	200
Infiltration rate, q_w	m/day	0.025	0.05	0.075
Saturated hydraulic conductivity, K_s	m/day	0.05	0.10	0.15
Soil porosity, Ø	m^3/m^3	0.30	0.40	0.50
Optimization run (L, q_w, Ø)	(m, m/day, m^3/m^3)	L=200	q_w=0.025	Ø=0.50

5.2.2.1 Breakthrough Curves and Attenuation Efficiencies for Total Coliform

Table 5.6 gives the simulated steady-state total coliform concentration and mass removal efficiencies in the effluent at the bottom of the soil pile for lower and upper range of first-order decay rate constants for clay loam soil. Simulations were performed under different soil thickness, infiltration rate, saturated hydraulic conductivity and porosity conditions. Table 5.6 shows that steady-state total coliform concentration decreases, in turn, removal efficiency increases with increasing soil thickness and porosity and with decreasing infiltration rate. Increasing soil thickness and porosity imply low packing density of soil pile while decreasing infiltration rate implies increasing detention time of pollutants in the soil pile. Porosity values 0.3, 0.4, and 0.5 used in the simulations correspond to soil bulk (packing) densities of 1855, 1590, and 1325 kg/m^3, respectively. Steady-state concentration and removal efficiencies of total coliform seem to be insensitive to saturated hydraulic conductivity of soil pile. However being the upper limit of infiltration rate, K_s affects the operational parameter of soil pile, such as q_w and θ_w (see equations 4.4 and 4.5). In soil with very low hydraulic conductivity, wastewater effluent is unable to move through the soil profile. In soil with very high hydraulic conductivity, the effluent will move through too quickly, and will not be treated properly. So, soil hydraulic conductivity must be considered when designing a soil pile system. It turns out that optimizing the soil pile with respect to L, q_w, and ϕ significantly improves the total coliform attenuation efficiencies (see the last optimal parameter case in Table 5.6).

Table 5.6 Simulated steady-state mass removal efficiencies of the total coliform and chlorine in the effluent at the bottom of the soil pile for clay loam soil

Cases for model runs	**TOTAL COLIFORM** **C_0=48000 unit/L**				**CHLORINE** **C_0=150 mg/L**			
	μ= 0.069 d^{-1}		**μ= 0.85 d^{-1}**		**μ= 0.024 d^{-1}**		**μ= 0.12 d^{-1}**	
	C (unit/L)	**R(%)**	**C (unit/L)**	**R(%)**	**C (mg/L)**	**R(%)**	**C (mg/L)**	**R(%)**
L=100 cm	30050	37	53	98.9	127	15	67.7	55
L=150 cm	23350	51	5	99.9	116.1	23	44.1	71
L=200 cm	18150	62	0	100	106.1	29	28.8	81
q_w=0.025 m/d	22100	54	12	99.7	112.7	25	41.9	72
q_w=0.05 m/d	30050	37	53	98.9	127	15	67.7	55
q_w=0.075 m/d	34320	28	136	97.2	133.3	11	84.3	44
K_s=0.05 m/d	29410	39	46	99	126	16	65.3	56
K_s=0.10 m/d	30050	37	53	98.9	127	15	67.7	55
K_s=0.15 m/d	30420	37	57	98.8	127	15	69	54
Ø=0.30 m^3/m^3	33320	31	108	97.7	131.9	12	80.2	47
Ø=0.40 m^3/m^3	30050	37	53	98.9	127	15	67.7	55
Ø=0.50 m^3/m^3	27340	43	31	99.4	122.6	18	58.1	61
L=200 cm **Ø=0.50 m^3/m^3** **q_w=0.025 m/d**	6930	86	0	100	71.8	52	6.7	96

Finally, simulation results reveal that the most important parameter for coliform attenuation efficiency is the first-order decay coefficient. With a μ value at the lower end of the range, total coliform attenuation efficiency ranged between 28 and 62% depending on the simulation cases considered. Optimization of soil pile with respect to L, q_w, and ϕ increased the attenuation efficiency up to 86%. With a μ value at the upper end of the range, total coliform attenuation was almost complete regardless of soil pile parameters. It is well known that the uncertainty in the value of μ is very high and affected very much by soil-environmental conditions, such as temperature, soil moisture content adsorption to soil particle, soil pH, solar radiation and soil type.

Figure 5.4 shows effluent total coliform concentration (breakthrough curves) at the bottom of the soil pile as a function of time for the lower and upper range of μ values, different soil thickness and infiltration rate conditions. These figures also show that soil system is highly sensitive L and q_w with respect to total coliform attenuation, especially when μ values are close to the lower end of the range. This means that soil-environmental conditions with in the soil pile will have a great impact on the overall total coliform attenuation performance of the system.

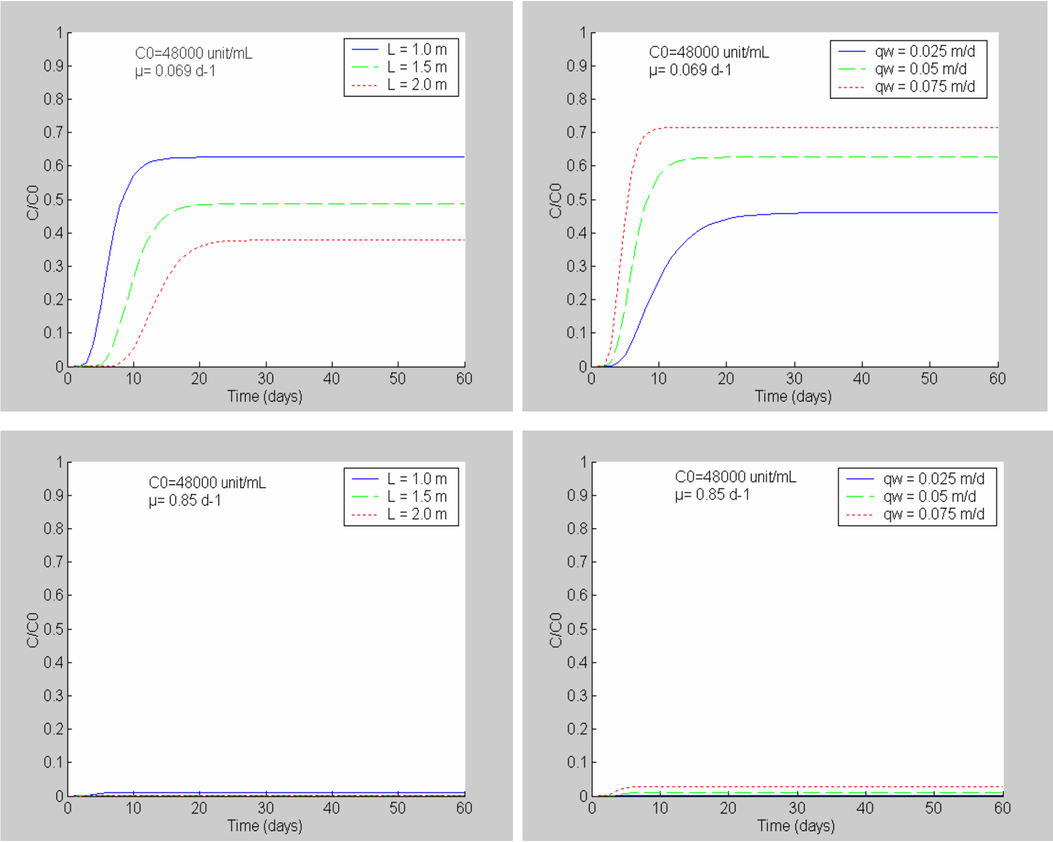

Figure 5.4 Simulated total coliform effluent concentrations (breakthrough curves) at the bottom of the soil pile different soil thicknesses and infiltration rates for clay loam

Simulation results are also consistent with the findings of literature reported for attenuation efficiencies of microorganisms (pathogens) in SAT systems based pilot scale laboratory column SAT simulations, AWWA (1998) reported that pathogen removal efficiency is inversely correlated with infiltration rate and directly correlated with retention time (soil thickness). Removal efficiencies in this SAT study ranged from 45 to 90% during water flow through 1 m of soil. FAO (1992) reported that soil is an effective filter to remove microorganisms from wastewater effluents (except coarse soils such as sand and gravels or fractured rocks). Bacteria are physically strained from water, whereas small viruses are usually adsorbed. This adsorption is favored by a low pH and a high salt concentration in wastewater. Most bacteria and viruses die in a few weeks to a few months, but much longer survival times have also been reported. Many studies indicate essentially complete fecal coliform removal after percolation of 1 to a few meters through the soil of medium texture.

5.2.2.2 Breakthrough Curves and Attenuation Efficiencies for Chlorine

The results of simulation runs for chlorine concentrations in the effluent are shown in Table 5.6 and Figure 5.5. Simulations were performed under different soil thickness, infiltration rate, saturated hydraulic conductivity and porosity conditions. Chlorine breakthrough and attenuation behavior in the soil pile is very much similar to total coliform attenuation behavior.

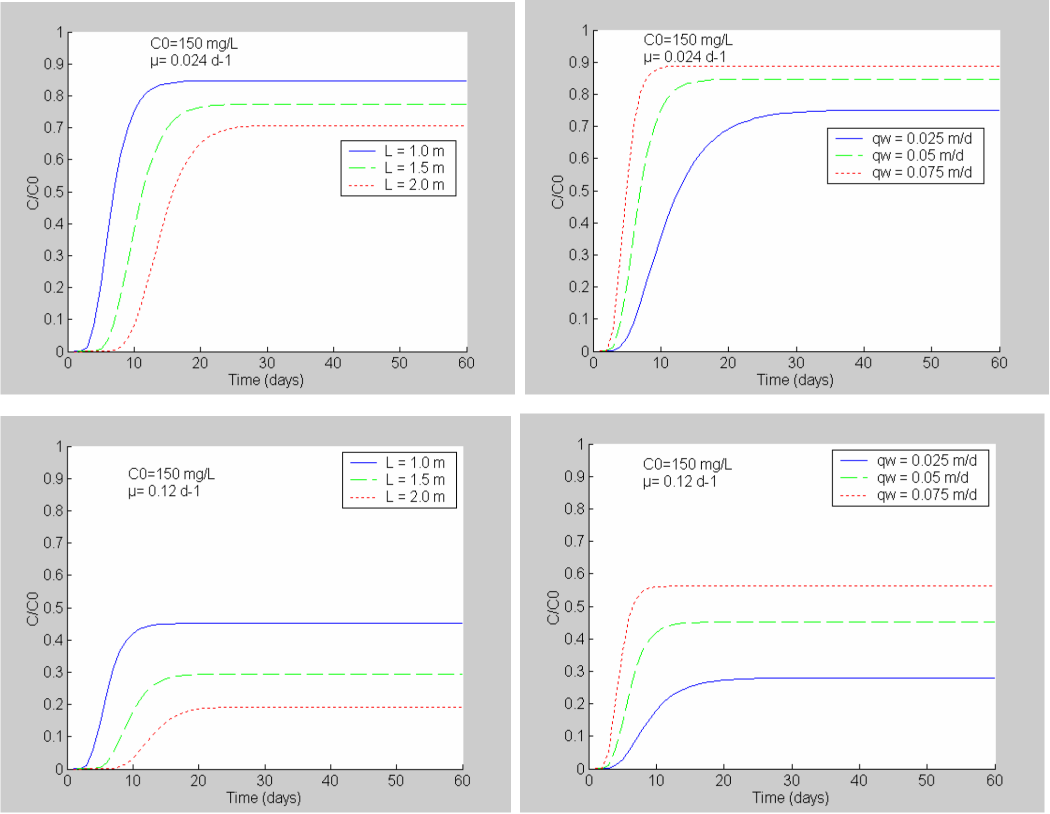

Figure 5.5 Simulated total chlorine effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for clay loam

As seen from the Table 5.6, chlorine attenuation efficiencies ranged between 11-29% and 44 - 81% with a μ value at the lower and upper end of the range, respectively.

Removal efficiencies of chlorine were obtained 15, 23, and 29% for soil thicknesses of 100, 150, and 200 cm at the lower end of the μ value, respectively. Removal efficiencies changed with 0.025, 0.05 and 0.075 m/day infiltration rate conditions within a range of 25, 15, and 11%, respectively. Infiltration rate of 0.025 m/day provides less concentration at the bottom of the system because of reflecting long detention time in the soil pile. Removal efficiencies of chlorine were found 12, 15, and 18% for 0.3, 0.4, and 0.5 porosities, respectively.

Optimizing the soil pile with respect to soil thickness, infiltration rate, and porosity significantly improved the chlorine attenuation efficiency from 29 to 52% for low μ and 81 to 96% for high μ value (see the last optimal parameter case in Table 5.6).

5.2.3 Numerical Model Application for Clay Loam Soil

Considering the lack of relevant information and the analytical nature of the developed model, the findings of analytical modeling study need to be taken some caution. For example, steady-state assumption for water flow introduce some uncertainty in the model results; and achieving steady-state water flow conditions through soil pile may take very long time especially for fine textured such as clay loam soils, which may pose operational problems due to low infiltration capability of soil pile, in turn reduce treatment capacity (infiltration volume) per day. Therefore, it was decided that transient nature of water infiltration and redistribution through soil pile need to be considered and its effects need to be investigated. For this purpose, use of numerical unsaturated flow and transport modeling approach was planned.

A total of 52 runs were performed to simulate fate and transport of total coliform and chlorine in SPS. The same input data used for analytical model (Table 4.1 and 5.5) were also used in the numerical model, together with the additional hydraulic parameters of θ(h) and K(h) functions (α, n, and m) presented in Table 5.7.

Table 5.7 Hydraulic parameters of θ(h) and K(h) functions

Hydraulic functions	Value
α	0.0066
n	1.5903
m	0.3709
Saturated hydraulic conductivity, K_s, m/day	0.0216

∗ α , n and m are empirical constants affecting the shape of the retention curve

5.2.3.1 Breakthrough Curves and Attenuation Efficiencies for Total Coliform

The simulated transient total coliform concentrations and mass removal efficiencies in the effluent at the bottom of the SPS for the first-order decay rate constants of 0.069 d^{-1} and 0.85 d^{-1} under different soil thickness, infiltration rate, saturated hydraulic conductivity and soil porosity conditions were presented in the Table 5.8.

Table 5.8 Simulated transient mass removal efficiencies of the total coliform and chlorine in the effluent at the bottom of the soil pile for clay loam soil

Cases for model runs	**TOTAL COLIFORM C_0 = 48000 unit/L**				**CHLORINE C_0 = 150 mg/L**			
	μ= 0.069 d^{-1}		**μ= 0.85 d^{-1}**		**μ= 0.024 d^{-1}**		**μ= 0.12 d^{-1}**	
	C (unit/L)	**R(%)**	**C (unit/L)**	**R(%)**	**C (mg/L)**	**R(%)**	**C (mg/L)**	**R(%)**
L=100 cm	28320	41	384	99.2	124.5	17	61	59
L=150 cm	21840	54.5	48	99.9	112.95	24.7	39.45	74
L=200 cm	16944	64.7	0	100	103.2	31.2	24.75	84
q_w=0.025 m/d	17760	63	0	100	104.25	30.5	27.6	82
q_w=0.05 m/d	28320	41	384	99.2	124.5	17	61	59
q_w=0.075 m/d	33792	29.6	1392	97.1	131.7	12.2	82.2	45
K_s=0.05 m/d	28320	41	384	99.2	124.2	17.2	60.9	59
K_s=0.10 m/d	28320	41	384	99.2	124.5	17	61	59
K_s=0.15 m/d	28560	40.5	384	99.2	124.5	17	61	59
Ø=0.30 m^3/m^3	32352	32.6	1008	97.9	130.2	13.2	75.75	50
Ø=0.40 m^3/m^3	28320	41	384	99.2	124.5	17	61	59
Ø=0.50 m^3/m^3	24960	48	144	99.7	119.1	20.6	50.25	67
L=200 cm **Ø=0.50 m^3/m^3** **q_w=0.025 m/d**	4128	91.4	0	100	60	60	2.25	99

Numerical model showed similar results with the analytical model for total coliform attenuation. Based on Table 5.8 results of numerical modeling can be interpreted as follows. Coliform concentrations decrease and mass removal efficiencies increase at the bottom of the soil pile with increasing soil thickness and soil porosity. At the lower end of the μ value, total coliform attenuation efficiencies were found 41, 54.5 and 64.7% for soil thickness of 100, 150, and 200 cm, respectively. For soil porosities of 0.3, 0.4, and 0.5 m^3/m^3, total coliform attenuation efficiencies ranged between 32.6-48%. With a μ value of 0.85 d^{-1}, total coliform attenuation efficiencies reach almost

100% for both different soil thickness and porosity conditions. Coliform removal efficiencies decrease with increasing infiltration rates. Total coliform attenuation efficiency changed with infiltration rate with in a range of 30 to 63% when decay rate is at the lower end while it ranged between 97 and 100% when decay rate is at the upper end of the range. Hydraulic Conductivity does not have significant effect on the effluent concentrations.

Numerical model showed that in order to improve the total coliform attenuation efficiencies the soil pile should be optimized with respect to soil thickness, infiltration rate, and soil porosity like analytical model. As seen from Table 5.8, the total coliform attenuation efficiency ranges between 30% - 65% with a μ value of 0.069 d^{-1} depending on the simulation cases. Attenuation efficiency increased up to 91.4% for μ value of 0.069 d^{-1} with the optimization of SPS with respect to soil thickness, infiltration rate, and soil porosity.

Consequently, the transient simulation results showed that the total coliform attenuation was independent from soil pile parameters with a μ value at the upper end of the range (0.85 d^{-1}) and the first order decay coefficient is the most crucial parameter for total coliform attenuation efficiency as is the case in steady-state simulation.

Figure 5.6 shows simulated total coliform effluent concentrations (breakthrough curves) at the bottom of the soil pile for μ values of 0.069 d^{-1} and 0.85 d^{-1} at different soil thickness and infiltration rates conditions, respectively. As seen from the figures infiltration rate and soil thickness is very important parameters with respect to coliform attenuation.

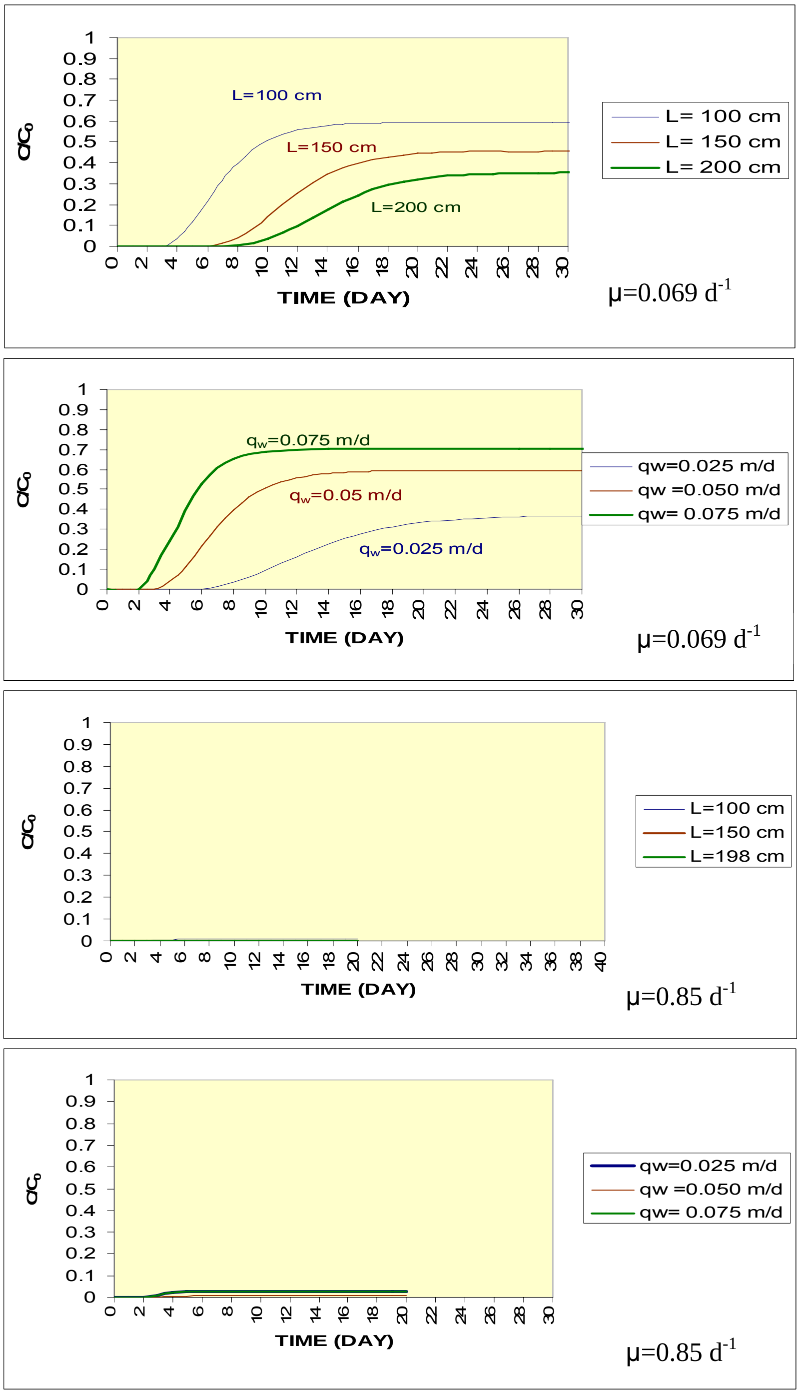

Figure 5.6 Simulated total coliform effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for clay loam soil

5.2.3.2 Breakthrough Curves and Attenuation Efficiencies for Chlorine

The simulated transient total chlorine concentrations and mass removal efficiencies at the bottom of the soil pile system were presented in the Table 5.8 for μ values of 0.024 and 0.12 d^{-1}.

Breakthrough curves of chlorine (Figure 5.7) show the similar physical properties as the breakthrough curves of total coliform. Chlorine concentrations decrease and mass removal efficiencies increase at the bottom of the soil pile with increasing soil thickness and soil porosity and decreasing infiltration rates. As seen from the Table 5.8, the chlorine attenuation efficiencies range between 12.2 - 31.2 % and 45-84% with a μ value of 0.024 d^{-1} and 0.12 d^{-1}, respectively. Following the optimization of soil thickness, infiltration rate, and soil porosity, the attenuation efficiencies increase up to 60% and %99 for μ values of 0.024 d^{-1} and 0.12 d^{-1}, respectively.

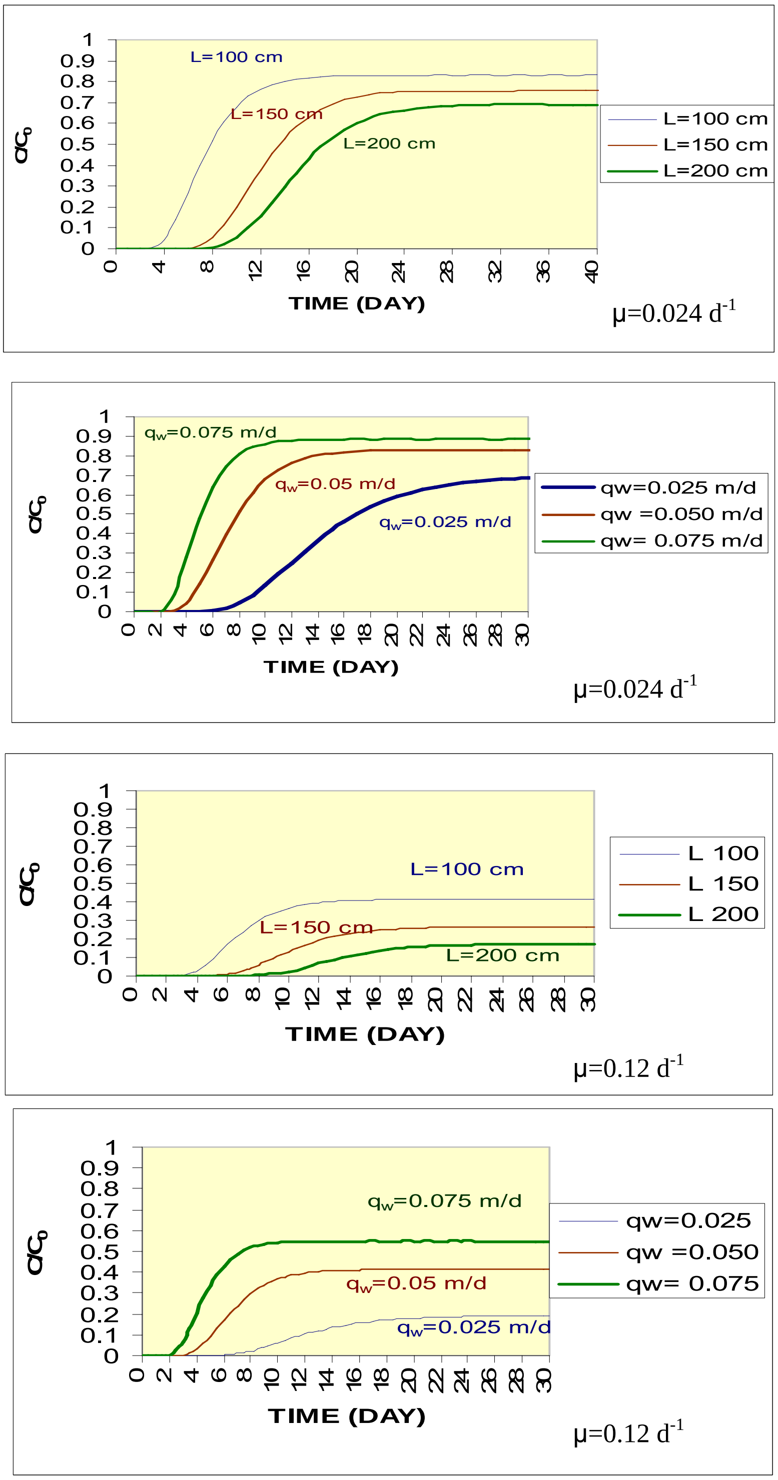

Figure 5.7 Simulated total chlorine effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for clay loam soil

Numerical modeling results indicated that better chlorine removal efficiencies were obtained with the upper end of the µ value. Chlorine attenuation efficiencies increased up to 84% with the µ value of 0.12 d^{-1}. Like analytical model results, numerical model results also show that soil system is highly sensitive to L and q_w and ϕ with respect to chlorine attenuation, especially when µ values are close to the lower end of the range.

5.3 COMPARISON OF ANALYTICAL AND NUMERICAL MODEL RUNS

In this section, unsaturated steady-state and transient flow and transport model results will be compared in terms of distribution of water content and chlorine and total coliform removal efficiencies to see the effect of the transient nature of water infiltration and redistribution through a clay loam soil pile.

5.3.1 Water Content

Analytical model assumes that water content (WC) is constant with depth and time during the wastewater infiltration through SPS. Calculation of steady-state water content was given by Eqn (4.4).

During the steady state flow in the soil pile, water content is calculated as 0.29-0.45 m^3/m^3 depending on the simulation cases.

In transient flow condition, water content changes with depth. As seen from the Figure 5.8 and 5.9, soil reaches steady-state at different days for different infiltration rates and soil thicknesses under the transient flow condition. At high infiltration rates, water flows faster in the SPS than low infiltration rate. So, soil reaches steady-state in a shorter period of time. For a thickness of 1 m and porosity of 0.4 m^3/m^3 soil pile reaches steady-state at the seventh, forth and third day for the infiltration rates of 0.025, 0.05 and 0.075 m/d, respectively.

As seen from Figure 5.8 and 5.9, for the entire soil pile time to reach steady-state increases with increasing soil thickness and decreasing infiltration rate. It is observed that it takes about 17 days for soil pile with a thickness of 2 m to reach steady-state flow conditions when infiltration rate is 0.025 m/d and soil porosity is 0.5 m^3/m^3. At the end of the 17th day water content reached to value of 0.49 m^3/m^3. In this simulation case, water content value for analytical model is 0.45 m^3/m^3. During the comparison of steady-state and transient flow model results, it was understood that transient numerical model results are much more reliable than analytical steady-state model results, when soil thickness of SPS is high especially for fine textured soils.

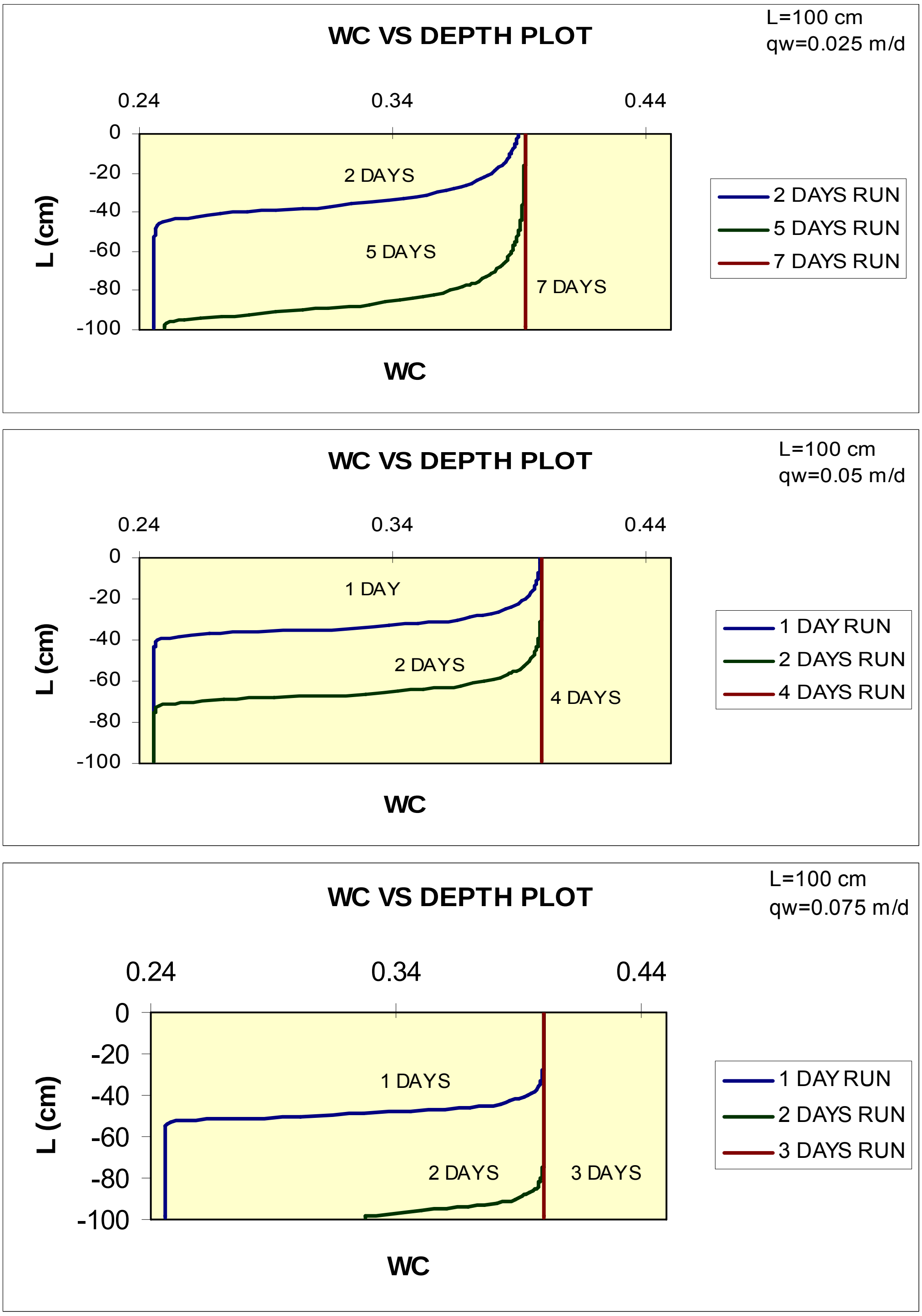

Figure 5.8 Simulated water content (WC) distributions as a function of depth and time for different infiltration rate values.

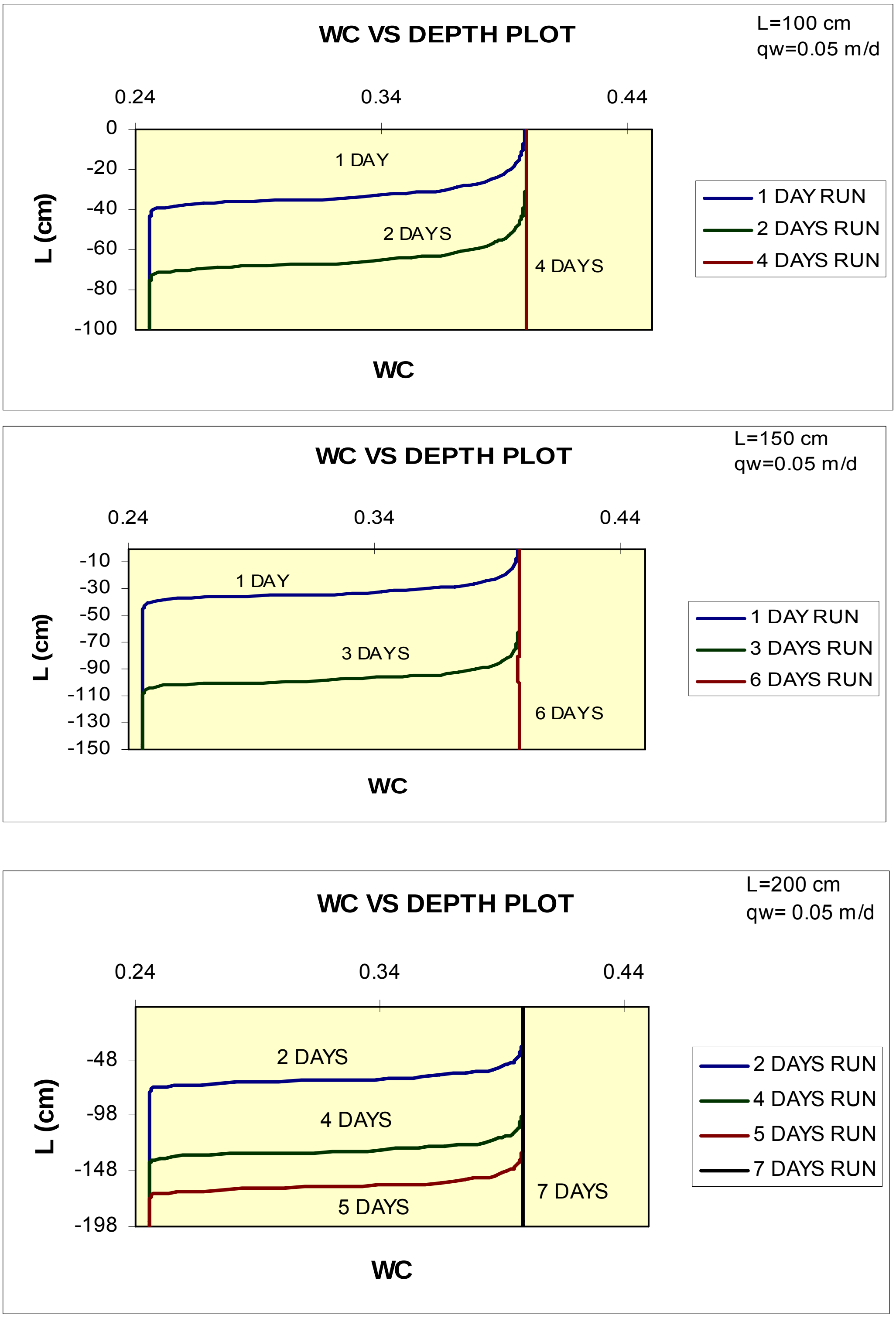

Figure 5.9 Simulated water content (WC) distributions as a function of depth and time for different soil thicknesses values.

5.3.2 Contaminant Attenuation

As seen from the Table 5.9, simulated steady-state total coliform mass removal efficiencies for μ value of 0.069 d^{-1} are 37, 51, and 62% at the soil thicknesses of 100, 150 and 200 cm, respectively. Transient simulation results are 4 to 22% higher than steady-state simulation results depending on soil thickness, infiltration rate, and soil porosity for the μ value of 0.069 d^{-1}.

Table 5.9 Simulated steady-state and transient mass removal efficiencies of the total coliform and chlorine in the effluent at the bottom of the soil pile for clay loam soil

Cases for model runs	**TOTAL COLIFORM REMOVAL EFFICIENCIES R(%)**				**CHLORINE REMOVAL EFFICIENCIES R(%)**			
	μ= 0.069 d^{-1}		**μ= 0.85 d^{-1}**		**μ= 0.024 d^{-1}**		**μ= 0.12 d^{-1}**	
	Steady state	**Transient**	**Steady state**	**Transient**	**Steady state**	**Transient**	**Steady state**	**Transient**
L=100 cm	37	41	98.9	99.2	15	17	55	59
L=150 cm	51	54.5	99.9	99.9	23	24.7	71	74
L=200 cm	62	64.7	100	100	29	31.2	81	84
q_w=0.025 m/d	54	63	99.7	100	25	30.5	72	82
q_w=0.05 m/d	37	41	98.9	99.2	15	17	55	59
q_w=0.075 m/d	28	29.6	97.2	97.1	11	12.2	44	45
K_s=0.05 m/d	39	41	99	99.2	16	17.2	56	59
K_s=0.10 m/d	37	41	98.9	99.2	15	17	55	59
K_s=0.15 m/d	37	40.5	98.8	99.2	15	17	54	59
Ø=0.30 m^3/m^3	31	32.6	97.7	97.9	12	13.2	47	50
Ø=0.40 m^3/m^3	37	41	98.9	99.2	15	17	55	59
Ø=0.50 m^3/m^3	43	48	99.4	99.7	18	20.6	61	67
L=200 cm **Ø=0.50 m^3/m^3** **q_w=0.025 m/d**	86	91.4	100	100	52	60	96	99

For μ value of 0.85 d^{-1}, simulated steady-state total coliform mass removal efficiencies are almost same with transient mass removal efficiencies. At the upper end of the μ value range, total coliform attenuation efficiencies are above 97% for both analytical and numerical model.

Steady-state and transient chlorine attenuation behavior in the soil pile is very similar to coliform attenuation behavior. At the lower end of the μ value (0.024 d^{-1}) chlorine attenuation efficiencies changes with soil pile parameters within a range of 11 – 52% and 12.2 – 60% for steady-state and transient simulations, respectively. Removal efficiencies range between 44 – 96% for steady-state simulation and 45 – 99% for transient simulation when decay rate is at the upper end of the range (0.12 d^{-1}). Thus, it is observed that when soil environmental conditions are less favorable for the decay process, then transient model results are much more reliable and may be preferred over simplistic steady-state models.

Both analytical and numerical modeling results showed that there is not significant difference between steady-state and transient simulation results in terms of total coliform and chlorine attenuation efficiencies and SPS is highly sensitive to soil thickness, infiltration rate, and soil porosity. Steady-state and transient simulation results also revealed that the most important parameter for total coliform and chlorine attenuation is the first-order decay coefficient, which is highly dependent on the favorability of soil environmental conditions with respect to decay process.

Overall results revealed that since the difference between removal efficiencies of steady-state and transient models differ by of the most 22% even under the most conservative soil conditions (e.g. clay loam), then steady-state models can be used for most practical purposes of system design and operation, especially when site specific data regarding unsaturated hydraulic parameters are not available.

5.4 DEVELOPMENT OF GUIDELINES FOR DESIGN AND OPERATION OF SOIL PILE

5.4.1 Partial Calibration of Analytical Model

A partial calibration analysis for steady-state analytical model was performed as a part of this modeling study to obtain site-specific kinetic data for total coliform. Since the pilot plant could not be operated as planed and some problems were occurred during the operation (cold season conditions), data could not be obtained from the plant as desired. Therefore, calibration study was carried out with a very limited data obtained from the pilot plant.

The wastewater was applied to SPS uniformly across the soil surface (60 m^2) with the flowrate of 20 m^3/day. Wastewater infiltrated through clay loam SPS during 11 days. At the end of the 11th day wastewater effluent sample was taken at the depths of 50, 100, and 150 cm. Total coliform concentration of 17000 unit/L was found at 50 cm depth. Total coliform concentrations in the samples collected from 100 and 150 cm were measured as <4800 unit/L. Calibration study was performed to obtain site-specific decay rate constant for total coliform using data presented Table 5.10.

Table 5.10 Input data used for calibration of the analytical model

Parameters	**Symbol**	**Unit**	**Value**
Infiltration rate	q_w	m/day	0.04
Saturated hydraulic conductivity	K_s	m/day	0.04
Soil porosity	Ø	m^3/ m^3	0.39
Residual water content	θ_w	m^3/ m^3	0.1
van Genuchten psd parameter	n	unitless	1.31
Dispersion coefficient	D	$m^2/$ day	0.01
Soil thickness	m	m	1.0
Influent concentration	C_o	Unit/100 mL	4800

Table 5.11 The results of calibration study conducted for total coliform first-order decay rate

k_b (day^{-1})	**Predicted total coliform concentration (unit/L)**	
	Soil pile depth, 50 cm[a]	**Soil pile depth, 100 cm[b]**
0.1	33116	21156
0.2	23675	10242
0.3	17390	5304
0.35	15028	3894
0.4	13049	2891
0.5	9965	1642
0.6	7722	964
0.7	6058	582
0.8	4805	360
0.9	3847	225
1.0	3106	146
1.1	2527	96
1.2	2070	64

[a] *Measured total coliform concentration at 50 cm depth is 17000 unit/L*

[b] *Measured total coliform concentration at 100 cm depth is <4800 unit/L*

Firstly, calibration was conducted for 17000 unit/L total coliform concentration measured at the depth of 50 cm of pilot plant. Calibration results showed that approximately total coliform concentrations were obtained 17000 unit/L at the depth of 50 cm and 4981 unit/L at the depth of 100 cm using 0.31 d^{-1} first-order decay rate constant.

Calibration results showed that total coliform project discharge standard (4000 unit/L) was provided with a first-order decay rate constant of 0.35 d^{-1}. For this μ value total coliform concentrations were obtained 15028 unit/L at the depth of 50 cm and 3894 unit/L at the depth of 100 cm. The results also indicated that total coliform first-order decay rate obtained from calibration study fall within the range of 0.069-0.85 d^{-1} reported in the literature and the used in the simulations with both the analytical and numerical models. Since the calibrated value aggress well with the literature data, the analytical model can be consider as validated to a limited extent.

5.4.2 Analytical Model Application for different soil types

As a result of comparison of contaminant attenuation efficiencies obtained from numerical and analytical modeling study conducted for clay loam soil pile, it was decided that analytical modeling approach can be used to assess total coliform and chlorine attenuation through SPS with different soil types (silt loam, loam and sandy loam soils). A total of 52 runs for each of the three soil types were carried out to simulate fate and transport of total coliform and chlorine using analytical modeling. Literature information of contaminant data and soil hydraulic parameters were used in the modeling study (Finamuzi et al., 2004; Choi et al., 2004; Carsel and Parrish, 1988). Values of input parameters for base case and sensitivity simulation runs used in the analytical model for each soil type are presented in Table 5.12 and Table 5.13, respectively. Modeling results was used for developing a guideline for assessing the design and operation conditions of SPS consisting of silt loam, loam, and sandy loam soils.

Table 5.12 Simulation runs for sensitivity analysis

Cases for model runs	**Silt loam**	**Loam**	**Sandy loam**
Soil thickness, L (m)	100 150 200	100 150 200	100 150 200
Infiltration rate, q_w (m/day)	0.027 0.054 0.108	0.0625 0.125 0.25	0.265 0.53 1.06
Saturated hydraulic conductivity, K_s (m/day)	0.054 0.108 0.216	0.125 0.25 0.5	0.53 1.06 2.12
Soil porosity, Ø (m^3/ m^3)	0.37 0.45 0.53	0.33 0.43 0.53	0.32 0.41 0.50
Optimization run (L, q_w, Ø)	L=200 q_w=0.027 Ø=0.53	L=200 q_w=0.0625 Ø=0.53	L=200 q_w=0.025 Ø=0.5

Table 5.13 Analytical model input parameters

Parameters	**Symbol**	**Unit**	**Value for silt loam soil**	**Value for loam soil**	**Value for sandy loam soil**
Infiltration rate	q_w	m/day	0.054	0.125	0.53
Saturated hydraulic conductivity	K_s	m/day	0.108	0.25	1.06
Soil porosity	Ø	m^3/ m^3	0.45	0.43	0.41
Residual water content (θ_w)	θ_w	m^3/ m^3	0.067	0.078	0.065
van Genuchten psd[a] parameter	n	unitless	1.41	1.56	1.89
Dispersion coefficient	D	m^3/ day	0.01		
Soil thickness	L	m	1.0		
First-order decay rate coefficient	μ	d^{-1}	(0.069 - 0.85)[b] (0.024 - 0.12)[c]		
Influent concentration	C_0	Unit/100 ml – mg/L)d	(4800 – 150)[d]		

[a] Pore Size Distribution
[b] Lower and upper range decay rate values, respectively for total coliform.
[c] Lower and upper range decay rate values, respectively for chlorine.
[d] Influent concentration values and units for total coliform and chlorine, respectively. Maximum measured influent concentration values are selected both for total coliform and chlorine to respect the worse cases.

5.4.2.1 Silt Loam Soil

Total coliform and chlorine attenuation process were presented in Figure 5.10 and 5.11 for silt loam soil pile. Attenuation graphs were plotted for the μ values of 0.069 d^{-1} and 0.85 d^{-1} at different soil thickness and infiltration rate conditions, respectively. As seen from the figures, total coliform and chlorine attenuation behavior of silt loam soil is very much similar to attenuation behavior of clay loam soil. Textural proportions of silt loam soil are given in the Appendix A.

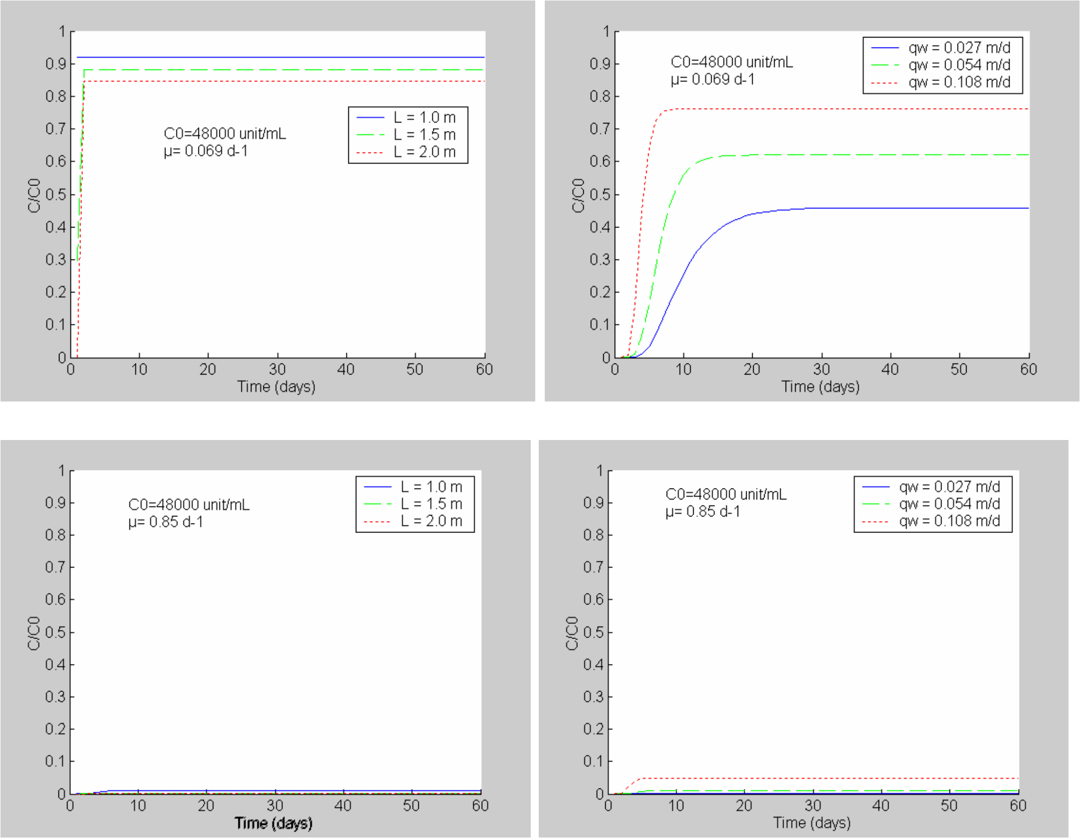

Figure 5.10 Simulated total coliform effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for silt loam soil

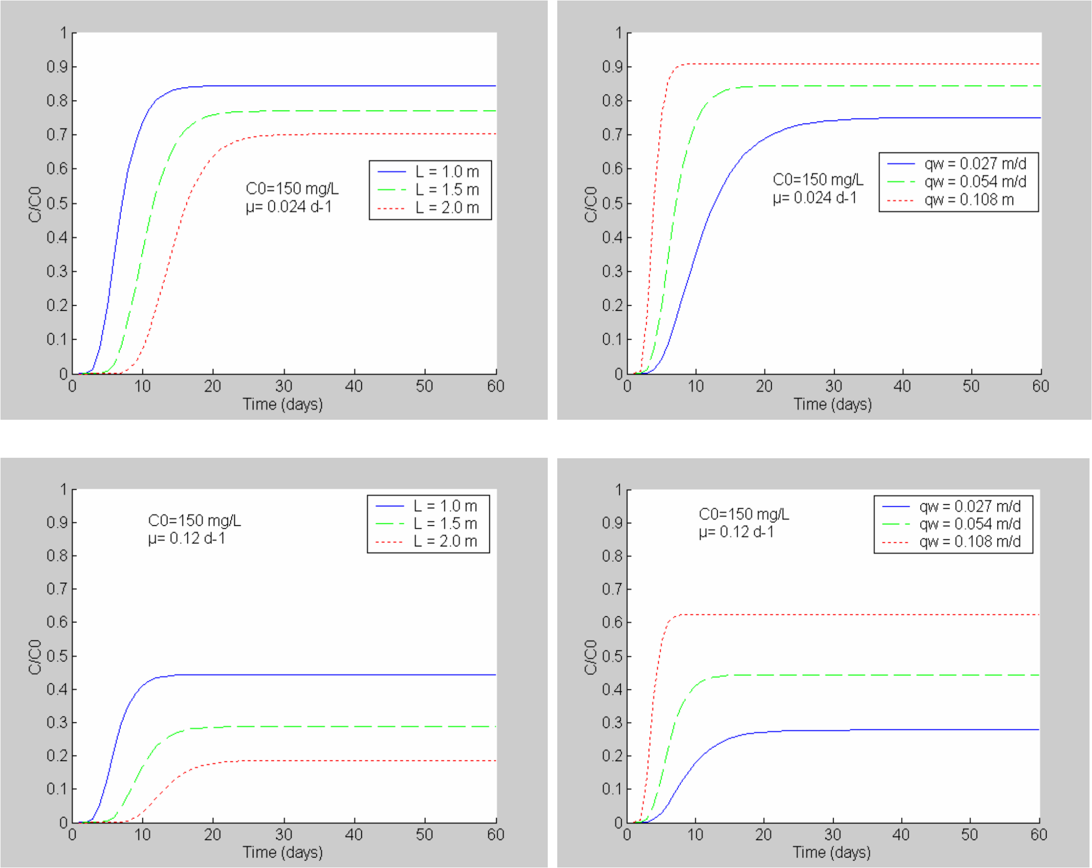

Figure 5.11 Simulated total chlorine effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for silt loam soil

Table 5.14 shows concentrations at the bottom of the silt loam soil pile and removal efficiencies of total coliform and chlorine that were obtained from analytical model. Model results show that silt loam soil has effective treatment capacity in terms of total coliform and chlorine as is the case in clay loam soil. At the soil thickness of 200 cm total coliform attenuation efficiencies were increased up to 63% and 100% with a μ value of 0.069 and 0.85 d^{-1}, respectively and 30% and 81% of chlorine removal efficiencies were provided with a μ value of 0.024 and 0.12 d^{-1}, respectively.

Table 5.14 Simulated steady-state mass removal efficiencies of the chlorine and total coliform in the effluent at the bottom of the soil pile for silt loam soil

Cases for model runs	**TOTAL COLIFORM C_0=48000 unit/L**				**CHLORINE C_0=150 mg/L**			
	μ= 0.069 d^{-1}		**μ= 0.85 d^{-1}**		**μ= 0.024 d^{-1}**		**μ= 0.12 d^{-1}**	
	C (unit/L)	**R(%)**	**C (unit/L)**	**R(%)**	**C (mg/L)**	**R(%)**	**C (mg/L)**	**R(%)**
L=100 cm	29770	38.0	498	99.0	127	15.3	67	55.3
L=150 cm	23006	52.1	45	99.9	116	22.7	43	71.3
L=200 cm	17779	63.0	4	100.0	105	30.0	28	81.3
q_w=0.027 m/d	22031	54.1	119	99.8	113	24.7	42	72.0
q_w=0.054 m/d	29770	38.0	498	99.0	127	15.3	67	55.3
q_w=0.108 m/d	36551	23.9	2334	95.1	136	9.3	94	37.3
K_s=0.054 m/d	28912	39.8	419	99.1	125	16.7	64	57.3
K_s=0.108 m/d	29770	38.0	498	99.0	127	15.3	67	55.3
K_s=0.216 m/d	30604	36.2	593	98.8	128	14.7	70	53.3
Ø=0.37 m^3/m^3	32057	33.2	812	98.3	130	13.3	75	50.0
Ø=0.45 m^3/m^3	29770	38.0	498	99.0	127	15.3	67	55.3
Ø=0.53 m^3/m^3	27773	42.1	334	99.3	123	18.0	60	60.0
L=200 cm Ø=0.53 m^3/m^3 q_w=0.027 m/d	7388	84.6	0.1	100.0	73	51.3	7.20	95.2

Total coliform removal efficiencies of 54 and 99.8% were achieved at infiltration rate of 0.027 m/d for the lower and upper end of the μ values, respectively. Chlorine removal efficiencies of 25 and 72% were achieved with the μ values of 0.024 and 0.12 d^{-1}, respectively. At the porosity of 0.53 m^3/m^3 higher removal efficiency was obtained than at the porosities of 0.37 and 0.45 m^3/m^3 for total coliform and chlorine, respectively.

With optimization of soil pile system in terms of soil thickness, infiltration rate and soil porosity, total coliform removal efficiencies increased up to 85 % and 100% at the μ values of 0.069 and 0.85 d^{-1} and chlorine removal efficiencies increased up to 51.3 % and 95.2% at the μ values of 0.024 and 0.12 d^{-1}, respectively. As a result, at the upper end of the μ value (0.85 d^{-1}) total coliform removed very effectively by silt loam SPS.

5.4.2.2 Loam Soil

Simulation cases and analytical model results for loam soil were presented in the Table 5.15. Total coliform and chlorine attenuation efficiencies achieved by loam soil are less than clay loam and silt loam soils. Textural proportions of loam soil are given in the Appendix A. But contaminant attenuation behavior is similar to those of clay loam and silt loam soil. Breakthrough curves for loam soils are shown in Figures 5.12 and 5.13 at the lower and upper end of the μ ranges. Total coliform and residual chlorine attenuation efficiencies in soil pile range between 11-35% and 4-14% at the lower end of the μ values, respectively and 91.2-99.3% and 18.3-52% at the upper end of the μ values, respectively.

Removal efficiencies of contaminant increased with decreasing infiltration rate. Total coliform removal efficiencies are 31.2% and 97.9% at infiltration rate of 0.0625 m/d for the lower and upper end of the μ values, respectively. 12.4 and 47.4% chlorine removal efficiencies were achieved with μ values of 0.024 and 0.12 d^{-1}, respectively.

For porosity of 0.53 m^3/m^3, total coliform removal efficiencies are 23 and 94.4% with a μ value of 0.069 and 0.85 d^{-1}, respectively. Chlorine removal efficiencies are 8.6 and 35.8% with a μ value of 0.024 and 0.12 d^{-1}, respectively.

With optimization of soil pile system in terms of soil thickness, infiltration rate and soil porosity, total coliform removal efficiencies increased up to 61 % and 100% at the μ values of 0.069 and 0.85 d^{-1}. For chlorine, removal efficiencies increased up to 28.1% and 79.4% with the μ values of 0.024 and 0.12 d^{-1}. It turned out that optimizing the soil pile with respect to L, q_w, and $\phi\, m^3/m^3$ significantly improved total coliform and chlorine removal efficiencies.

Table 5.15 Simulated steady-state mass removal efficiencies of the chlorine and total coliform in the effluent at the bottom of the soil pile for loam soil

Cases for model runs	**TOTAL COLIFORM C_0=48000 unit/L**				**CHLORINE C_0=150 mg/L**			
	μ= 0.069 d^{-1}		**μ= 0.85 d^{-1}**		**μ= 0.024 d^{-1}**		**μ= 0.12 d^{-1}**	
	C (unit/L)	**R(%)**	**C (unit/L)**	**R(%)**	**C (mg/L)**	**R(%)**	**C (mg/L)**	**R(%)**
L=100 cm	38865	19.0	4213.1	91.2	139.3	7.1	104.1	30.6
L=150 cm	34852	27.4	1204.6	97.5	134.1	10.6	86.2	42.5
L=200 cm	31254	34.9	344.4	99.3	129.1	13.9	71.4	52.4
q_w=0.0625 m/d	33004	31.2	1003.3	97.9	131.4	12.4	78.9	47.4
q_w=0.125 m/d	38865	19.0	4213.1	91.2	139.3	7.1	104.1	30.6
q_w=0.25 m/d	42725	11.0	11798	75.4	144	4.0	122.6	18.3
K_s=0.125 m/d	38235	20.3	3577.9	92.5	138.5	7.7	101.2	32.5
K_s=0.25 m/d	38865	19.0	4213.1	91.2	139.3	7.1	104.1	30.6
K_s=0.5 m/d	39451	17.8	4912.2	89.8	140.1	6.6	106.8	28.8
Ø=0.33 m^3/m^3	40718	15.2	6872.8	85.7	141.6	5.6	112.8	24.8
Ø=0.43 m^3/m^3	38865	19.0	4213.1	91.2	139.3	7.1	104.1	30.6
Ø=0.53 m^3/m^3	37139	22.6	2704.9	94.4	137.1	8.6	96.3	35.8
L=200 cm Ø=0.53 m^3/m^3 q_w=0.0625m/d	18964	60.5	6.04	100.0	107.9	28.1	30.9	79.4

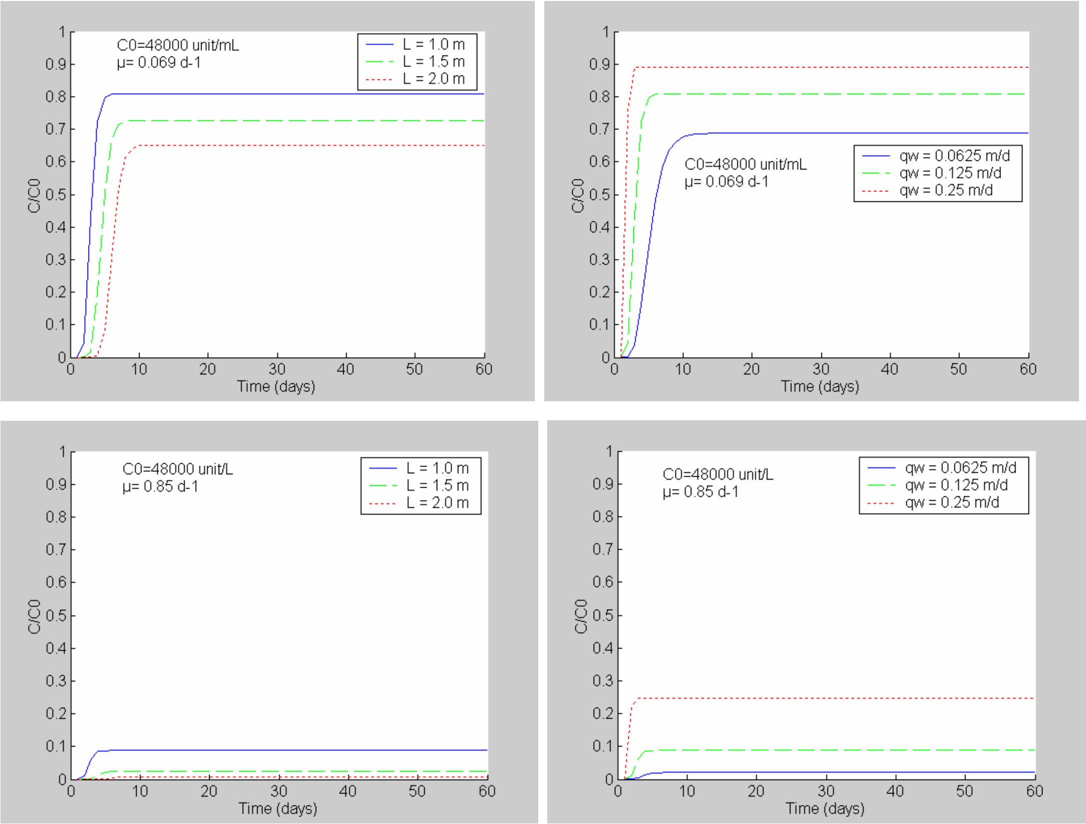

Figure 5.12 Simulated total coliform effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for loam soil

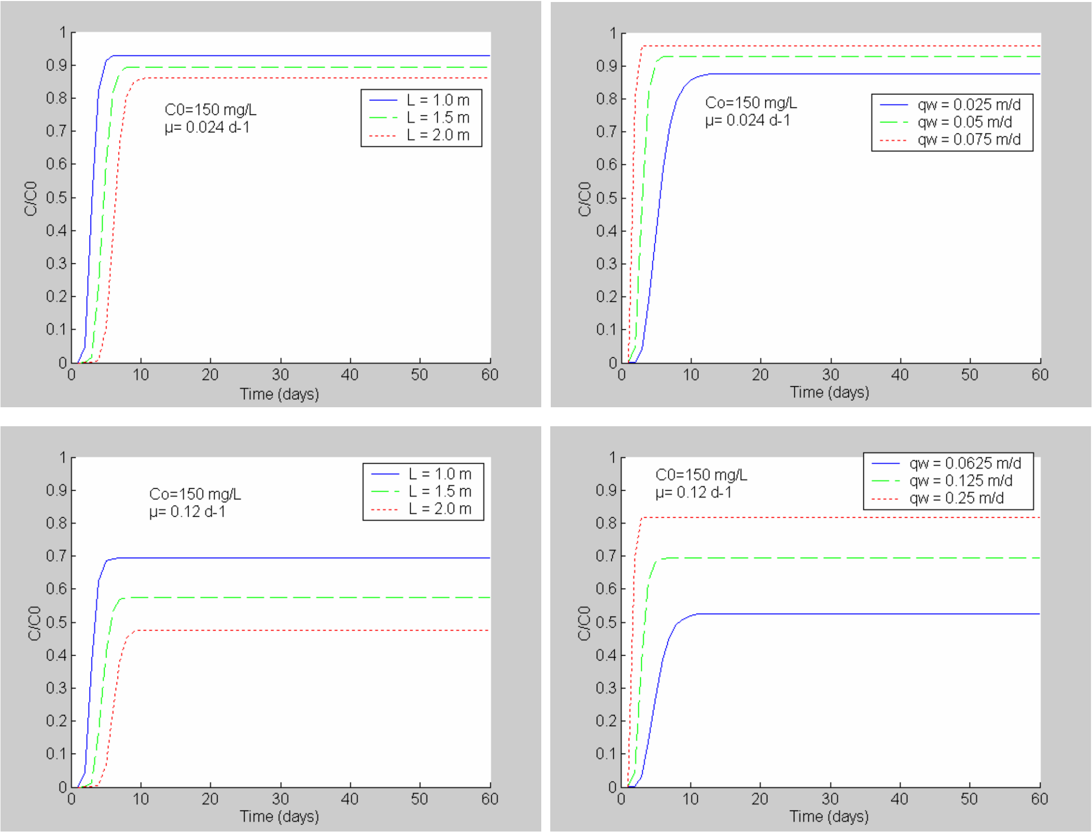

Figure 5.13 Simulated total chlorine effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for loam soil

5.4.2.3 Sandy Loam Soil

Simulation cases and analytical model results for sandy loam soil were presented in the Table 5.16. Textural proportions of sandy loam soil are given in the Appendix A. Simulated total coliform effluent concentrations (breakthrough curves) at the bottom of the soil pile at different soil thickness and infiltration rates for sandy loam soil were given in Figures 5.14. For soil thicknesses of 100, 150, and 200 cm removal efficiencies of total coliform are 4.7, 7.0, and 9.2%, respectively and for infiltration rates of 0.265, 0.53, and

1.06 m/d, removal efficiencies of total coliform are 8.3, 4.7, and 2.6%, respectively. Figure 5.23 presents breakthrough curves for sandy loam at the upper end of the range of μ value (0.85 d^{-1}). As seen from the figures, least total coliform attenuation efficiencies are achieved by sandy loam soil.

Table 5.16 Simulated steady-state mass removal efficiencies of the chlorine and total coliform in the effluent at the bottom of the soil pile for sandy loam soil

Cases for model runs	**TOTAL COLIFORM C_0=48000 unit/L**				**CHLORINE C_0=150 mg/L**			
	μ= 0.069 d^{-1}		**μ= 0.85 d^{-1}**		**μ= 0.024 d^{-1}**		**μ= 0.12 d^{-1}**	
	C (unit/L)	**R(%)**	**C (unit/L)**	**R(%)**	**C (mg/L)**	**R(%)**	**C (mg/L)**	**R(%)**
L=100 cm	45748	4.7	26614	44.6	147.5	1.7	138	8.0
L=150 cm	44654	7.0	19776	58.8	146.3	2.5	132.3	11.8
L=200 cm	43587	9.2	14695	69.4	145.1	3.3	126.8	15.5
q_w=0.265 m/d	44010	8.3	16697	65.2	145.5	3.0	129	14.0
q_w=0.53 m/d	45748	4.7	26614	44.6	147.5	1.7	138	8.0
q_w=1.06 m/d	46741	2.6	34609	27.9	148.6	0.9	143.2	4.5
K_s=0.53 m/d	45525	5.2	25078	47.8	147.3	1.8	136.8	8.8
K_s=1.06 m/d	45748	4.7	26614	44.6	147.5	1.7	138	8.0
K_s=2.12 m/d	45880	4.4	28065	41.5	147.7	1.5	139	7.3
Ø=0.32 m^3/m^3	46221	3.7	30174	37.1	148	1.3	140.5	6.3
Ø=0.41 m^3/m^3	45748	4.7	26614	44.6	147.5	1.7	138	8.0
Ø=0.50 m^3/m^3	44549	7.2	23499	51.0	147	2.0	135.5	9.7
L=200 cm Ø=0.50 m^3/m^3 q_w=0.265 m/d	38866	19.3	3732.1	92.2	139.4	7.1	104	30.7

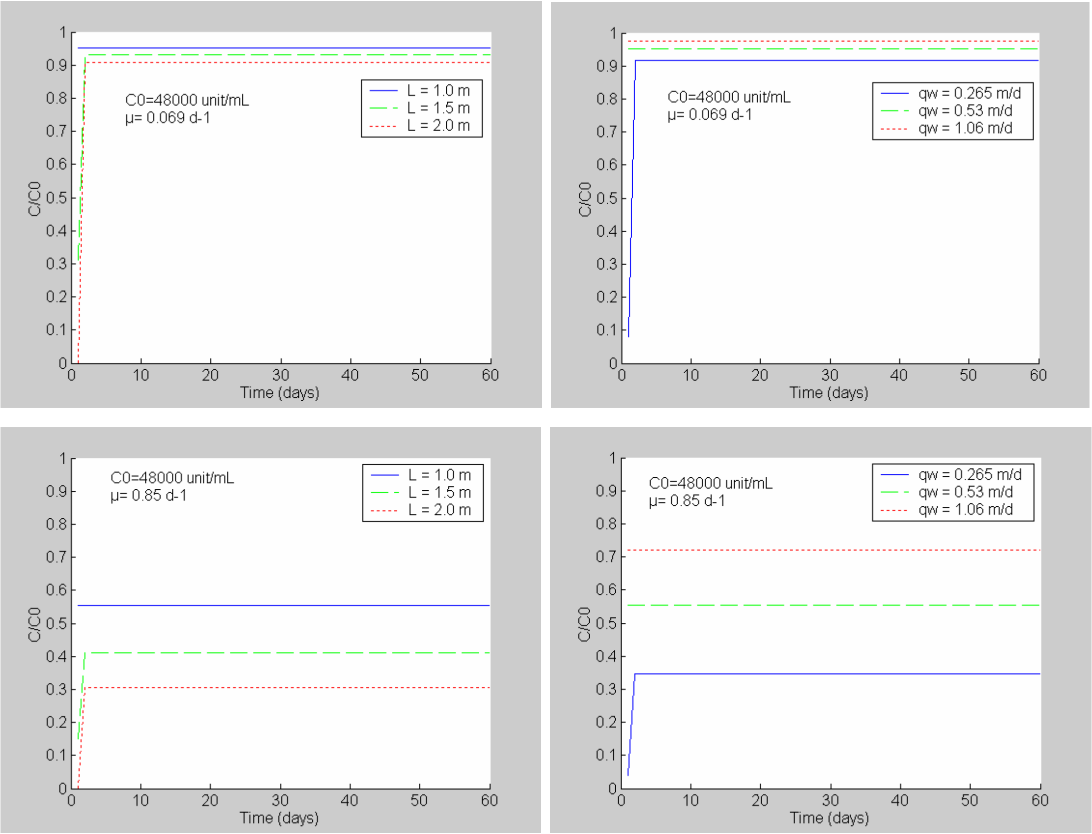

Figure 5.14 Simulated total coliform effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thicknesses and infiltration rates for sandy loam soil

Simulated total chlorine effluent concentrations (breakthrough curves) at the bottom of the soil pile for μ values of 0.024 and 0.12 d^{-1} at different soil thickness and infiltration rates for sandy loam soil were given in Figures 5.15. For soil thicknesses of 100, 150, and 200 cm removal efficiencies of chlorine are 1.7, 2.5, and 3.3%, respectively; and for 0.265, 0.53, and 1.06 m/d infiltration rates, removal efficiencies of chlorine are 3.0, 1.7, and 0.9 %, respectively. The lowest chlorine attenuation efficiencies were observed in sandy loam soil compared to other soils.

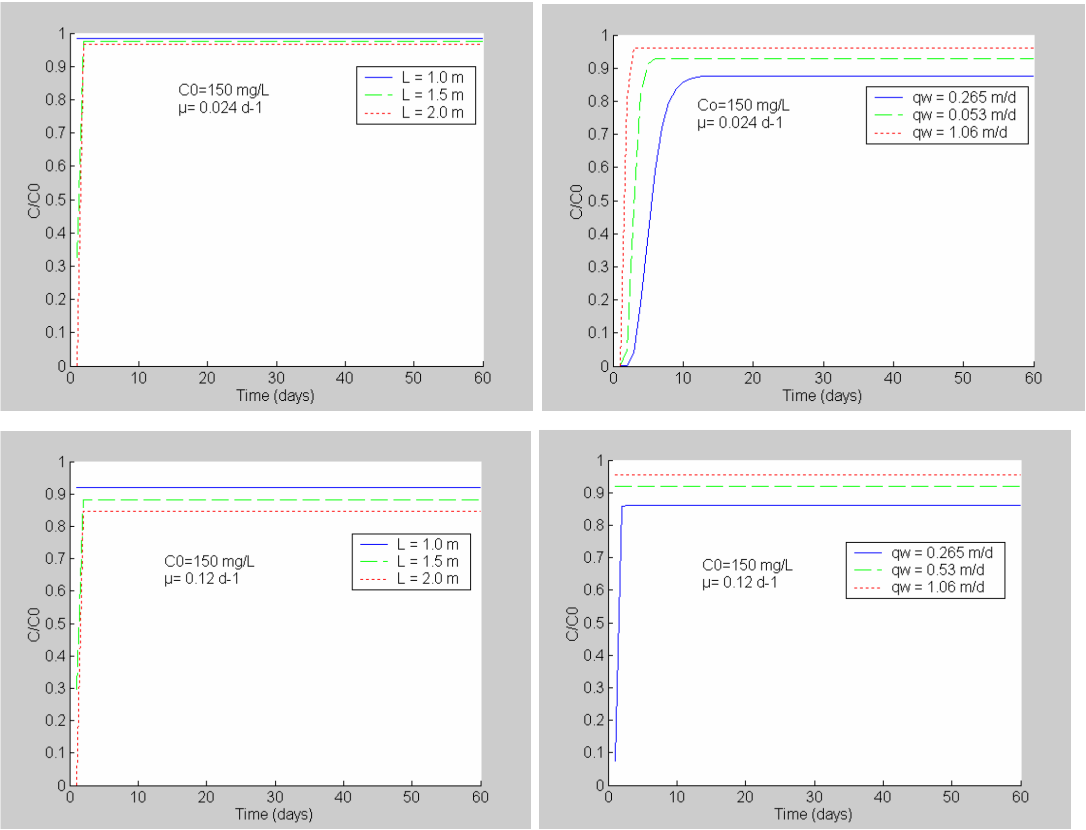

Figure 5.15 Simulated total chlorine effluent concentrations (breakthrough curves) at the bottom of the soil pile for different soil thickness and infiltration rates for sandy loam soil

As seen from the model results; maximum 92.2% total coliform and 31% chlorine removal were provided under optimal design construction and operation conditions. Total coliform discharge standards could be only met with the optimization of SPS in terms of L, q_W, and θ when decay rate is 0.85 d^{-1}. Consequently, sandy loam soil pile may appropriate as SPS material for tertiary treatment of domestic wastewater unless soil environmental conditions are maintained highly favorable during operations.

5.4.3 General Design Considerations of Soil Pile Systems

In this modeling study, total coliform and chlorine removals through SPS were assessed for four different types of soils using analytical modeling approach. Table 5.17 shows total coliform and chlorine attenuation efficiencies obtained under optimal conditions for clay loam, silt loam, loam and sandy loam soils. As seen from the Table, same contaminants removal efficiencies were achieved by using clay loam and silt loam soils. While total coliform attenuation was almost completed with a high μ value, chlorine attenuation efficiencies of 96, 95 and 80% for clay loam, silt loam, and loam soils, respectively. This means that, with a high μ value, high degree of contaminant removal can be achieved under favorable soil environmental conditions. The lowest total coliform and chlorine attenuation efficiencies were observed in sandy loam soil compared to other soils. Consequently, clay loam and silt loam soils may appropriate as SPS material while sandy loam soil pile may appropriate unless soil environmental conditions are maintained highly favorable during operations.

Table 5.17 Steady-state mass removal efficiencies of the chlorine and total coliform under optimal conditions for different type of soils

Optimal conditions	**Total coliform removal efficiencies R(%)**		**Chlorine removal efficiencies R(%)**	
	μ= 0.069 d^{-1}	**μ= 0.85 d^{-1}**	**μ= 0.024 d^{-1}**	**μ= 0.12 d^{-1}**
Clay loam				
L=200 cm **Ø=0.50** **q_w=0.025 m/d**	86	100	52	96
Silt loam				
L=200 cm **Ø=0.53** **q_w=0.027 m/d**	85	100	51	95
Loam				
L=200 cm **Ø=0.53** **q_w=0.0625 m/d**	61	100	28	80
Sandy loam				
L=200 cm **Ø=0.50** **q_w=0.265 m/d**	19	92	7	31

Based on modeling considerations, it is proposed that an ideal (typical) soil pile system, from top to bottom, should have a minimum of five principal components: a wastewater infiltration system, a soil treatment zone, a drainage system coupled with a surrounding lined drainage ditch, an impermeable bottom layer, and finally a lined treated wastewater collection pond. A Schematic diagram of SPS is shown in Figure 5.16.

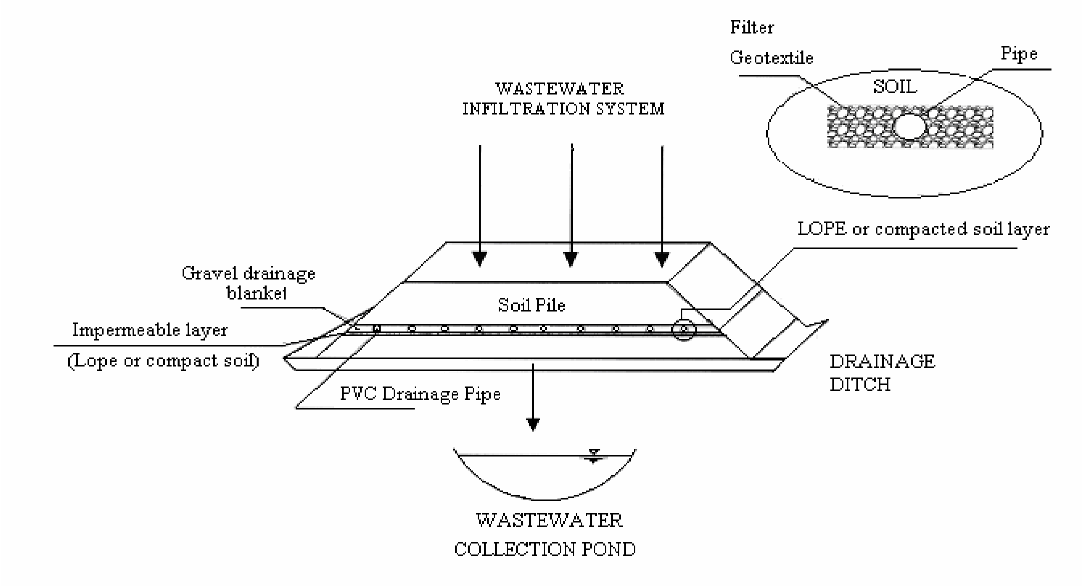

Figure 5.16 A Schematic diagram of soil pile system

For wastewater infiltration system, a sprinkler or subsurface drip irrigation system or an irrigation system composed of a network of perforated pipes can be used at the top of the soil pile. Infiltration system should be able to distribute wastewater uniformly across the soil surface. For uniform infiltration, the surface of soil pile should be constructed as flat as possible. The desired infiltration rate should be selected to maintain the optimum soil moisture content needed for contaminant attenuation. Surface of soil pile can be covered with plastic sheets during rainy season to avoid pile damage by erosion effect of intense rainfall.

Soil treatment zone is the zone of mass attenuation and consists of a soil pile packed uniformly to meet the desired packing density, porosity and thickness. The size of pile can be covered with light colored plastic sheets to prevent possible development of horizontal moisture gradients and possible water loss through leakage during high infiltration operations. However for some instances size of soil pile can be left uncovered to enhanced evaporation and reduce water volume to be collected. The base and top area of a soil pile should be consistent with the desired operation capacity the system.

A drainage system is necessary to collect wastewater percolating through the soil treatment zone. Drainage layer placed underneath the soil treatment zone can consist of a course gravel blankets. Gravel layer should be separated from overlaying soil layer with a filter geotextile to prevent clogging of gravel pores by soil sedimentation. Perforated PVC piles should be installed in the gravel blanket at sufficient spacing in order not to cause mounding of wastewater within the soil pike, which will be imported for the stability of soil pile. The pipes should be laid across the whole bottom with of the pile. Each pile should be discharged into the drainage ditch. The whole pile should be surrounded by a lined drainage ditch to collect and transport the drained wastewater to the collection pond.

An impermeable layer is necessary to make the drainage layer function effectively as well as prevent infiltration of wastewater into underlying soil and nearby groundwater. If soil pile system is to be constructed at the site of excavated soil, compaction may be necessary to decrease permeability of the native soil under the soil pile. Ideally, the drainage layer should be underlain at the bottom with the low permeability compacted clay soil or low density polyethylene (LDPE) liner, which should be sloped to allow gravity drainage along the bottom and prevent loss of infiltrated wastewater to the underlying vadose zone.

A retention pond or collection sump is usually required to collect and retain the treated wastewater before discharging into the appropriate receiving environment. Storage capacity required depends on the site location and expected amount of wastewater to be treated in the soil pile system.

5.4.3.1 Design Specifics of Pilot Scale Soil Pile System

Technical details of proposed pilot scale soil pile system design are presented in this section. For infiltration of wastewater, a drip irrigation system consisting of a network of perforated (punctured) Poli-Vinyl-Chlorid (PVC) or plastic pipes with an internal diameter of 3 to 5 cm and a wall thickness of 1 mm can be used at the surface of soil pile. The spacing of pipes should be arranged such that uniform infiltration across the soil surface and uniform unsaturated moisture content through out the pile can be achieved; 0.3 m of pipe spacing can be reasonable. Holes (perforations) on pipes can have a circular shape with 2 mm diameter and the number of holes along the pipe should be distributed uniformly to meet the desired overall infiltration rate.

Soil pile should be constructed over a suitable area (for pilot ,scale it can be 10 m by 10 m at the surface and 14.5 m 14.5 m a the bottom to meet 3:1 side slope) by packing surface soils carefully to have a soil treatment zone with a uniform thickness of 1.5 m and a uniform bulk density of 1.325 g/cm^3 , corresponding to a porosity of 50 % , throughout , the treatment zone. Area requirement should be consistent with desired waste water treatment capacity achievable by the selected infiltration rate. Initially, the moisture content of soil should be relatively dry (air dry) to ease the construction of pile . Side surfaces of pile should be constructed smoothly and have a slope of 1 vertical to 3 horizontal.

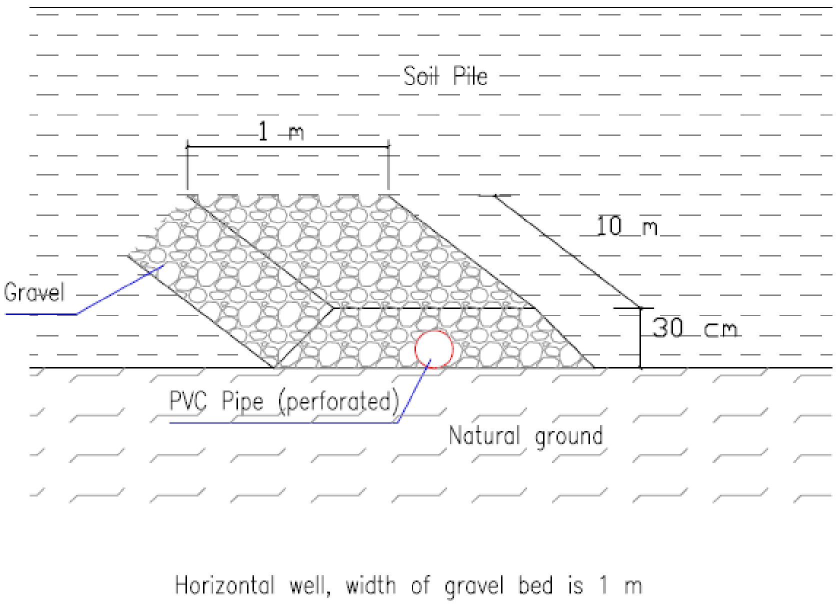

Figure 5.17 Construction detail of SPS pilot plant

The drainage layer should consist of appropriately spaced perforated PVC pipes, with a diameter of 10 cm and a wall thickness of 5 mm, imbedded in 30 cm thick blanket type gravel material with a diameter of 30 to 50 mm. the appropriate spacing is determined based on infiltration rate and soil hydraulic conductivity.

As infiltration rate decreases and soil hydraulic conductivity increases, the required drainage pipe spacing increases. Thus, using the lowest infiltration rate of 0.025 m^3/m^2.d and hydraulic conductivity of 0.15 m/day considered in the AMS, the maximum spacing between drainage pipes should be taken as

0.75 m and should not exceed 1 m. An alternative drainage system to gravel blanket layer could be a French type drainage layer, which, instead of having continuous gravel layer, contains gravel bed only around PVC pipes. Gravel blanket provides a continuous high conductivity flow path for water across the bottom, and thus work much more effectively than French drains to collect the water. Considering the soil used in the pile has high clay content and thus low hydraulic conductivity, the performance of French drains could be affected adversely. The slopes on the pipe and lined drainage ditch should be a minimum of 1 % along the flow direction. A "V" shaped cross-section with a side slope of 1:1 and a depth of 30 cm can be used for the drainage ditch.

The drainage layer must be underlain by an impermeable layer with hydraulic conductivity at least an order of magnitude smaller than that of overlying soil treatment zone. Creating such hydraulic conductivity contrasts is necessary to make the drainage layer function effectively. Two alternatives can be considered for impermeable layer; one is 30 to 60 cm tick compacted natural soil (or clay) layer or 1 mm thick (LDPE) liner. Impermeable bottom layer should have sloped at a minimum of 1% to allow gravity drainage along the bottom. At the site, construction of an impermeable layer for a pilot scale soil pile system having a reasonable base area can be relatively easy, while construction can be tedious and laborious for large field scale soil piles system which will be constructed at the site from already excavated soil requiring displacement and relocation of larges soil masses. However, considerable reduction of permeability at the base (via either soil compaction or placement of LDPE or any other way possible) is necessary to effectively collect wastewater drained from soil treatment zone. An alternative approach to avoid relocation of large soil masses would be construction of multiple smaller size soil pile systems instead of single giant system.

Storage capacity of retention pound can be designed based on expected amount of wastewater to be treated in the soil pipe system and in turn size of the pile. A storage capacity of 0.075 m^3 per m^2 per day can be satisfactory. The final storage capacity can be design based on a weekly or monthly discharge frequency. For example, for the proposed pilot scale soil pile system (with infiltration surface area of 100 m^2) storage capacity of pond can be taken as 52.5 m^3 assuming q weekly discharge frequency. Table 5.18 summarizes the technical details of proposed pilot scale soil pile system design.

Table 5.18 Technical details of the proposed pilot scale soil pile system design.

Infiltration system	
Perforated wastewater delivery pipe size	3 to cm i.d, 3.2 to 5.2 cm o.d.
Spacing of pipes	0.3 m
Length of pipe	Equal to the width of soil pile
Shape of holes	Circular
Size of holes	2 mm
Number of holes	Uniform along the pipe to meet infiltration rate
Soil treatment zone (soil pile)	
Area	10 m x 10 mm top ; 14.5 x 14.5 bottom
Side slopes of faces	3 horizontal: 1 vertical (3:1)
Thickness	1.5 m, uniform
Packing (bulk) density	1,5 m, g/cm^3
Porosity	0.50
Initial, pre-packing moisture content	Air dry
Drainage system	
PVC drainage pipe size	10 cm i.d., 10.5 cm o.d.
Pipe length	Width of pile
Pipe perforation size	1 cm width x 3 cm length on top of pipe
Pipe spacing	0.75 m(or <1 m)
Slope on the pipes	1%
Gravel blanket thickness	30 cm
Gravel size	3 to 5 cm
Filter and separator between soil and gravel	geotextile
Depth of "V" shaped drainage ditch	30 cm
Width of "V" shaped drainage ditch	60 cm
Side slopes of ditch	1:1
Slope on the ditch	1 %
Liner for drainage ditch	1 mm LDPE
Impermeable bottom layer	
Compacted soil or clay thickness	60 cm compacted soil, 30 cm compacted clay
Hydraulic conductivity	10^{-7} m/s for compacted soil, 10^{-8} m/s compacted clay
LDPE thickness	1 mm
LDPE hydraulic conductivity	> 10-11 m/s
Bottom layer slope	% 1 along the drainage pipes
Filter and separator between gravel and liner	geotextile
Treated wastewater collection pond	
Storage capacity	0.075 m^3/ m^2/ day
Liner for collection pond	1 mm LDPE

5.4.4 General Operational Considerations of Soil Pile Systems

Once the soil pile system having all proposed components has been constructed over a suitable area by packing surface soils carefully to have a uniform thickness, density and porosity throughout the pile, wastewater is applied across the surface of the pile uniformly using surface or below-surface irrigation systems to achieve uniform unsaturated moisture content distribution. In the soil pile, wastewater will percolate through soil treatment zone predominantly in the vertical direction by gravity flow. During percolation, contaminants are removed from wastewater and treated water ultimately reaching the bottom layer will be collected by underlying drainage system into a collection pond.

The overall operational objective of SPS will be to reduce the contaminant concentrations during percolation of wastewater through soil below project discharge standards. The modeling results showed that, to meet the operational objectives of SPS, the most important system parameters are soil thickness, porosity and in turn soil packing density, infiltration rate and first-order decay rate constant (which is affected very much by soil environmental conditions such as temperature, soil moisture content, adsoption to particle, soil pH, solar radiation and soil type). Contaminant removal efficiencies increased with increasing soil thickness, L, porosity, ϕ, and first-order decay rate, μ, and with decreasing infiltration rate, q_w. Increasing soil thickness and porosity imply low packing density of soil pile while decreasing infiltration rate implies increasing detention time of pollutants in the soil pile. It turned out that optimizing the soil pile with respect to L and q_w, which are design parameters, ϕ and μ, which are operational parameters, significantly improved contaminant attenuation efficiencies.

One of the most important operational aspects of SPS is maintaining steady and uniform application of wastewater at the surface of soil pile (i.e., maintaining optimal –uniform and constant infiltration rate- conditions). Another important issue is maintaining optimal soil environmental conditions, which will be relatively easy during worm seasons but difficult in cold seasons.

Monitoring the effluent quality of SPS is necessary during operation to verify that desired quality is achievable in the effluent. The following water quality parameters need to be measured both in the influent and effluent of SPS: BOD, COD, TSS, chlorine, total and fecal coliform, chloride, calcium magnesium, sodium, Electrical conductivity (EC), pH, and temperature. In addition, in order to monitor the hydraulic performance of the system, measuring flow rates of influent and effluent waters (i.e., both infiltration and drainage rates) are also necessary. In order for accurate estimation of attenuation efficiencies and overall performance of the SPS, the recommended frequency of measurements are on a daily basis for water quality parameters, while a minimum two measurements per day for flow rates of influent and effluent water.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

In this modeling study, a simplistic analytical modeling and a numerical transient unsaturated flow and transport modeling approaches developed based on available site data and literature information was used to assess total coliform and residual chlorine attenuation efficiencies in soil pile systems. Breakthrough curves of total coliform and chlorine were simulated using the developed models to determine the range of possible attenuation efficiencies. The following conclusions are obtained regarding the performance of soil pile systems.

- Breakthrough curves and mass attenuation efficiencies showed that SPS operations are to be highly sensitive to soil thickness, infiltration rate, soil bulk density and most importantly decay rate coefficients controlled by soil environmental conditions. It is understood that in order to improve the total coliform and chlorine attenuation efficiencies the soil pile should be optimized with respect to soil thickness, infiltration rate, and soil porosity.

- Model results indicated that the depth of the soil pile system is an important factor in attenuation process of total coliform and chlorine. Simulation runs were performed for soil thicknesses of 100, 150, and 200 cm. The better result in removal efficiencies was achieved at soil thickness of 200 cm. But for fine-textured soils some operational problems resulting from low infiltration capability of soil pile may be occurred at this depth. Calibration study performed for clay loam soil pile indicated that soil thickness of 100 cm is sufficient to decrease total coliform concentration below project discharge standard.

- Steady-state and transient concentrations and removal efficiencies of total coliform and chlorine seem to be insensitive to saturated hydraulic conductivity of soil pile. However, being the upper limit of infiltration rate, K_s affects the operational parameters of soil pile, such as q_w and θ_w.

- Although 99% removal efficiency of chlorine is obtained under optimal design and operation conditions (i.e. soil thickness, porosity, infiltration rate and soil texture), the project discharge standard of chlorine (0.2 mg/L) prescribed for the BTC Project could not be met with SPS. The possible reasons for this may include:

  - Firstly, as chlorine first-order decay rate constant in soil is not available in the literature, first-order decay rate of chlorine in reclaimed wastewater was used in this study.

  - Secondly, wastewater sample could not be taken in the effluent of the SPS due to the ineffective operation of pilot scale SPS.

Site specific kinetic data for chlorine therefore could not be obtained.

The result obtained from modeling study does not necessarily mean that chlorine discharge standards can not be met with SPS. It is quite possible that chemical reaction between chlorine and organic matter is higher in soil environment compared to reclaimed wastewater due to high organic matter content of the soil. Consequently, better chlorine removal, which satisfies BTC requirements, would be achieved in the field scale SPS, if accurate site specific kinetic data could have been obtained. Besides this, DBPs such as THM, TOX , which are more hazardous compounds, are produced during the infiltration of the partially treated chlorinated-wastewater through soil. Chlorination-by-products should be considered when designing the SPS.

- Since first-order decay rates are controlled by soil environmental conditions such as soil temperature, water content and soil type, soil environmental conditions are also very important factors for total coliform and chlorine attenuation.

- Soil type has great impact on the performance of soil pile systems in terms of total coliform and chlorine attenuation process. The analytical model results indicated that clay loam and silt loam soil have more effective treatment capacity than loam and silt loam soils. Very coarse sand and gravel are not ideal because wastewater passes too rapidly through the soil pile system.

- Model results conducted for clay loam soil showed that there is not important difference between analytical and numerical model results in terms of total coliform and chlorine attenuation efficiencies.

- The results of the analytical and numerical modeling study indicated that soil pile systems can be effective reducing chlorine and total coliform concentrations of produced wastewater. However the results of this study also indicated that the performance of soil pile system is highly dependent on the design, construction, operation characteristics and soil-environmental conditions of the system.

6.2 RECOMMENDATIONS

The following recommendations are made for the future

- The best results in terms of contaminant attenuation efficiencies were achieved using clay and silt loam soils for soil pile system. Clay loam soil has low infiltration rate due to the high clay content. This can create operational problems for soil pile system.

- In this study, there was some operational trouble in pilot plant of soil pile system. So, effluent sample could not be taken effectively from pilot plant. For future studies on soil pile system, a comprehensive pilot scale SPS operation need to be conducted using different soil types to obtain site specific kinetic data to calibrate and validate the developed model.

REFERENCES

Addo, B.K., 2002, Bacterial plume dynamics in the marshland upwelling system employed in the near freshwater conditions. M.S. Thesis, The Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College.

Amy, G., Wilson, L.G., Conroy, A., Chahbandour, J., Zhai, W., Siddiqui, M., 1993, Fate of chlorination byproducts and nitrogen species during effluent recharge and soil aquifer treatment (SAT), Water Environment Research, 65(6), 726-734.

Andelman, J., Bouwer, H., Charbeneau, R., Christman, R., Crook, J., Fan, A., Fort, D., Gardner, W., Jury, W., Miller, D., Pitt, R., Robeck, G., Vaux, H., Vecchioli, J., Yates, M., 1994, Groundwater recharge using waters of impaired quality. National Research Councill Commitie on Groundwater Recharge, National Academy Press.

AWWA, 1988, Research Foundation, Soil treatebility pilot studies to design and model soil aquifer treatment Systems, USA.

Bales, R. C., LI, S. M., Maguire, K. M., Yahya, M. T., and Gerba, C. P., 1993. MS2 and poliovirus transport in porous media: Hydrophobic effects and chemical pertubations. W at. Resources Res. 29 (4):957 63.

Brooks, R.H. and Corey, A.T., 1964, Hydraulic properties of porous media. Hydrol. Pap. No 3. Civil engineering Department, Colo. State Univ., Fort Collins, Colorado, USA.

Bouwer, E., Mccarthy, P.L., Bouwer, H., Rice, R. C., 1984, Organic contaminant behavior during rapid infiltration of secondary wastewater at the Phoenix 23rd. Avenue Project, Water Research, Vol. 18, No. 4, pp. 463-472.

Burdine, N. T., 1953, Relative permeability calculation size distribution data, Trans. Am. Inst. Min. Metall. Pet. Eng., 198, 71– 78.

Carsel, R. F., and Parrish, R.S., 1988, Developing Joint probability distributions of soil water retention characteristics. Water Resources Research 24(5), 755-769.

Castro, P., and Neves, M., 2003, Chlorine decay in water distribution systems case study, Lousada Network. Electronic Journal of Environmental, Agricultural and Food Chemistry 2(2), 261-266.

Choi, C., Song, I., Stine, S., Pimentel, J., Gerba, C.P., 2004, Role of irrigation and wastewater reuse: comparison of subsurface irrigation and furrow irrigation. Water Science and Technology 50(2), 61-68.

Corapcioglu, M.Y., and Haridas, A. 1985, Microbial transport in soils and groundwater: A numerical model Computational Mechanics Publications, Journal of Advanced Water Resources, Vol. 8, pp. 188-198.

Cuyk, S.V., Siegrist, R.L., Lowe, K., and Harvey, R.W., 2004, Evaluating Microbial Purification during Soil Treatment of Wastewater with Multicomponent Tracer and Surrogate Tests. J. Environ. Qual. 33:316–329.

FAO, 1992, Wastewater treatment and use in agriculture. FAO irrigation and drainage paper 47, Rome, Italy.

Farooq, S., and Al-Youssef, A. K., 1993, Slow sand filtration of secondary effluent. J. Environ. Eng. ASCE 119 (4): 615 30.

Fontes, D. E., Hornberger, G. M., Mills, A. L., and Herman, J., 1991, Physical and chemical factors influencing transport of microorganisms through porous media. Appl. Environ. Microb. 57 (9):2473 81.

Funamizu, N., Iwamoto, T., and Takkakuwa, T., 2004, Mathematical Model for describing reactions of residual chlorine with organic matter in reclaimed wastewater. Water Science and Technology 50(2), 195-291.

Gerba, C.P., and Bitton G., 1984, Microbial Pollutants: Their survival and transport pattern to groundwater. In Groundwater Pollution Microbiology (ed. Bitton, G. and C.P. Gerba), pp. 65-88.

Gerba, C. P., Goyal, S. M., Hurst, C. J., and LaBelle, R. L., 1980, Type and strain dependence of enterovirus adsorption to activated sludge, soils, and estuarine sediments. W at. Res. 14 (9): 1197 98.

Güngör, K., 2001, Treatment of Domestic Wastewater Using Soil Aquifer Treatment System. M.S. Thesis, The Graduate School of Natural and Applied Sciences of METU.

Hurst, C. J., Gebra, C. P., and Cech, I., 1980, Effect of environmental variables and soil characteristics on virus survival in soil. Applied and Environmental Microbiology, 1067-1069.

Jansons, J., Edmonds, L., Speight, B., and Bucens, M., 1989, Survival of viruses in groundwater. W at. Res. 23 (March): 301 06.

Jin, Y., 1997, Sorption of viruses during flow through saturated soil columns. Environ. Sci. Tech. 31 (2): 548 55.

Johnson, W., and Logan, B., 1996, Enhanced transport of bacteria in porous media by sediment-phase and aqueous-phase natural organic matter. W at. Res. 30 (April): 923 31.

Kim, J. Choi, H. Schwartz, F., 2002, Modeling Soil Aquifer Treatment for Artificial Recharge for Sustainable Wastewater Reuse. American Geophysical Union.

Klute, A., and Dirksen, C., 1986, Hydraulic conductivity and diffusivity: Laboratory methods. p. 687–734. In A. Klute (ed.) Methods of soil analysis. Part 1. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Land Remediation and Pollution Control Division, National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, Ohio, 2006, Process Design Manual Land Treatment of Municipal Wastewater Effluent, EPA/625R-06/016 United States Environmental Protection Agency.

Lance, J. C., and Gerba, C. P., 1984a, Effect of ionic composition of suspending solution on virus adsorption by a soil column. Appl. Environ. Microb. 47 (3): 484 88.

Lance, J. C., and Gerba, C. P., 1984b, Virus movement in soil during saturated and unsatured flow. Appl. Environ. Microb. 47 (2): 335 37.

Lawrence A. Baker and Paul Westerhoff, A Low-Tech Treatment Strategy for Treating and Reusing Wastewater, The U.S. Mexican Border Environment.

Leij, F.J., van Genuchten, M.Th., Yates, S.R., Russell W. B., and Kaveh, F., 1992, RETC: A Computer Program for analyzing soil water retention and hydraulic conductivity data. P. 263-272, In M. Th. Van Genuchten, F.J. Leij and L. J. Lund (ed.) Proc. Int. Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils. University of Colifornia, Riverside, CA.

Lyndon, L., Gyürek, L., and Finch, G.R., 1998, Modeling water treatment chemical disinfection kinetics. Journal of Environmental Engineering 124(9), 783-793.

Menon, P., Billen, G., and Servais, P., 2003, Mortality rates of autochthonous and fecal bacteria in natural aquatic ecosystems. Water Research, Vol. 37, pp. 4151-4158.

Mualem, Y., 1976, A new model for predicting the hydraulic conductivity of unsaturated porous media, Water Resour. Res., 12, 513–521.

Naval Facilities Engineering Service Center (NFESC), 1998, Bioremediation of hydrocarbon contaminated soil at Mare Island: Laboratory treatability study. Port Hueneme, CA.

Naval Facilities Engineering Service Center (NFESC), 1996, Biopiles: A viable and cost effective method to remediate hydrocarbon contaminated soil.

O'Kane Consultants Inc., 2000, Demonstration of the Application of Unsaturated Zone Hydrology for Heap Leach Optimization, Industrial Research Assistance Program Contract.

Otis, R.J., 1985, Soil Clogging: Mechanisms and Control In Onsite Wastewater Treatment: Proceedings of the Fourth National Symposium on Individual and Small Community Sewage Systems, American Society of Agricultural Engineers, St. Joseph, MI.

Otis, R.J., 1997, Considering Reaeration In Proceedings: Ninth Northwest On-Site Wastewater Treatment Short Course and Equipment Exhibition, ed. R.W. Seabloom. University of Washington, Seattle, WA.

Pieper, A., Ryan, J., Harvey, R., Amy, G., Illangasekare, R., and Metge, D., 1997, Transport and recovery of bacteriophage PRD1 in a sand and gravel aquifer: Effect of sewage derived organic matter. Environ. Sci. Tech. 31 (April): 1163 70.

Powelson, D., and C. P. Gerba. 1994. Virus removal from sewage effluents during saturated and unsaturated flow through soil.

Quanrud, D.M., Arnold, R.G., Wilson, L.G., Conklin, M.H., 1996a, Effect of Soil Type on Water Quality Improvement during Soil Aquifer Treatment, Water Sci. Tech., 33(10-11), 419-431.

Quanrud, D.M., Arnold, R.G., Wilson, L.G., Gordon H.J., Graham, E.W., Amy, G.L., 1996b, Fate of Oganics during Column Studies of Soil Aquifer Treatment, J. Environmental Engineering, April, 314-321.

Quanrud, D.M., Conroy, O., Turney, K.D., Lansey, K.E., and Arnold, R.G., 2002, Fate of estrogenic activity in reclaimed water during soil aquifer treatment, 2002 Water Sources AWWA conference, Las Vegas, NV., January 27-30, 2002.

Quanrud, D.M., S. Carroll, Gerba C.P., and Arnold, R.G., 2003, Virus removal during simulated SAT. Water Research. 37(4):753-762.

Rawls W.J., Brakensiek D.L., Saxton K.E., 1982, Estimation of soil water properties. Transaction of the ASAE, 26, 1747–1752.

Reddy, K.R., Khaleel, R., and Overcash, M.R., 1981, Behavior and transport of microbial pathogens and indicator organisms in soils treated with organic wastes. Journal of Environmental Quality. Vol. 10, pp. 255-266.

Reed, S.C., E.J. Middlebrooks, and R.W. Crites. 1988. Natural Systems for Waste Management and Treatment. New York, McGraw-Hill.

Reneau, R. B., Pettry, D. E., Shanholtz, M. I., Graham, S. A., and Weston, C. W., Public Health Reports, Vol. 92, No. 3.

Roberts, P.V., Schreiner, J., Hopkins, G.D, 1982, Field Study of Organic Water Quality Changes during Groundwater Recharge in the Palo Alto Baylands, Water Research, 16, 1025-1035.

Seymour, I. J., and Appleton, H., 2001, A review of foodborne viruses and fresh produce. Journal of Applied Microbiology, 91, 759-773.

Siegrist, R.L., D.L. Anderson, and D.L. Hargett., 1986, Large Soil Absorption Systems for Wastewaters from Multiple-Home Developments. EPA/600/S2-86/023, U.S. Environmental Protection Agency, Cincinnati, OH.

UNEP, 1997, Source Book of Alternative Technologies for Freshwater Augmentation in Latin America and the Caribbean. Unit of Sustainable Development and Environment General Secretariat, Organization of American States Washington, D.C.

U.S. Environmental Protection Agency, 1980, Process Design Manual: Onsite Wastewater Treatment and Disposal Systems, EPA-625/1-80-012, Cincinnati, Ohio.

U.S. Environmental Protection Agency, Solid Waste and Emergency Response, 2004, How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites: A Guide for Corrective Action Plan Reviewers, EPA 510-R-04-002, Cincinnati, Ohio

U.S. EPA, 1992, Wastewater Treatment/Disposal for Small Communities, EPA-625/R-92-005. Cincinnati, Ohio.

U.S. Environmental Protection Agency, 1983, Land Treatment of Municipal Wastewater Process Design Manual.

U.S. Environmental Protection Agency,1997, Volunteer Stream Monitoring: A Methods Manual, EPA 841-B-97-003.

U.S. Environmental Protection Agency, 2002, Onsite Wastewater Treatment Systems Manual, EPA/625/R-00/008.

Unlu, K., 2004, Feasibilty Study on Disposal of Partially Treated Domestic Wastewater Using Soil Piles: Assessment of Chemical Attenuation Rates, 04-03-11-1-00-17, Middle East Technical University, Environmental Engineering Department.

Unlu, K., Kemblowski, M. W., Parker, J. W., Stevens, D., Chong, P. K., and Kamil, I., 1992, A screening model for effects of land-disposed wastes on groundwater quality. Journal of Contaminant Hydrology 11, 27-49.

Wilson, L.G., Amy, G.L., Berba, C.P., Gordon, H., Johnson, B., Miller, J., 1995, Water quality changes during soil aquifer treatment of tertiary effluent, Water Environment Research, 67(3), 371-376.

Wang, D., Gerba, C.P., and Lance, J.C., 1981, Effect of Soil Permeability on Removal through Soil Columns. Applied and Environmental Microbiology, Vol. 42, No.1, pp. 83-88.

Van Cuyk S., Siegrist R., Logan A., Masson S., Fischer E. and Figueroa L., 2001, Hydraulic and Purification Behaviors and Their Interactions during Wastewater Treatment in Soil Infiltration Systems, Water Research Vol. 35, No. 4, pp. 953-964.

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44:892–898.

van Genuchten, M.Th., 1987, A numerical model for water and solute movement in and below the root zone. U.S. Dept. Agric., Agric. Res. Serv., U.S. Salinity Lab., Tech Bull. No. 1661, Riverside CA.

van Genuchten, M. Th., Alves, W. J., 1982, Analytical solutions of one-dimensional convective-dispersive solute transport equation. U.S. Dept. Agric., Agric. Res. Serv., U.S. Salinity Lab., Tech Bull. No. 1661, Riverside CA.

van Genuchten, M. Th., Leij, F. J., and Yates, S. R., 1991, The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils, Version 1.0. EPA Report 600/2-91/065, U.S. Salinity Laboratory, USDA-ARS, Riverside, California.

Yates, M.V., and Yates S.R., 1988, Modeling microbial fate in the subsurface environment. Critical Reviews in Environmental Science, CCECAU 17(4):307-344.

Yates, M.V. and Gerba, C.P., 1998, Microbial considerations in wastewater reclamation and reuse, Wastewater Reclamation and Reuse, T. Asano, ed. Technomic, Lancaster, PA.. ch. 10.

Yates, S.R., van Genuchten, M.Th., Warrick, A.W., and Leij, F.J., 1992, Analysis of measured, predicted, and estimated hydraulic conductivity using the RETC computer program. Soil Sci. Soc. Am. J. 56:347–354.

Yeh T.-C. J., 1989, One-dimensional steady-state infiltration in heterogeneous soils. Water Resources Research 25(10), 2179-2158.

APPENDIX A

Table A.1 Soil Textural Proportions

Soil Type	**SOIL TEXTURAL PROPORTIONS**		
	Sand	**Silt**	**Clay**
Clay loam	25 to 45	15 to 35	27 to 40
Loam	23 to 52	< 50	7 to 27
Silt loam	< 50	50 to 88	<27
Sandy loam	43 to 85	< 50	< 20