Treatment of dairy soiled water using an aerobic woodchip filter and a sand filter

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For my parents

The woods are lovely, dark and deep.
But I have promises to keep,
And miles to go before I sleep,
And miles to go before I sleep.-

Robert Frost

(Robert Frost, *New Hampshire: A Poem with Notes and Grace Notes* (New York: Henry Holt and Co., 1923), p. 87. D-11 0397 Fisher Library)

ABSTRACT

The milking process produces dairy soiled water (DSW) that contains variable concentrations of nutrients. The most common method of disposal is by application to land. However, this practice can result in the pollution of nearby receiving water bodies. It is proposed that aerobic woodchip filters would decrease contaminant concentrations of nutrients in DSW. A laboratory-based experiment investigated woodchip as a filter medium to treat DSW. Subsequently, farm-scale filters investigated the system under normal farm conditions. The effectiveness of two types of sand filters (SFs), single-layer and stratified, were compared to treat effluent from the farm-scale woodchip filters.

0.5, 1, and 1.5 m-deep laboratory filters (n=3) containing Sitka Spruce (*Picea sitchensis (Bong.) Carr.*) treated DSW at two loading rates: 280 g suspended solids (SS) m^{-2} d^{-1} (S1) and 840 g SS m^{-2} d^{-1} (S2). Average chemical oxygen demand (COD), SS and total nitrogen (TN) decreases of 95, 99 and 88 %, respectively, were achieved and the effect of depth was negligible. Based on these findings, three replicated farm-scale 1 m-deep filters, each with a surface area of 100 m^2, were constructed and loaded at 30 L m^{-2} d^{-1} for 11 months. Average decreases of 65, 84 and 60 % for COD, SS and TN, respectively, were achieved. Three replicated single-layer SFs and stratified SFs were operated for 82 days and loaded at 20 L m^{-2} d^{-1} with the effluent from the farm-scale filters. Average influent COD, SS and TN concentrations were decreased by an average of 39, 52 and 36 % for the single-layer SFs and 56, 62 and 57 % for the stratified SFs, respectively.

These results demonstrate the potential use of woodchip as a filter medium for treating DSW to produce an effluent for re-use in washing yards, or for application to land as an organic fertiliser. This would reduce water usage and the environmental risks associated with land spreading. Woodchip filters are a low cost, minimal maintenance treatment system, using a renewable resource, which can be easily integrated into existing farm infrastructure.

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Abbreviations

5-day biochemical oxygen demand – BOD_5

Advanced pond system – APS

Ammonia – NH_3

Ammonium – NH_4

Ammonium-N – NH_4-N

Chemical oxygen demand – COD

Coliform forming units – CFU

Constructed wetlands – CW's

Dairy soiled water – DSW

Dissolved organic carbon – DOC

Dissolved organic N – DON

Dissolved reactive P – DRP

Dry matter – DM

Ecological treatment system – ETS

Effective size – D_{10}

Facultative waste stabilisation pond – FWSP

Farm dairy effluent – FDE

Faecal coliforms – FC

Field-saturated hydraulic conductivity - K_{fs}

Filtered COD – COD_F

Filtered TN – TN_F

Free water surface CW – FWS CW

Greenhouse gas – GHG

Horizontal flow biofilm reactor – HFBR

Horizontal SSF CW – HSSF CW

Hydraulic loading rate – HLR

Hydraulic retention time – HRT

Intermittent SF – ISF

Loss on ignition – LOI

Magnetic activated system – MAS

Maximum allowable concentration – MAC

Nitrate – NO_3

Nitrate N – NO_3-N

Nitrite – NO_2

Nitrite N – NO_2-N

Nitrogen gas – N_2

Nitrous oxide – N_2O

Organic loading rate – OLR

Particulate N – PN

Particulate P – PP

Phosphate – PO_4-P

Permeable reactive barrier – PRB

Sand filter – SF

Soil test P – STP

Sub surface flow CS – SSF CW

Suspended solids – SS

Total kjeldahl nitrogen – TKN

Total nitrogen – TN

Total oxidised N – TON

Total phosphorus – TP

Unfiltered COD – COD_T

Unfiltered TN – TN_T

Vertical subsurface flow constructed wetland – VSSF CW

Chapter 1

Introduction

Dairy farming is a key sector in Irish agriculture and dairy products represent over a quarter of all Irish agri-food exports (Department of Agriculture, Food and Fisheries, 2010). Rising population levels, improved standards of living, and changing dietary patterns, particularly in Asia (Fuller and Beghin, 2004; OECD/FAO, 2009), have all contributed to increased demand for dairy food products. This increased demand has been, and will continue to be, met by more intensive agricultural practises (European Communities, 2008). The Farm Structure Survey of 2007 (CSO, 2008) highlighted the trend towards a smaller number of dairy cow herds with increasing herd sizes. This intensification of farming will most likely result in the concentrations of nutrients to be treated increasing. In 2007, there were a greater number of cow herds in the 50-99 head category compared with 1991, when the majority of cow herds fell within the 10-19 head category (CSO, 2008) (Figure 1.1). Intensification on farms may lead to the production of greater volumes of wastewater, which will require effective management options.

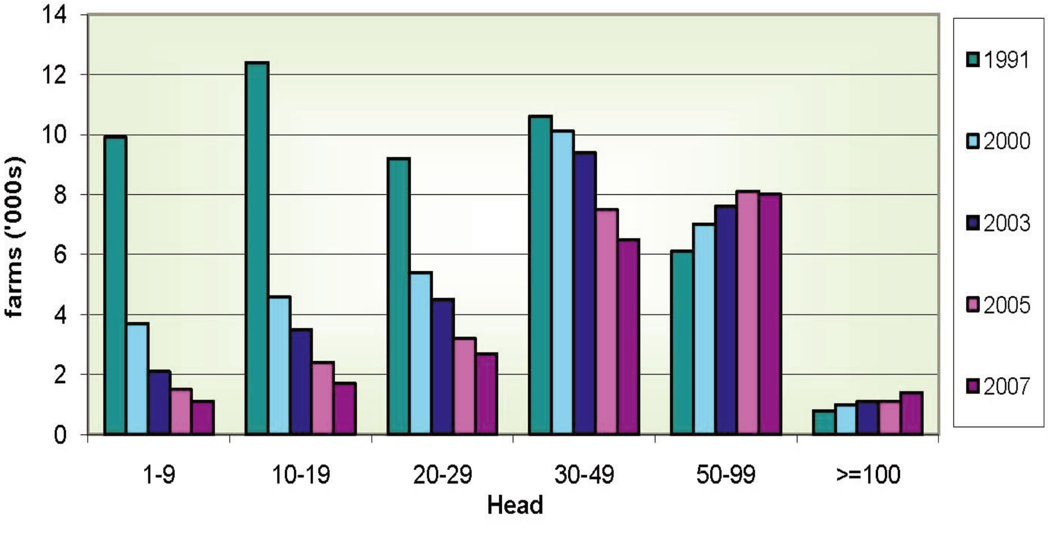


Figure 1.1 Dairy cow herd size breakdown between 1991 and 2007. Figure taken from the Farm Structure Survey 2007 (CSO, 2008)

Agricultural activities are recognised as significant sources of nutrient inputs to European waters (EEA, 2002). These may contribute to a deterioration in water quality in the form of eutrophication (Carpenter et al. 1998), potential toxicity to aquatic species (Kadlec et al., 2005), and groundwater contamination (Knudsen et al., 2006). Legislation in the form of the EU Nitrates Directive (91/676/EEC; EEC, 1991) and the Water Framework Directive (WFD) (2000/60/EC; EC, 2000) has been introduced to address this issue.

Dairy soiled water (DSW) is water from concreted areas, hard stand areas, and holding areas for livestock that has become contaminated by livestock faeces or urine, chemical fertilisers and parlour washings (SI No.101 of 2009; Martínez-Suller et al., 2010). It contains high and variable levels of nutrients such as nitrogen (N) and phosphorus (P), as well as other constituents such as spilt milk and cleaning agents (Fenton et al., 2008). Dairy soiled water is legally defined in Ireland as having a five-day biochemical oxygen demand (BOD_5) of less than 2,500 mg L^{-1} and less than 1 % dry matter (DM) content (S.I. No.101 of 2009).

Application of DSW to the land has long been the most common method of disposal employed by farmers (Martínez-Suller et al., 2010). However, when DSW is land applied at rates that exceed the nutrient requirements of the pasture, it can create a number of problems. These include the threat of loss of P and N in runoff and subsurface leaching of N and P, depending on the soil type (Silva et al., 1999; Knudsen et al., 2006; Regan et al., 2010). Other problems application of wastes include odour, greenhouse gas (GHG) and ammonia (NH_3) emissions (Bhandral et al., 2007), and the build-up of heavy metals in the soil (Wang et al., 2004). However, the European Communities (Good Agricultural Practice for the Protection of Waters) Regulations, introduced in 2006 and amended in 2009 (hereafter referred to as S.I. No.101 of 2009) (EC, 2009), brought about the introduction of a number of restrictions with regard to land spreading of these wastes. Among the restrictions, it imposed a maximum application rate of 50,000 L ha^{-1} in any 48-day period.

Therefore, treatment and re-use of DSW may be considered as a management option to divert DSW from land application.

In order to reduce costs and labour requirements, simple, low-maintenance systems utilising natural processes are preferable for the treatment of waste streams on dairy farms. Constructed wetlands (CWs) have been investigated for the treatment of agricultural wastewaters (Mantovi et al., 2003; Dunne et al., 2005; Wood et al., 2007). In Australia and New Zealand, facultative waste stabilisation ponds (FWSPs) are the most common method of treating DSW (Bolan et al., 2004). Though they are capable of successfully decreasing suspended solids (SS) and BOD_5 concentrations to acceptable levels, they are not very successful at decreasing nutrient concentrations (Craggs et al., 2004; Healy et al., 2007a). Sand filters (SFs), noted for their simplicity and low capital and operating costs, have been used to treat synthetic DSW at laboratory-scale (Campos et al., 2002; Healy et al., 2007b).

Woodchip is already in use on farms to provide outdoor standing areas for cattle during winter months (Vinten et al., 2006; O'Driscoll et al., 2008). A study in Scotland (Vinten et al., 2006) found that filtration through these outdoor woodchip standing areas, known in Scotland as Corrals, resulted in a 5-to 10-fold decrease in faecal indicator bacteria concentrations and dissolved organic carbon (DOC) when compared with fresh slurry. As a result of EU-funded schemes introduced in the 1980s to encourage afforestation, Ireland has a young forest stock and a large area of forests that have not yet been thinned (Teagasc Forestry Development Unit, 2007). Thinnings from these young forests could provide a steady supply of woodchips for use in wastewater filters.

Studies have examined the potential of wood-based products to treat various types of contaminated water such as groundwater high in nitrate (NO_3) and groundwater contaminated by septic systems (Robertson et al., 2000; Schipper and Vojvodic-Vukovic, 2001), aquaculture, other high-strength wastewaters (Healy et al., 2006;

Saliling et al., 2007), and subsurface drainage water (Greenan et al., 2006). These studies focused on saturated woodchip filters, and hypothesised that the carbon (C) contained in the woodchip acts as a C source for microbial respiration. Under anaerobic conditions in these filters, denitrification occurs. This method of treatment is viewed increasingly unfavourably, as denitrification can lead to increased emissions of nitrous oxide (N_2O), a potent greenhouse gas. Aerobic woodchip filtration offers the potential to treat DSW without the N_2O emissions and loss of fertiliser N value associated with anaerobic filtration.

The future of the dairy industry is likely to be characterised by intensification on farms, which will result in the production of increasingly large volumes of DSW. Several problems are associated with the current practise of spreading DSW on the land. Treatment systems, such as those mentioned above, have been investigated for their potential to treat DSW. However, these treatment systems have problems associated with their operation and maintenance. A simple treatment system that promotes natural nutrient transformation processes with low operational and maintenance requirements merits investigation.

1.1 Objectives

This work was carried out as part of a study to develop a treatment system that would treat DSW. The first hypothesis proposed the use of an aerobic filter with woodchip as the filter medium to treat fresh DSW. Given the large volumes of fresh water used daily on farms to clean down the holding yard and milking parlour, the aim was to produce an effluent that could be recycled to wash down these areas.

The second hypothesis investigated the potential of two types of SFs, a single-layer SF and a stratified SF, to further polish the effluent from the woodchip filters. The ability of SFs to remove solids, nutrients and pathogens from influent wastewaters is well documented (Harrison et al., 2000; Prochaska, and Zouboulis, 2003; Stevik et al., 2004; Rodgers et al., 2005; Wanko et al., 2005; Torrens et al., 2009a; Torrens et al., 2009b).

1.2 Procedure

A literature review was carried out to investigate evidence that woodchip could act as a filter medium in an aerobic filter. The various types of waste management options for DSW were critically reviewed from a technical and environmental aspect. Current uses of woodchip as a filter medium were critically appraised. The use of SFs to treat a variety of influents was reviewed to assess the applicability of different types for use in this study. The literature review provided the information necessary to successfully design the experimental units.

Laboratory experiments were carried out to test the hypothesis that woodchip - acting as a filter medium - could decrease the nutrients in DSW. The purpose of the laboratory filters was to assess the ability of the woodchip to treat DSW with two different SS concentrations: 10,000 mg L^{-1} (1 % DM) and 30,000 mg L^{-1} (3 % DM). Three different depths of woodchip were investigated (0.5, 1 and 1.5 m) to determine the design guidelines for the construction of the farm-scale filters.

The purpose of the farm-scale filters was to test the hypothesis under realistic conditions in a working farm. Farm-scale filters (n=3) were constructed on a research farm at Teagasc, Moorepark, Research Centre in South West Ireland. Each filter was capable of treating DSW produced from 100 cows. The filters were monitored over the period of eleven months.

Subsequent to this, two types of SFs were investigated for their ability to treat the effluent from the woodchip filter to a higher standard. This was examined – at laboratory-scale – using replicated (n=3) single-layer and stratified SFs. The purpose of the comparison was to assess which type of filter would produce an effluent with the lowest organic, nutrient, SS and microbial concentration. This data would then provide information to determine which SF would be more suitable for construction at a full-scale.

The project was divided into five main stages:

Stage I:	Literature review and design of laboratory study
Stage II:	Construction, operation and analysis of laboratory experiments for a period of 277 days for S1 (1 % solids loading) and 197 days for S2 (3 % solids loading)
Stage III:	Design and construction of farm-scale filters based on the results of the laboratory study. The farm-scale filters were operated for 320 days
Stage IV:	Design and construction of laboratory-scale SFs. They were operated for 82 days
Stage V:	Collation and analyses of results and final write up

1.3 Structure of dissertation

Chapter 2 presents a review of the literature on the currently employed methods of disposal and treatment of DSW, and the current use of woodchip and sand as a filter medium. Chapter 3 details the methodology employed and the results of a laboratory study investigating the potential of the woodchips to treat DSW. Chapter 4 details the design, construction and operation of the farm-scale woodchip filters. A comparison between two types of SFs to treat effluent from the farm-scale woodchip filters is discussed in Chapter 5. In Chapter 6, conclusions from the studies are made and recommendations for future work are presented.

Chapter 2

Literature Review

Overview

This chapter reviews current and potential treatment methods for DSW. To provide a context for the review, an introduction to DSW and its characteristics is provided. A comprehensive analysis of the technical and environmental aspects of the various types of DSW management options is given, namely land application, natural treatment systems, and emerging technologies. Research concerning the use of woodchip as a filter medium is reviewed. The final section reviews the use of SFs to treat influents with low SS and organic matter concentrations.

2.1 Dairy soiled water and water quality

Dairy soiled water is produced on dairy farms through the washing-down of the animal collecting yard, milking plant, parlour, roads and silos (Ryan, 1990). It contains high and variable levels of nutrients, such as N and P, as well as other constituents such as spilt milk and cleaning agents (Demirel et al., 2005). It is legally defined in Ireland as having a BOD_5 of less than 2,500 mg L^{-1} and less than 1 % DM (S.I. No.101 of 2009). It has been referred to as farm dairy effluent (FDE), dairy shed effluent, dairy farm effluent and liquid dairy waste (Barkle et al, 2000; Zaman et al., 2002; Bolan et al., 2009).

Dairy soiled water is inherently variable and concentrations also vary from season to season (Ryan, 1990). Concentrations of total N (TN), total P (TP) and SS have been shown to vary over a large range: 65 – 825, 13 – 89 and 353 – 12,000 mg L^{-1}, respectively (Table 2.1). Farm management practices, such as the amount of water used for washing on individual farms, are the primary reason for the large variation in concentrations (Longhurst et al., 2000). Compared with slurry (liquid manure), DSW has much lower concentrations of N, P and SS. A study by Martinez-Suller et al. (2010) found that the average concentration of TN, TP and SS from a dairy farm located in the South West of Ireland was 3430 ± 1400 mg L^{-1}, 560 ± 250 mg L^{-1} and 62700 ± 20700 mg L^{-1}, respectively.

Both slurry and DSW have high concentrations of pathogenic bacteria. Kern et al. (2000) recorded counts of faecal coliforms (FC) in DSW of approximately 460,000 coliform forming units (CFU) ml^{-1}. This is significantly higher than other waste streams, such as municipal wastewater, which has an average count of approximately 10,000 CFU ml^{-1} (Kern et al., 2000). While the nature of these FCs are not widely reported for DSW, pathogenic bacteria, such as *E. coli, Salmonella*, *Cryptosporidium* and *Giardia*, have been associated with dairy slurry (Schijven et al., 2004; McGarvey et al., 2007). It could therefore be assumed that less concentrated numbers of these pathogens are present in DSW. The presence of bacteria in these waste streams is important given its potential to contaminate nearby water bodies, and should be given due consideration when disposing of and treating dairy wastes (Wilcock et al., 2009).

Table 2.1 Comparison of concentrations of nutrients in DSW for several different studies (mg L^{-1})

Reference	Location	BOD_5	COD	TN	NH_4-N	NO_3-N	NO_2-N	TP	PO_4-P	SS
Crumby et al., 1999	England	6,593	13,383	825	457				415	1 *
Healy et al., 2007b	Ireland	2,208	2,921	176	85	9			23	353
Lansing and Martin, 2006	USA	517			52				21	
Longhurst et al., 2000	New Zealand			269	48	2		69		1%
Mantovi et al., 2003	Italy	451	1219	65	22			13		690
Martinez-Suller et al., 2010	Ireland	3084		351	32	0	0.3	44		12,000
Schaafsma et al., 1999	USA	2,178		164	72	6		53	57	1645
Sarkar et al., 2006	India	350-600	1500-3000							250-600
Wood et al., 2007	UK	2,811	6,690	540	366			89		6,144

* Unit %

Agricultural activities are recognised as significant sources of nutrient inputs to European waters (European Environment Agency, 2002; Toner et al., 2005) and legislation in the form of the Nitrates Directive (91/676/EEC; EEC, 1991) and WFD (2000/60/EC; EC, 2000) has been introduced to address this issue. The aim of the Nitrates Directive is to enforce protection of receiving water bodies against contamination by NO_3 produced by agricultural activities. The WFD endeavours to protect and enhance the water quality of surface, ground and coastal waters, and to ensure that they achieve 'good status' by 2015. The introduction of legislation has made the farmer more accountable for nutrient management (Longhurst et al., 2000).

Agricultural pollution arising from the land spreading of wastes is classified as a non-point, or diffuse, source where pollutants are transported to a receiving water body from large areas of the landscape through surface and subsurface water flow (Csathó et al., 2007). The application of dairy wastes to land poses a significant threat to water quality due to potential release of NO_3 and P (Mawdsley et al., 1995). A study investigating the quality of rivers and streams around Ireland found that the majority of recorded instances of slight pollution were as a direct result of farmyard runoff and inappropriate timing of slurry spreading (EPA, 2008). The same study found that agricultural pollution accounted for the largest number of fish kills between 2004 and 2006. With half of the land surface area of Europe currently used for agricultural purposes (EC, 2009), the focus of legislation, policy and actual practices to mitigate pollution has to be on farm and land management (FAO, 1996).

2.1.1 Nitrogen

Nitrogen in the environment is extremely versatile, and exists in a variety of different compounds due to the number of oxidation states it can assume (USEPA, 1993a). It is a vital component of life contained in DNA, proteins and amino acids. Its gaseous form, nitrogen gas (N_2), constitutes the largest fraction, 78 %, of the atmosphere. The principal forms of N in soils and wastewaters occur in both organic and inorganic (nitrite (NO_2), NO_3 and ammonium (NH_4) forms, and is represented by the following equation:

$$\text{Total N} = \text{Organic N} + NH_3 + NH_4 + NO_2 + NO_3 \qquad [2.1]$$

There are five main processes associated with the N cycle: fixation, uptake, mineralization, nitrification and denitrification. Nitrogen gas must be converted to more readily accessible forms before it can be utilised by most organisms. Nitrogen fixation is the process of conversion of N_2 to NH_4. This process occurs in the presence of Nitrogenase, a naturally found catalyst. Fixation is predominantly biological, brought about by N fixing bacteria that can exist in symbiotic associations with plant hosts, or as free living soil microorganisms. Bacteria associated with fixing N in plant hosts include *Rhizobium* and *Azotobacter*, and are associated with the free-living bacteria in aerobic soils (Miller and Cramer, 2005).

Ammonium can be converted to organic N by the plant host or by the soil microorganisms into which it has been incorporated during the fixation process. During decay and decomposition of organic matter, the organic N can be mineralised by soil microbes to produce NH_4. In soils, NH_4 may be taken up by plants or may be absorbed onto the surface of the soil. Its positive molecular charge means it can be held by soil colloids and can be released again by cation exchange (Pidwirney, 2006).

Nitrification is the process by which NH_4 is biologically oxidised to NO_2 and then to NO_3. Nitrite is relatively unstable and is the intermediate oxidation state of the nitrification process. Nitrate is the final product in the process of biological oxidation of NH_4.

Nitrification is carried out by two specific chemoautorophic bacteria (USEPA, 1993a). The first step involves the conversion of NH_4 to NO_2, which is carried out by *Nitrosomonas*; and the second step is carried out by *Nitrobacter*, and involves the conversion of NO_2 to NO_3. Figure 2.1 provides a schematic overview of the nitrification process. Both of these processes can be described by the following stoichiometric equations:

$$NH_4^{\ +} + 3/2O_2 \xrightarrow{nitrosomonas} 2NO_2^{\ -} + H_2O + 4H^+$$

$$NO_2^{\ -} + 1/2O_2 \xrightarrow{nitrobacter} NO_3^{\ -} \qquad [2.2]$$

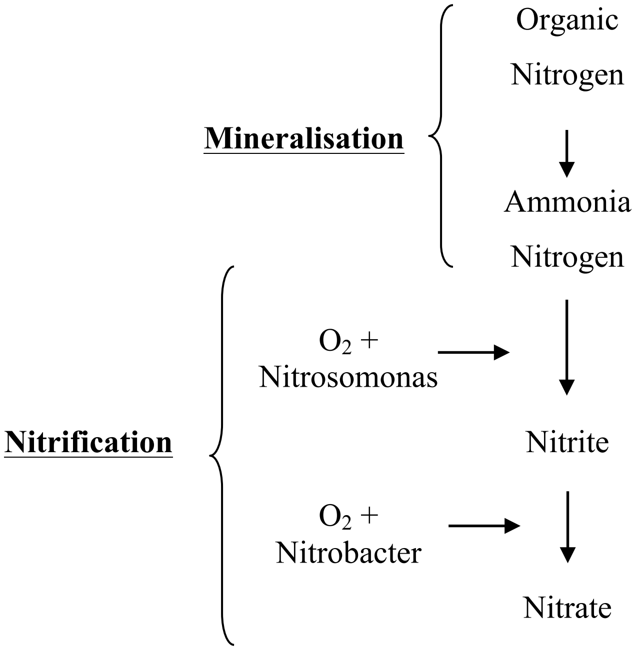


Figure 2.1 Schematic overview of the processes of mineralisation and nitrification.

Several factors can affect the nitrification process. In wastewater treatment plants, dissolved oxygen (DO) levels of less than 1 mg L^{-1} can result in oxygen (O_2) becoming a limiting factor in the process, and can slow down or halt the process of nitrification. The effect of temperature is significant. The rate of nitrification increases with increasing temperature and is slowed down at temperatures below 10 ºC (Owens et al., 1973; Water Environment Federation, 1998; Kim et al., 2006). Other factors that can inhibit oxidizing bacteria include the sludge retention time, substrate concentration and load, and pH (Peng and Zhu, 2006). A pH range of 7.5 to 8.6 is deemed optimal (Tchobanglous, 1998). In soils, the rate at which the wastewater is applied is important if the pore space between the filter media becomes saturated, or if it limits the amount of O_2 within the filter matrix resulting in less O_2 availability for the aerobic bacteria responsible for nitrification (Tchobanglous, 1998).

Denitrification may occur under anoxic conditions. This involves the metabolic reduction of NO_3 into N_2. This process is carried out by facultative heterotrophic bacteria. Facultative organisms derive O_2 first from DO and then from NO_3. Denitrification occurs in soils when they are flooded and the soil atmosphere O_2 concentration is depleted (Moiser et al., 2002). During denitrification, NO_3 replaces O_2 in the respiratory system of the bacteria (Xie et al., 1999). Temperature, amount of organic matter present, soil water content and pH all greatly affect the rate at which denitrification takes place (Luo et al., 1999). Denitrification generally proceeds through the following states: NO_3, nitrogen dioxide (NO_2), nitric oxide (NO), N_2O and N_2:

$$NO_3^- \longrightarrow NO_2^- \longrightarrow NO \longrightarrow N_2O \longrightarrow N_2 \qquad [2.3]$$

Metabolism of the microbes responsible for denitrification may be incomplete if the organisms become stressed during the process. This may result in the release of intermediate gases. The intermediate gases produced during the process of denitrification can be detrimental to the environment. Nitrous oxide has a 100-year global warming potential 297 times greater than carbon dioxide (CO_2) and the majority of N_2O emissions are as a direct result of agricultural activities (Pachauri and Reisinger, 2007). Nitrogen oxide (NO_x) in the atmosphere consists primarily of NO_2 and NO (World Bank Group, 1998). Agriculture accounted for 9.8 % of the overall NO_x emissions in 2008 (EPA, 2010). The production of soil NO_x is controlled by several factors such as inorganic N availability, soil temperature and the soil water content (Hall et al., 1996). The processes involved in the conversion of N to various compounds are vital in producing fractions of N that are beneficial for the growth of plants and in decreasing concentrations of fractions that may be harmful to water bodies and the atmosphere.

2.1.2 Phosphorus

Phosphorus is an essential nutrient for plants and animals. It can be found in soil, water and sediments. Unlike N, P doesn't exist in a gaseous state. Phosphorus is taken up by plants in the form of phosphate ions, PO_4^{3-} and HPO_4^{2-}, and can then be consumed by animals. Through the process of decomposition, P is returned to soil and water bodies by enzymatic hydrolysis.

Phosphorus is often a limiting nutrient in plant growth. Human intervention has altered the P cycle with the land application of chemical fertilisers and organic wastes to supplement plant growth. In cases where this P is applied in excess, it can make its way into receiving fresh water bodies and trigger eutrophication (Regan et al., 2010). Phosphorus can accumulate on the surface of soils or in the top layers of the soil profile if applied in excess of plant requirements (Geohring et al., 2001; Soupir et al., 2006; Toth at al., 2006). Once P has accumulated in the upper layers of the soil profile it adsorbs to SS, surface soil and vegetation. Erosion of the soil surface can lead to transport of sediments in surface runoff (Lee et al., 1989). It can also be taken up by microorganisms and plants and move downwards through the soil profile (Lee et al., 1989). Agriculture is the single biggest contributor of P to Irish waters and eutrophication remains Ireland's most serious environmental pollution problem (DOELG, 2002).

Dissolved P and sediment-bound P are the two major sources of P loss to receiving water bodies (Karthikeyan et al., 2004). The three most common forms of P found in wastewater influents are: i) orthophosphates (PO_4), ii) polyphosphates and iii) organic phosphates. Dissolved P consists of orthophosphate anions, inorganic polyphosphates and some organic P compounds. Polyphosphates may undergo hydrolysis in water and be converted to PO_4. Dissolved P is the most readily available form of P for plant and algae uptake (Karthikeyan et al., 2004). Therefore, it is essential to reduce the level of P in discharges, as PO_4 is associated with eutrophication and algal blooms.

2.2 Current methods of disposing of DSW

2.2.1 Land application

Application of DSW to the land remains the most common management option for farmers in Ireland and internationally (Martinez-Suller et al., 2010). The purpose of land application is to take advantage of a soil/plant system's ability to assimilate waste components and to decrease the need for inorganic fertilizers (Cameron et al., 1997; Zaman and Cameron, 1999). Land application of nutrients avoids the point source discharge of wastes to water bodies and enables an economic return by recycling nutrients for plant growth (Bhandral et al., 2007). There are many benefits associated with the application of DSW to the land. Increased herbage yield, improvements in the long term fertility of soil, and increases in soil microbial biomass have all been noted (Hawke and Summers, 2006; Minogue et al., 2010). A study by Barkle et al. (2000) found that the application of DSW increases the pH of gleysoil, which favours microbial activity and decreases the need for lime application. A study by Zaman et al. (2002) found that inorganic N, extracellular enzyme activities, microbial biomass, and C and N increased after application of DSW with the greatest increases occurring in the top 5 cm of the soil. Therefore, land application of DSW can be beneficial. However, over-application of DSW may result in immediate nutrient losses or the build-up of nutrients within the soil matrix.

The chemical, biological and physical processes that occur naturally within a soil system are similar to those that occur within filter systems. Filters are effectively engineered systems that mimic and enhance natural processes. The effectiveness of both a soil system and a filter to decrease and transform influent concentrations of SS, N and P are similar.

2.2.2 Removal mechanisms associated with land application

2.2.2.1 Solids

The principal method of removing solids from DSW or slurry applied to the land is by filtration. Surface straining occurs as the applied wastewater passes through the surface and the top few centimetres of the soil. Deeper in the soil profile, straining is referred to as interception (Barkle et al., 1999). Physical clogging occurs as the SS within the wastewater accumulates in the soil pores. The anaerobic conditions that may develop after a wastewater has been applied to a soil can result in biological clogging within the soil matrix (Rice, 1974).

2.2.2.2 Nitrogen

Regulation dictates that N in DSW is the guiding factor in determining the optimum rate of application. When applied in the correct quantities, it can produce herbage yields comparable to those achieved when using chemical fertilisers (Minogue et al., 2010). Nitrogen applied to soil is subject to movement and transformation through leaching, NH_3 volatilisation, nitrification and denitrification. When DSW is applied to the land, the N fraction consists mostly of organic N (Zaman et al., 1999). The rate at which this form of N is mineralised depends on the activity of microorganisms, and the rate is increased with the addition of organic C and nutrients in the DSW (Barkle et al., 1999). Organic N present in DSW undergoes mineralization due to the presence of readily mineralizable substrates and nutrients that promote microbial activity (Zaman et al., 1999). The rate of mineralization is strongly dependent on the availability of water within the soil structure (Zaman et al., 1999).

The application of DSW increases the amount of soluble organic C and soil microbial biomass C (Zaman et al., 2002). The extent to which leaching occurs is influenced by the amount of available soluble organic C in the soil, as the microbial communities responsible for various N transformation processes compete for this C. Once the pool of soluble organic

C has been exhausted, no additional N will be denitrified and leaching may occur (Zaman et al., 1999; Di and Cameron, 2000; Silva et al., 2005). The amount of leaching is dependant upon a number of factors including: soil chemical and physical properties, climate, effluent composition, and method of application of wastes (Unwin et al., 1986).

Several studies have investigated the N forms in DSW, after it has passed through a soil (Barkle et al., 2000; Houlbrooke et al., 2008). A study by Singleton et al. (2001) found that the majority of N was in the organic form with only a small percentage of ammonium-N (NH_4-N). It was found that the low concentration of NO_3-N was attributed to denitrification within the soil and the greater amount of organic N was as a result of preferential flow through the soil (Singleton et al., 2001). The type of soil to which the DSW is applied plays an important role in determining the nature of N transformations. If the soil structure contains macropores, preferential flow can occur, meaning that influent inorganic N fractions pass through the soil profile unaffected by soil biological processes. In well-aerated agricultural soils, NO_3 is the dominant form of N present in leachate. In waterlogged soils, where nitrification is limited or inhibited, NH_4 tends to dominate (von Wirén et al., 1997).

When movement of N occurs in overland runoff, NH_4 typically constitutes the largest fraction of TN (Zebarth et al., 1999). The concentration on N in runoff tends to be highest if a rainfall event occurs shortly after land application of agricultural waste (Eghball et al., 2002). Soils with a low permeability, such as clay, are more susceptible to losses of N *via* surface runoff (Withers et al., 2002).

As DSW filters down through the soil matrix, the water displaces the air present and creates anoxic conditions suitable for denitrification (Russell, 1993). A large volume of water present in the soil at the time of land application can increase the occurrence of denitrification (Cameron et al., 1997; Bergsma et al., 2002). Aerobic decomposition of easily decomposable organic compounds found in animal waste results in decreased amounts of O_2 in the soil, which provides a favourable atmosphere for denitrification (Rice et al., 1974). The increased concentration of soluble C and mineral N is a source of food for microorganisms present within the soil structure, resulting in an increased amount of microbial biomass, thus creating conditions suitable for denitrification (Zaman et al., 2002; Bhandral et al., 2007).

Anaerobic treatment has the disadvantage that denitrification will lead to a loss of the fertiliser value of N in soiled water and the potential for increased N_2O emissions. Denitrification within the soil structure can result in emissions of N_2O (Mikkelsen and Gilliam, 1996; Bhandral et al., 2007). Due to its chemical stability, N_2O gas is considered a long-lived GHG that can have a long-term impact on climate (IPCC, 2007). Denitrification in soil accounts for 88 % of the N_2O emissions from agriculture in Europe (EC, 2009). At 29.1 % of the total emissions, agricultural activities are the largest contributor to Ireland's GHG emissions (EPA, 2010). Therefore, research is necessary to achieve reductions in N_2O emissions as a result of land spreading of dairy wastes.

2.2.2.3 Phosphorus

Phosphorus is an essential nutrient for plant growth and, if P is applied at a rate that closely matches the requirements of the crops, the potential for surface and subsurface P pollution is minimised (Csathó et al., 2007). Unlike N, when P is applied to the land in quantities exceeding crop requirements, it can accumulate in surface soils (Geohring et al., 2001; Soupir et al., 2006; Toth at al., 2006). Such accumulation may result in increased instances of P runoff to nearby water bodies. A study conducted on twelve soil types in Ireland found that soils with higher levels of organic matter (OM), such as peat, had a lower P sorption capacity than mineral soils (Daly et al., 2001). The increased amount of OM in peat soils decreases the number of sites, normally occupied by aluminium (Al) and iron (Fe), where sorption can occur. This results in a higher concentration of P in solution in peat soils, which may be available to overland flow.

Phosphorus becomes more soluble and mobile under wet conditions, and is susceptible to transport to nearby receiving water bodies by surface runoff. Heavy rain increases the potential for high erosion of the soil and therefore increases the potential for P loss (Csathó et al., 2007).

Approximately 90% of the P applied can typically be accounted for in the top 5 cm of the pasture soil (Toth et al., 2006; McDowell and Wilcock, 2007). The greatest proportion of P in this section is readily bioavailable (Shafqat and Pierzynski, 2010). Shafqat and Pierzynski (2010) investigated depths from 0 -15 cm and found the concentration of various forms of P from continuous slurry applications was highest at a depth of between 0 – 5 cm in the soil profile. It is the P held in this section of the soil profile that attaches to soil particles through processes such as desorption, dissolution and diffusion, and can then be eroded and transported in runoff water (Hansen et al., 2002). Therefore, with the accumulation of P in the top layers of the soil profile, the potential for P release in runoff increases (Vadas et al., 2005).

The P in runoff water can be organic or inorganic, and either in solution (as dissolved reactive P; DRP) or in particulate form (particulate P; PP). The PP form is associated with eroded soil particles (Reynolds and Davies, 2001). Dissolved reactive P in runoff is directly related to the concentration of soil test P (STP) in the top layers of the soil profile (Regan et al., 2010). Dissolved reactive P is readily available for rapid biological uptake or fixation to the soil, whereas only a certain proportion (typically 20 % of the PP) is bio-available (Sharply, 1997; Toor et al., 2004). Several reactions, such as reduction-oxidation and precipitation-dissolution, over time can result in PP being made bioavailable for plant uptake (Ellison and Brett, 2006). A study by Kleinman and Sharply (2003) found that the concentration of DRP and TP in surface runoff is a function of application rate, method of application, slurry type and timing. Toor et al. (2004) examined the P fractions of fresh DSW and effluent DSW after passing through a stony silt loam soil. The largest P fraction found in the influent DSW was PO_4, with organic forms of P comprising less than 14 %. However, after passing through the soil column, the inorganic PO_4 accounted for only 12

%, with organic P forms constituting the largest fraction. The implication is that organic P forms of DSW are less likely to be sorbed to the soil and are more mobile in the soil matrix than inorganic P (Toor et al., 2004).

Leaching through the soil profile is a significant form of P loss in some soils, especially those that have a low P sorption capacity, such as sandy soils. The type of soil and its P sorption capacity is an important factor in determining losses of specific P fractions from applied DSW (Toor et al., 2004). The presence of plants and their roots can result in preferential flow of DSW applied to a stony silt loam soil and may result in losses of P (Toor et al., 2004). Adding DSW to a soil will decrease the capacity of that soil to retain P and increase the potential for P release (Daniel et al., 1998; Dou et al., 2009; Shafqat and Pierzynski, 2010). Several studies have found that between 51 and 80 % of the TP associated with leachate is in sediment-bound form after slurry application (Schelde et al., 2006; Kleinman et al., 2009). Kleinman et al. (2009) looked at the application of dairy manure (0 – 100 kg TP ha^{-1}) to two types of soils, Clymer and Wharton, and found there was a direct link between slurry application and increased losses of P in leachate.

2.2.3 Problems associated with land spreading

When wastewater is applied to the soil surface, the main mechanisms of nutrient and organic matter removal are plant uptake, filtration, microbial decomposition, and soil adsorption (Barkle et al., 1999; Hawke and Summer, 2003). However, the uncertainty associated with nutrient release and availability means that it is often difficult to ensure that the nutrients applied are trapped within the soil profile or beneficially utilised by plants, and not discharged to nearby water bodies. Land application rates are typically based on the N and P concentration of the wastewater applied to the land (Cabrera and Gordillo, 1995; Toth et al., 2006). Current methods of land application lead to various assumptions regarding the nutrient concentration of the wastewater. It is assumed that farmers have the ability to continuously monitor the concentrations of all forms of N and P. It is also assumed that the rate at which the various forms of N are mineralized can be predicted, as well as estimating the extent to which soil and other environmental conditions will affect the rate and extent of mineralization (Sims et al., 2000). Often when slurry is applied to the land, its precise nutrient concentration, and therefore fertiliser value, is unknown. This makes it difficult to manage land application in order to meet plant requirements and to mitigate pollution.

As transporting DSW can be costly, it is typically spread on fields in the vicinity of the parlour. This can lead to large increases in soil nutrient status in these fields, which can give rise to nutrient losses to receiving water bodies (Mulqueen et al, 2004). The intensification of farming and recycling of nutrients to the land has raised questions about the exploitation of our limited renewable resources and the sustainability of current disposal methods (Casthó et al., 2007).

In an attempt to alleviate potential problems occurring when applying DSW to land, various constraints have been imposed to restrict the application of DSW by the introduction of S.I. No.610 of 2010. These include minimising the quantity of DSW by preventing any clean water from roofs and unsoiled paved areas entering waste storage facilities. Stipulations regarding the capacity of storage facilities require the farmer to have the capacity to store all soiled water produced during a ten-day period. Land application of DSW is forbidden under the following circumstances: if the land is water logged; if the land is flooded or likely to flood, or if heavy rain is forecast within 48 hours; if land is snow or frost covered; or if the ground slopes steeply. Application using an umbilical system or tanker with an upward-facing splash plate is forbidden. Dairy soiled water cannot be applied in quantities exceeding 50,000 L ha^{-1} in a 42-day period (the equivalent of 170 kg N ha^{-1}), or by an irrigation rate greater than 5 mm per hour. The constraints imposed by legislation have served to place additional restrictions on farmers regarding land spreading of wastes. Therefore, options that make it easier to deal with the large volumes of dairy waste should be investigated as an aid to farm management.

2.2.4 Summary of current methods of disposal of DSW

Land spreading is the most widely used method of disposal of DSW. It has been shown to have several benefits. However, due care has to be taken to avoid the potential for pollution of nearby water bodies and the atmosphere. The intensification of farming will result in the production of increased volumes of DSW. The introduction of legislation governing current land application methods ensures DSW is disposed off in the most beneficial way possible. Despite this, pollution is still possible, as factors not accounted for by legislation, such as soil moisture content, quantity of available organic C, soil structure and the activity of soil micro-organisms, all influence the rates of transformations of N and P.

2.3 Current methods of treating DSW

Current methods of treating DSW on farms involves relatively simple and low maintenance systems. With intensification of farming, larger volumes of DSW will be produced that have to be spread on land. Disposing of large volumes of DSW is laborious and becoming increasingly difficult in light of stringent environmental legislation. Ideally, treatment systems on farms should to be capable of treating fluctuating influent concentrations with minimal maintenance, and have low capital and operational costs. Treatment structures should take up a small footprint and be capable of being easily expanded as farm herd numbers increase.

Constructed wetlands and other naturally engineered systems, such as oxidation ponds and advanced pond systems (APSs), have been investigated at a farm-scale. These systems are described in this section. Other novel technologies, such as horizontal flow biofilm reactor (HFBRs), submerged bioreactors, and the magnetic activated sludge (MAS) process, have been investigated at a laboratory- or pilot-scale to treat DSW. These technologies are now described. The potential for these systems to be retro-fitted into existing farm infrastructure is also considered.

2.3.1 Constructed wetlands

2.3.1.1 Configuration/classification

There are two types of CWs: free water surface CW (FWS CW) and sub-surface flow CW (SSF CW). Both consist of a shallow basin filled with a substrate, such as soil or gravel that provides a bed for emergent aquatic plants to grow. A FWS CW maintains water above the top surface of the substrate in the wetland and the SSF CW maintains the water below the surface of the media in the wetland (USEPA, 1993b). There are two types of SSF CWs: horizontal SSF CW (HSSF CW) in which the wastewater flows horizontally through the substrate, or vertical flow SSF CW (VSSF CW) where the wastewater is dosed onto the surface of the substrate (Healy et al., 2007a). The most popular CWs for treating agricultural wastes in Ireland and in the US are FWS CWs (Babatunde et al., 2008).

2.3.1.2 Treatment processes within the system

Constructed wetlands are effective at reducing concentrations of BOD_5, SS, N, P, metals and pathogens from influent wastewaters (Kadlec, 2009). Sub-surface flow CWs allow for both aerobic and anaerobic processes of removing N to occur simultaneously because they contain anaerobic zones and aerobic zones around the root of the wetland vegetation (Paredes et al., 2007). Other methods of removal in SSF CWs include: sedimentation; filtration through the substrate; adsorption and ion exchange on the surfaces of substrate and plants; breakdown, transformation and uptake of pollutants by plants and microorganisms (USEPA, 1995).

The effectiveness of a CW to treat water is a combination of microbial action and filter material (Truu et al., 2009). Planted CWs have demonstrated a greater ability to remove N and P from DSW than unplanted CWs (Tanner et al., 1995). Microbial activity and processes depend upon various factors such as concentration of nutrients and pollutants in the influent wastewater, hydraulic loading rate (HLR), environmental conditions, filter material and plants (Truu et al., 2009).

The presence of substrate and plants helps to slow down the flow of water through the wetland. Substrate provides a support for living organisms and increases the potential for settlement of SS. Substrate also provides a surface for attached microbial growth and the clay content of the soil enables P sorption (Dunne et al., 2005). Nguyen (2000) found that litter from plants was deposited mostly in the top 10 cm of the gravel bed in a HSSF CW and that microbial biomass and respiration were significantly correlated with these deposited sediment fractions. However, this build-up of microbes within the substrate has been found to contribute to accelerated clogging (Zhao et al., 2009). Clogging of the substrate can lead to a decrease in the removal of P and hydraulic retention time (HRT) (Vohla et al., in press). Sub-surface flow CWs are more susceptible to clogging and therefore are not advisable for use in situations where the influent wastewater is high in SS (Hammer, 1994).

Plants provide additional contact area for attached growth of microbes, shelter to limit the growth of algae within the wetland, and create an aerobic zone to facilitate nitrification (Reed and Brown, 1995). Upon death, they provide additional substrate and are a source of C for microorganisms (Cronk, 1996). A study by Gottschall et al. (2007) investigated the role of plants in removing N and P in a CW treating wastewater containing runoff from a holding yard, milking parlour washwater and slurry runoff. That study found that the ability of plants to decrease concentrations of influent N and P was significant at low influent concentrations. Nitrification occurs in aerobic zones within the CW, mostly located near the roots of plants where O_2 is released through a process known as 'radial oxygen loss' (Paredes et al., 2007; Kadlec, 2008). Kadlec et al. (2008) found that the death of vegetation in a wetland in Arizona was accompanied by a drastic reduction in the amount of mineralisation and nitrification due to the changes in temperature, DO, pH and C content associated with the vegetation. A study by Majer Newmann et al. (1999) highlighted the importance of the role of vegetation in a FWS CW treating milkhouse wastewater.

Following plant die-off in a FWS CW, there was an increase in the amount of NH_4 in the outflow (Majer Newmann et al. 1999).

Denitrification occurs near the bed of the CW where microbial activity consumes the available O_2 faster than it can be replaced by diffusion from the atmosphere (Kadlec, 2008). This, coupled with the build-up of filtered material and the saturation of the substrate, creates anoxic conditions suitable for denitrification (USEPA, 1995). Organic matter can accumulate within the substrate, providing a source of C for denitrifying bacteria (Tanner et al., 1995).

Phosphorus removal in a CW is similar to the removal mechanisms associated with movement of P through a soil matrix – filtration and sorption on the substrate surface (Reed et al., 1995). Phosphorus transformations within a CW are dominated by the activity of microbes, which are associated with the biological mineralisation of organic P (Truu et al., 2009). Dissolved inorganic P in the wastewater is taken up by plants and microbes, and is converted into organic forms (Yates and Prasher, 2009). Depending upon the Al and Fe content of the soil and its cation exchange capacity (CEC), it can retain P via adsorption and precipitation (Yates and Prasher, 2009). The ability of a wetland to retain P is largely finite when adsorbed, precipitated or taken up by vegetation (Majer Newman et al., 1999). Tanner et al. (1995) suggested that the increased removal of N and P in planted wetlands over unplanted wetlands was not entirely due to plant uptake. That study suggested that other factors associated with the presence of plants, such as the increased storage and sorption potential associated with plant litter and organic residues, enhanced N and P removal. The only long-term sink of P in a wetland is the build up of sediment-buried P that is removed from contact with water within the wetland (Kadlec and Knight, 1996). However, the sustainability of sorption and storage of P associated with the substrate is limited at high loading rates and wetlands can experience release of P.

2.3.1.3 Effect of temperature

At lower temperatures, rates of microbial transformation within the wetland slow down, affecting the rate at which total kjeldahl nitrogen (TKN) and NH_4 are decreased (Akratos, and Tsihrintzis, 2007). An adequate flow during the summer will negate the risks associated with water loss due to evapotranspiration (USEPA, 1995). Nitrification and denitrification are also affected by temperature, with denitrification no longer occurring at temperatures below 5 ºC; and NH_4 oxidisers - rather than NO_2 oxidisers - flourishing at temperatures above 25 ºC (Truu et al., 2009). Majer Newmann (1999) reported a significantly higher rate of denitrification during the summer than the winter in a FWS CW. Free water surface CWs are more sensitive to temperature than SSF CWs with regard to N removal (Kadlec, 2009). In all types of CWs, vegetation contributes to thermal protection and there is an increase in the ability of plants to uptake N during warmer weather in temperate climates (Cronk, 1996; Majer Newman et al., 1999; Mander et al., 2008).

2.3.1.4 Performance in treating DSW

Majer Newmann et al. (1999) examined the performance of a FWS CW treating wastewater from a milkhouse at the University of Connecticut in the USA. The CW was loaded at a HLR of 2.65 $m^3 d^{-1}$ and achieved TSS, BOD_5, TP, and TKN reductions of 94, 85, 68, and 53 %, respectively (Table 2.2). Tanner et al. (1995) examined the effectiveness of a SSF CW to treat DSW after pre-treatment in oxidation ponds (Table 2.2). The results of that study concluded that the presence of plants in the SSF CW had no effect on the decrease of SS and FC in the effluent, but for total BOD_5, carbonaceous BOD_5, TN and TP, there was a greater overall decrease by the planted wetlands over the unplanted wetlands. Over the 2-year study period, the SSF CW, with mean influent concentrations of TP of 11.3 to 18 mg L^{-1}, did experience releases of accumulated TP from the CW in the effluent, suggesting that the long-term sustainability of wetlands may be limited (Tanner et al., 1995). Mantovi et al. (2003) conducted a study in Italy and reported good reductions in influent nutrients for a HSSF CW planted with reeds (Table 2.2). However, they concluded that only wastewater from the ‘clean’ areas such as the milk room and milking machine areas should be treated using CWs. The wastewater from the washing down of the milking parlour and holding areas was too high in solids to be effectively treated using a CW (Mantovi et al., 2003). Table 2.2 highlights the large variation in percentage removal rates between several different studies examining CWs to treat DSW. The effectiveness of different types of CWs to decrease influent nutrient concentrations varies greatly and some form of pre-treatment is generally required.

Table 2.2 Comparison of Constructed Wetlands to treat dairy soiled water

Author	Location	Type	HLR $m^3\ d^{-1}$	Size m^2	Pre-treatment	% Reduction TN	TKN	NH_4-N	TP	BOD_5	COD	TSS	SS
Tanner et al., 1995	NZ	HSSF*	20-63[a]	19	Two-stage oxidation pond	48-75		34-71	37-74	50-80			75
Mantovi et al., 2003	Italy	HSSF*	6.5	75	Imhoff tank	48.5			60.6	93.7	91.9	91	
Majer Newman et al., 1999	USA	FWS**	2.69	400	No		28		45	76		90	

*Horizontal sub-surface flow

**Free water surface flow

[a] mm d^{-1}

2.3.2 Waste stabilization ponds

In addition to CWs, other naturally engineered treatment processes have been used to treat DSW on dairy farms. In New Zealand, oxidation ponds, or FWSP, have been used to treat DSW (Hickey et al., 1989). These ponds consist of an anaerobic waste stabilization pond followed by an aerobic pond (Mason, 1997). A study by Mason (1997) looked at the ability of a FWSP (total liquid volume of 2300 m^3) to treat DSW from a dairy shed housing 500 cows so that the effluent could be discharged directly to a receiving water body. This study found that, although the overall system was capable of a good degree of O_2 demand transformation, N and P removal rates remained low (Table 2.3) and dilution would be required before discharge.

A study by Sukias et al. (2001) examined the performance of six FWSP that were upgraded by increasing the size of the facultative, or aerobic, ponds. Although improvements of between 20 - 70 % were noted in the removal of BOD_5, NH_4-N, TN and FC, rates of removal of SS did not improve by increasing the size of the facultative pond size (Table 2.3). It was also noted that the performance was highly variable and only half of the six facultative ponds studied consistently met an effluent standard of less than 100 g BOD_5 m^{-3}. Therefore, further improvements would be required before effluent would reach receiving water body guidelines (Sukias et al., 2001).

Another improvement to the FWSP that has been investigated is the APS. Craggs et al. (2004) examined the possibility of replacing the aerobic pond with a high rate pond, a pair of algae settling ponds, and a maturation pond. Analysis of this system at full-scale over a 2-year period found the effluent quality from the APS to be superior to the traditional pond system and suggested its use for upgrading ponds, particularly in areas where land application of DSW is problematic (Table 2.3).

Table 2.3 Comparison of effluent characteristics (median) from a traditional facultative waste stabilisation pond (FWSP) (Hickey et al., 1989), an upgraded FWSP (Sukias et al., 2001) and an advanced pond system (APS) (Craggs et al., 2004)

Parameter	FWSP	Upgraded FWSP	APS
		$g\ m^{-3}$	
BOD_5	98	65	34
SS	198	206	64
TKN		69	26
NH_4-N	75	37	8
TP	26.7		15

2.3.3 Ecological treatment system

An ecological treatment system (ETS) has been tested at a dairy facility in Columbus, OH, USA (Lansing and Martin, 2006; Morgan and Martin, 2008). This system consisted of an anoxic reactor, a closed aerobic reactor, a planted aerobic reactor, a clarifier, a SSF CW, two planted aerobic reactors, a clarifier and two SSF CWs arranged in series. The different reactors within the overall system make it possible to isolate and enhance the various nutrient removal processes. The system was tested for a range of different strength dairy wastewaters collected from two feed barns and the milking parlour. Respective removals in excess of 99, 95, 81, 96 and 98 % for NH_4-N, TN, TP, TSS and carbonaceous BOD_5 were achieved (Lansing and Martin, 2006) (Table 2.4).

2.3.4 Novel laboratory-scale treatment systems

Several novel treatment systems have been investigated, mostly at a laboratory-scale or pilot scale, to treat DSW. The University of Birmingham studied the potential for a submerged aerated bioreactor to treat DSW before further treatment in a reed bed before discharge to a water body (Cannon et al., 2000). The study examined the potential for two types of reactors, one packed with media and the other without any packing media, to treat simulated DSW at a laboratory-scale. The submerged aerated filter achieved good rates of nitrification (Table 2.4). However, reductions of influent SS concentration averaged only 57 %. The treatment process was also deemed to be inappropriate if the main objective of the treatment at a farm-scale was BOD_5 reduction. This system has, to the author's knowledge, not been introduced at a farm scale. Therefore, the effect of fresh DSW under operational conditions was not tested.

Both a laboratory- and pilot-scale study was carried out to investigate the potential for using a HFBR to partially treat DSW prior to land spreading (Clifford et al., 2008). The HFBR consisted of 45 horizontally stacked dimpled plastic sheets with influent pumped onto the first and thirtieth sheet intermittently. The units, at both the laboratory- and pilot-scale, were capable of good reductions, with removals of 69 % BOD_5, 75 % COD, 58 % NH_4-N, 56 % TN and 66 % SS for the pilot-scale unit (Table 2.4). The laboratory-scale unit achieved higher removal rates than the pilot-scale unit. The HFBR proved to be robust and can be adapted to accommodate an increase in incoming volumes. It can be easily fitted into an existing farm system to treat DSW prior to land spreading.

The use of a modified conventional activated sludge process, the MAS process, has been tested for its ability to improve the solid-liquid separation characteristics of DSW (Ying et al., 2010). Comparing continuous aeration and intermittent aeration regimes, the ability of the system to decrease the concentration of organic matter and N was examined. For both continuous aeration and intermittent aeration, the reduction in COD and NH_4-N averaged 91 and 99 %, respectively (Table 2.4). The intermittent aeration process resulted in the occurrence of simultaneous nitrification and denitrification.

Table 2.4 Comparison of various methods to treat dairy soiled water

Author	Type	HLR	Scale	COD	TN	PO_4-P	SS	NH_4-N	NO_3-N	COD	TN	PO_4-P	SS	NH_4-N	NO_3-N
				Influent concentration						*Effluent concentration*					
				mg L^{-1}											
Clifford et al., 2008	HFBR	4.5 L d^{-1}	Pilot	2904	178	37.1	977	134	0.7	728	79	14.8	332	56.8	18.7
Mason, 1997	Oxidation Pond**	25 m^3 d^{-1}	Pilot	884	172*		364	143		618	129*		226	100	
Morgan & Martin, 2008	ETS	2 m^3 d^{-1}	Pilot		173	33.6	2950	83.8	0.48		42	21.9	49	18.5	4.53
Rodgers et al., 2005	Single Pass SSF CW	1.412 L d^{-1}	Lab	1340	120	30	265	50	2	60	90	2	1	5	85
Ying et al., 2009	MAS	1.3 L d^{-1}	Lab	2086			1588	65	0.59	250-167			842	0.65	

*TKN

** Concentrations shown in g m^{-3}

2.3.5 Summary of current treatment options for DSW

Constructed wetlands have been investigated for their potential to decrease nutrients in several types of wastewaters including domestic and agricultural. However, despite their relatively widespread use, they have several limitations, most notably the large area of land they require to adequately treat wastewater. In FWS CWs, limited aerobic zones mean that nitrification is restricted. In addition, mineralisation of organic matter may occur (Zhao et al., 2009). The ability of a CW to retain P is also finite (Majer Newman et al., 1999). Wastewaters with a high level of influent SS are not recommended for treatment in a CW (Hammer, 1994; Mantovi et al., 2003). At lower temperatures, rates of microbial transformation reduce, decreasing the ability of the CW to treat influent TN and NH_4 (Akratos et al., 2007).

The use of FWSP in New Zealand has found that the final effluent produced is not consistent and the ability of the ponds to decrease influent DSW concentrations is limited. Upgrading a FWSP to an APS increases the treatment potential, but requires several stages of treatment and has a large area requirement. Treatment systems with such large footprints may not be suitable for incorporation on all existing farm systems.

The submerged aerated bioreactor, the HFBR and the MAS process are robust systems with smaller footprints. However, these systems are at relatively early stages of research with only the HFBR having been tested at a pilot-scale.

The review of the literature has highlighted that an on-farm treatment system must be capable of dealing with a variable influent. A system with a small footprint that requires minimal maintenance is preferable. The effluent produced should be consistent in nutrient concentration.

2.4 Woodchip as a filter medium

Studies have examined the potential of wood-based products to treat various types of wastewaters such as groundwater, aquaculture and other high-strength wastewaters (Robertson et al., 2000; Schipper and Vojvodic-Vukovic, 2000; Schipper and Vojvodic-Vukovic, 2001; Healy et al., 2006; Saliling et al., 2007) and subsurface drainage water (Greenan et al., 2006). These studies focused on saturated woodchip filters which promoted denitrification as the primary mechanism of removing TN. Studies examined the potential of aerobic filters containing woodchip have focused mainly on effluent from piggery operations (Buelna et al., 2008).

Permeable reactive barriers (PRBs) consist of a porous reactive material, such as woodchip or sawdust, in the path of a groundwater plume, to remove the contaminants from the plume as it flows through it (Gibert et al., 2008). Several porous reactive materials have been investigated for use in PRBs with softwoods suggested as the best substrate in terms of denitrification efficiency (Gibert et al., 2008). Permeable reactive barriers containing wood are sometimes referred to as 'biological organic barriers' due to the biologically mediated processes stimulating heterotrophic denitrification to remove, primarily, nitrate (Robertson and Cherry, 1997; Schipper and Vojvodic-Vukovic, 1998; Scherer et al., 2000). All of the above studies hypothesised that the C contained in the woodchip acts as a C source for microbial respiration and denitrification, thus removing N from the wastewater.

As the agricultural sector in Ireland is required to decrease GHG (EPA, 2009), anaerobic treatment is not desirable. Other problems associated with PRBs include the build-up of SS in the pore spaces of the filter media which can lead to eventual clogging of the system (Scherer et al., 2000). The production of gas bubbles as a result of denitrification can also lead to decreases in hydraulic conductivity and porosity (Soares et al., 1991).

Robertson et al. (1995; 1997; 2000) examined the potential of four configurations of reactive sawdust barriers to treat NO_3-N in groundwater originating from a septic-system soakage field. Trials were carried out over a period of between six and seven years at HLRs ranging from 6 -2000 L day^{-1}. The barrier was saturated, creating an anaerobic environment. Nitrification occurred during percolation of the water through unsaturated layers above the barrier. Results from these studies showed that influent NO_3-N was attenuated by amounts ranging from 58 -91 % (Table 2.5). In addition, it was suggested that heterotrophic bacteria had only consumed between 2 and 3 % of the initial carbon mass, indicating that the barriers could be capable of treating the ground water for a further ten years without replenishment of the sawdust.

Schnipper and Vojvodic-Vukovic (1998; 2000; 2001) also found that NO_3-N removal by organic C sources, such as wood material, was driven by microbial denitrification. Greenan et al. (2006) compared the potential of four organic materials, one of which was woodchip, to serve as C substrates for denitrification of subsurface drainage water. The objectives of this study were to investigate the contribution of the different C sources to denitrification and to examine the extent to which denitrification accounted for decreases in NO_3-N concentrations. After 180 days, the woodchip filter removed 74.5 % of TN. The results of this study indicated that all the C substrates stimulated a reduction in the concentration of NO_3-N (Table 2.5). Saliling et al. (2007) investigated the potential of woodchips to treat aquaculture and wastewaters with a high concentration of NO_3-N. These experiments found that the effectiveness of woodchip to denitrify the influent NO_3-N concentrations of 50, 120 and 200 mg L^{-1} varied from 95.9 to 99.7 % under steady-state conditions (Table 2.5). The highest rates of denitrification occurred in the lower sections of the 0.4 m-deep filters.

Table 2.5 Comparison of permeable reactive filters to decrease the concentration of influent NO_3-N

Author	Duration	Material	Influent type	Scale	NO_3-N in	NO_3-N out	Decrease
					mg L-1		%
Greenan et al., 2006	180 d	Woodchip	Synthetic subsurface drainage water	Lab	75	14.9	80
Roberston et al., 2000	6 - 7 yrs	Waste cellulose materials	Septic system wastewater	Pilot	1.2 - 57	0.2 - 11.6	58 - 91
Saliling et al., 2007	4 wks	Woodchips	Synthetic aquaculture wastewater	Lab	51.8 - 203.6 *	2.12 - 0.58*	95.9 - 99.7

*Figures quoted are for $NO_3 + NO_2$-N

Healy et al. (2006) looked at the potential of four different wood-based combinations to treat NO_3-rich synthetic wastewater. Four filter media consisting of sawdust, sawdust and soil, sawdust and sand, and medium-chip woodchip and sand were examined for their potential to denitrify the influent. Two concentrations of NO_3-N were used (200 mg L^{-1} and 60 mg L^{-1}). The filter containing the woodchip and sand mixture yielded the best NO_3-N removal rate of 97 % under steady-state conditions.

Woodchip as a filter medium, untreated and without additional substrate, has not been extensively investigated under aerobic conditions. A biofiltration system, BIOSOR^{TM}-Slurry, has been developed in Quebec, Canada consisting of a mixture of woodchips and peat moss to treat high-strength pig slurry. Despite a large variation in influent concentrations, the system maintained overall pollutant reductions of greater than 95, 97, 84 and 87 % for BOD_5, SS, TKN and TP, respectively. The CEC, adsorption and absorption capacity of the organic filter media was able to successfully treat influent across a wide variation of loads (Buelna et al., 2008).

The ability of woodchips to adsorb heavy metals, dyes, oils and salts from wastewater is well documented (McKay and Poots, 1980; Nag, 1995; Yu et al., 2001). Studies examining the potential for wood-based products to adsorb forms of P all involve the modification of the wood with chemicals (Karthikeyan et al., 2004; Tshabalala et al., 2004; Eberhardt et al., 2006).

An aerobic woodchip filter would provide the right environment for nitrification to occur. The porous nature of the woodchip could contribute to the adsorption of P. An additional benefit of the system is that the woodchip would act as a medium where liquid-solid separation occurs. This produces a liquid fraction that can be recycled on-farm and a solids fraction that can be composted, or used to produce bio-energy (Garcia et al., 2009). A large proportion of solids contained within the DSW are trapped within the woodchip matrix, and a high proportion of the nutrients in DSW are associated with the solid fraction (Garcia et al., 2009).

Two management options may be employed to re-use the final effluent from a woodchip filter. One management option would be to apply the effluent to the land. The high concentration of plant available nutrients and low SS concentration in the effluent from a woodchip filter would suggest it has potential to benefit plant growth and soil fertility without the traditional problems associated with the land spreading of fresh DSW. Given the large volumes of fresh water used daily on farms to clean down the holding yard and milking parlour, the other management option would be for the effluent to be used to wash down the collecting yard. This could lead to a decrease in the consumption of fresh water on farms. However, effluent concentrations of SS, nutrients and pathogens may need to be decreased further to achieve a standard of water suitable for washing down the milking parlour. Sand filters may provide an adequate level of tertiary treatment.

2.5 Sand filters

Sand filters are noted for their simplicity, and low capital and operating costs (Campos et al., 2002). Biological filtration of wastewaters through SFs is a long-established technology for rapid filtration and, although the structure of such a system is simple, the internal physical, chemical and biological activities are complex and variable (Bahgat et al., 1999). Single-pass intermittent SFs (ISF), wherein the wastewater passes (without recirculation) through the filter, have been investigated to treat a variety of wastewaters including domestic wastewater, lagoon effluent, olive mill wastewater, synthetic DSW, fish farm effluent and pond effluent (Sauer et al., 1976; Russell et al., 1983; Kristiansen and Cripps, 1996; Healy et al., 2007a; Achak et al., 2009; Torrens et al., 2009a).

Intermittent SFs consist of a bed of graded sand which is usually between 700 – 900 mm deep. The filter is overlain by a layer of gravel (normally 10 – 20 mm in size) that promotes an even distribution of wastewater over the surface. For open filters, sand with a uniformity coefficient, Cu, of less than 4 and an effective size, d_{10}, of between 0.7 and 1.0 mm is recommended in Ireland (EPA, 2009). In the US, a d_{10} of between 0.25 and 0.75 mm is recommended (USEPA, 1999). The particle size of the sand is important as it is related to the filtration capacity of the filter. The smaller the particle size, the higher the surface area and the greater the development of biomass which in turn increases the HRT of the filter. The increase in the HRT of the wastewater in the filter leads to an improved removal of soluble organic matter (Rolland et al., 2009). However, this can lead to problems of clogging with influents with a high SS concentration.

Intermittent stratified SFs consist of layers (typically three) of sand with different degrees of coarseness decreasing over the depth of the filter. Each layer is separated by a layer of gravel. The EPA in Ireland suggests guidelines for constructing a stratified SF (Figure 2.2). A HLR of less than 60 L m^{-2} d^{-1} is suggested for stratified SFs (Muqueen et al., 2000). However, a study by Healy et al. (2007b) found that, for synthetic DSW, a stratified SF loaded at 60 L m^{-2} d^{-1} clogged after 35 days due primarily to the high organic content of the influent. This highlights the problem of clogging with effluents with a high SS concentration and indicates that the HLR is highly dependant upon the SS and organic concentration of the influent to be treated.

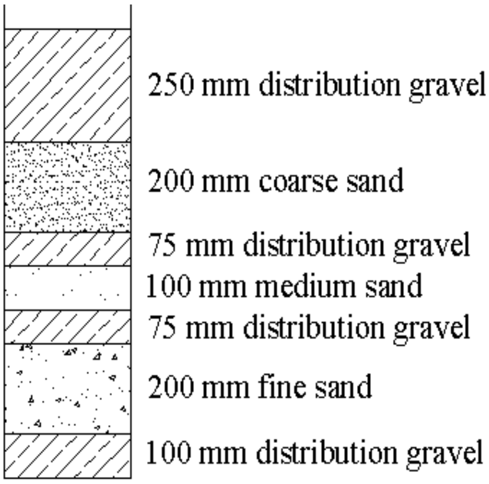


Figure 2.2 Depths of sand suggested by the Irish EPA for constructoin of an intermittent SF (Mulqueen et al., 2000)

The ability of SFs to remove solids, nutrients and pathogens from influent wastewaters is well documented (Prochaska, and Zouboulis, 2003; Stevik et al., 2004; Wanko et al., 2005; Rodgers et al., 2005; Torrens et al., 2009b). Prohaksa and

Zouboulis (2003) reported removal rates of 82 %, 50 – 70 % and more than 40% for SS, COD and phosphate (PO_4-P), respectively, from several types of synthetic wastewaters, such as storm water runoff and secondary treatment effluent. Rodgers et al. (2005) examined the effectiveness of stratified SFs to treat synthetic DSW and found removal rates of 96, 27, 88 and 94 % for COD, TN, NH_4-N and PO_4-P at a loading rate of 20 L m^{-2} d^{-1} (Table 2.4).

2.5.1 Treatment mechanisms in sand filters

Due to the aerobic nature of the SF, mineralisation and nitrification of influent N are the main transformation mechanisms (Prochaska and Zouboulis, 2003). Intermittent SFs have the ability to achieve rates of nitrification of up to 80 % (USEPA, 1999). Intermittent flow regimes have been shown to promote aerobic conditions within the SF and favour the growth of nitrifying bacteria (Bahgat et al., 1998). Loading regimes must allow sufficient time to pass between wastewater applications to allow for proper re-aeration of the pore space to occur (USEPA, 1999). A study by Leverenz et al. (2009) investigated the frequency of dosing on an ISF and found that reducing the dosing frequency increased the expected operational life of the filter. Diluted O_2 present in the influent and convection due to the intermittent loading regime also introduce O_2 into the matrix of the filter (Torrens et al., 2009a). At higher loading rates, there is also the potential for denitrification to occur in saturated microzones within the sand profile (Bahgat et al., 1998).

The ability of sand to remove P occurs via two main mechanisms – adsorption and precipitation. Both mechanisms depend on the occurrence of natural minerals and metals present in the sand, and the chemical characteristics of the influent wastewater (Søvik and Kløve, 2005; Gill et al., 2009). Both mechanisms are a function of pH (Erickson et al., 2007). Phosphorus can also be incorporated into the biofilm on the surface of the sand (Prochaska and Zouboulis, 2003). The ability of SFs to remove P is finite (Rodgers et al., 2005). Choosing sand with high P-binding capacity and/or a sand that releases minerals that promote the precipitation of P will extend the period during which P removal occurs (del Bubba et al., 2003). The calcium (Ca), Fe and Al content of the sand are important for P precipitation, depending on the pH of the wastewater to be treated (Arias et al., 2001).

The main mechanisms for removing or immobilising pathogens are straining and adsorption (Stevik et al., 2004). Other mechanisms, including cell lysis and protozoa and grazing, play an important role in the reduction in bacteria within a SF (Bomo et al., 2004; Auset et al., 2005). A study by Torrens et al. (2009b) found that the removal of microbial indicators in ISFs was a function of the depth of the filter, the HLR and the amount of influent applied per dose. Sand filters have the ability to retain up to 99.9 % of FC (Harrison et al., 2000).

Solids in a SF are removed physically through processes of filtration and surface straining (Healy et al., 2007b). The key factors contributing to clogging of SFs include the frequency of dosing and the concentration of COD and TSS in the influent (Leverenez et al., 2009). The major operational problems concerning SFs are related to biomass build-up within the filter and surface deposits that can cause premature clogging of the system and ultimate failure of the filter (Rodgers et al., 2004; Rolland et al., 2009). When a SF is loaded intermittently, biofilm growth occurs during and immediately after dosing. Decay of the biofilm occurs during the rest period between dosing. Increasing the time between dosing increases the endogenous decay period and thus maintains the biofilm at a depth that will not cause clogging (Leverenez et al., 2009). Microbial biomass in SFs has been found to increase with time and decrease with depth with most of the biomass accumulation occurring in the top 2 cm (Campos et al., 2002). This increase in biomass leads to a reduction in water flow through the SF (Rodgers et al., 2004). Clogging can be reduced by decreasing the influent concentrations of COD and SS (Leverenez et al., 2009).

2.5.2 Summary of sand filter treatment

The ability of SFs to decrease influent nutrient concentrations of several wastewaters has been extensively investigated. They are noted for an effectively simple structure, but are engineered to provide conditions suitable for decreasing influent concentrations of N, P, SS and pathogens. Operational problems such as clogging and the finite ability of sand to adsorb P mean that influents or effluents from secondary treatment systems, with a low SS and COD concentration requiring further polishing are most suitable for treatment in a SF.

2.6 Summary

This chapter looked at the composition of DSW produced on farms and the legislation governing disposal of DSW. Application of DSW to the land remains the most common management option for farmers in Ireland and internationally. The purpose of land application is to take advantage of the soil/plant systems' ability to assimilate waste components and decreases the need for inorganic fertilizers (Cameron et al., 1997; Zaman and Cameron, 1999). The application of DSW to land may pose a significant threat to water quality (Mawdsley et al., 1995).

Treatment of DSW is commonly carried out using CWs and FWSP. However, the large area required for a CW, the variability in performance in treating DSW, problems due to clogging (for SSF CWs), and the potential for releases of accumulated P suggests that the long-term sustainability of wetlands may be limited (Tanner et al. 1995; Majer Newmann et al. 1999; Zhao et al., 2009). The effluent produced from FWSP is inconsistent and the ability of the ponds to decrease influent DSW concentrations to acceptable levels is limited (Hickey et al., 1989; Mason, 1997). Other methods of treating DSW, including ETS, HFBR, submerged biofilters and MAS, have also been investigated (Cannon et al., 2000; Sukias et al., 2001; Lansing and Martin, 2006; Morgan and Martin, 2008; Healy et al., 2007; Clifford et al., 2008; Ying et al., 2010).

To date, studies on the use of woodchip as a filter medium have focused on saturated woodchip filter the promote denitrification of high-nitrate influents (Robertson et al., 2000; Schipper and Vojvodic-Vukovic, 2001; Healy et al., 2006; Saliling et al., 2007; Greenan et al., 2006). Aerobic woodchip filtration offers the potential to treat DSW without the N_2O emissions and loss of fertiliser N value associated with anaerobic filtration. Therefore, aerobic woodchip filtration appears to have potential as a treatment for DSW.

Biological filtration of wastewaters through SFs is a well established technology for rapid filtration of wastewaters and, although the structure of such systems is technically simple, the internal physical, chemical and biological activities are complex and variable (Bahgat et al., 1998). However, operational problems concerning SFs, related to biomass build-up within the filter and surface deposit, can cause premature clogging of the system and ultimate failure of the filter.

A SF, following a woodchip filter, may provide tertiary treatment for the DSW to bring the effluent to a standard that would make it suitable for use as an on-farm wash-water. Without passing through a SF, the effluent from the woodchip filters may be applied directly to the land. This effluent may be beneficial to plant growth and soil fertility, given the low concentration of SS and the high concentration of plant available nutrients.

Chapter 3

Laboratory-scale woodchip filters to treat reconstituted dairy soiled water

Overview

The design, construction, and operation of laboratory-scale woodchip filters used in this study are presented in this chapter. The contents of this chapter are published in the Journal of Environmental Management.

3.1 Introduction

Agricultural activities are recognised as significant sources of nutrient inputs to European waters (EEA, 2002) and legislation such as the Nitrates Directive (91/676/EEC; EEC, 1991) and the WFD (2000/60/EC; EC, 2000) has focused considerable attention on the environmentally-safe disposal of agricultural wastewaters. Dairy soiled water is produced on farms through the washing-down of milking parlours and holding areas. It contains nutrients and other constituents that pose a potential threat to water quality if not managed correctly. Application of DSW to the land has long been the most common method of disposal employed by farmers. However, when DSW is land applied at rates that exceed the nutrient requirements of the pasture, it can create a number of problems, the most significant threat being the loss of P and N in runoff (Silva et al., 1999; Regan et al., 2010) and leachate (Knudsen et al., 2006).

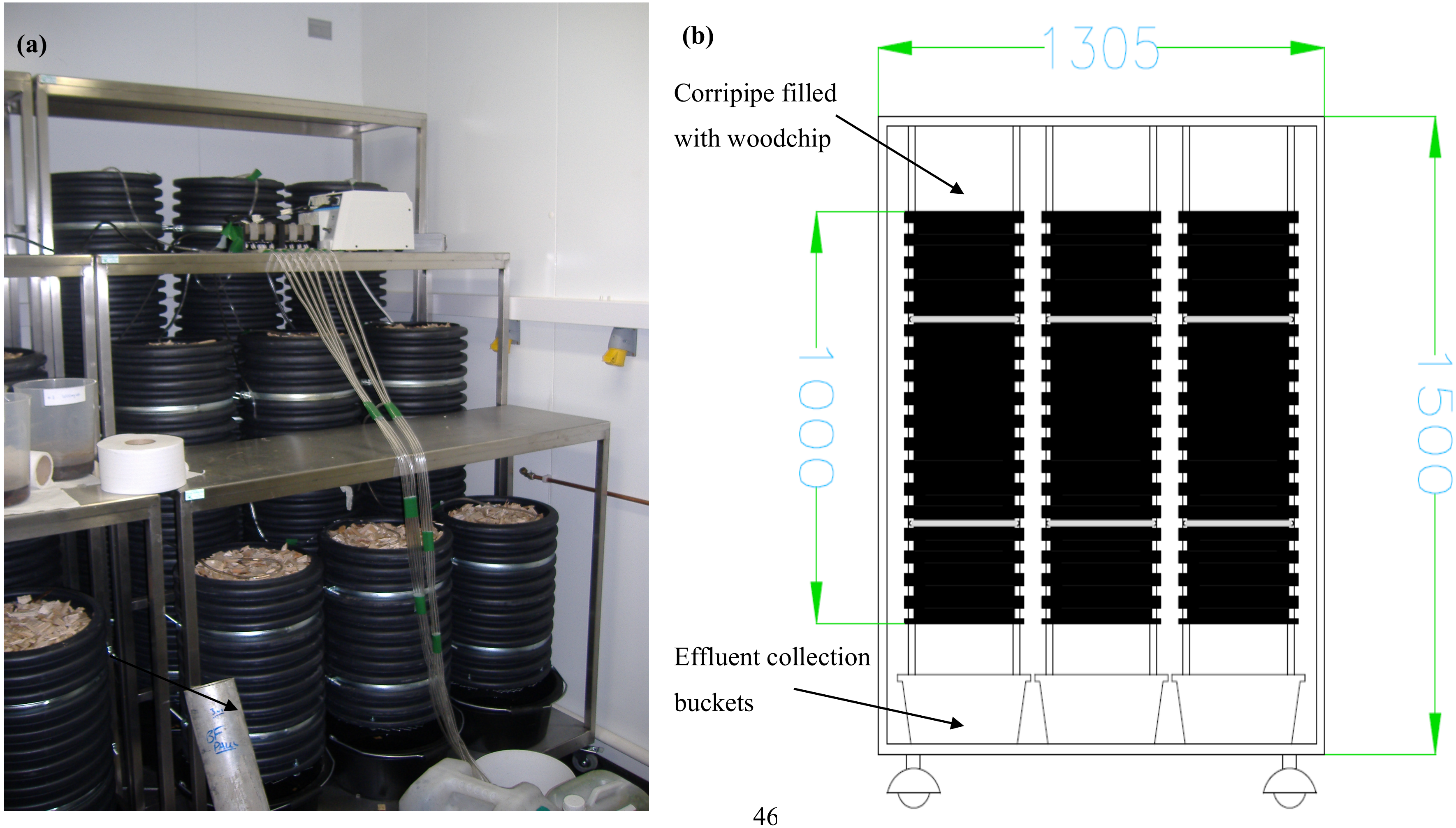
This experiment was carried out as part of a study to develop a treatment system that would treat DSW to a standard so that it can either be re-used to wash down collecting yards on dairy farms or safely applied to the land. This study proposes the use of an aerobic filter, with woodchip as the filter medium, to treat fresh DSW. Studies of aerobic woodchip filters have focused mainly on effluent from piggery operations (Buelna et al., 2008). Woodchip is already in use on farms to provide outdoor standing areas for cattle during the winter months (Vinten et al., 2006; O’Driscoll et al., 2008). As a result of state schemes introduced in the 1980s to encourage afforestation, Ireland has a young forest stock many of which have not yet been thinned (Teagasc, 2007). Thinnings from these young forests will provide a steady supply of woodchips for use in wastewater filters. Such a treatment system may provide a more economical and sustainable alternative to current management practices.

In this chapter, the findings of a laboratory-scale investigation into the potential for woodchip to act as a filter medium in a system for treating DSW is presented. The findings from the laboratory experiment were used to develop design guidelines for the construction of a farm-scale woodchip filter.

3.2 Materials and methods

Eighteen filter columns, operated in the laboratory at an ambient temperature of 10-11 ^{o}C, were used to treat DSW (Figure 3.1). Each column was filled with Sitka spruce chips (*Picea sitchensi (Bong.) Carr)*, sourced from a forest in Sligo, northwest Ireland. Sitka spruce is Ireland's most common commercial tree species and covers almost 66 % of the area planted (Coillte, 2008). Logs were de-barked and then chipped using an industrial wood chipping machine (Elmot-Schäfer, Germany), which chipped the wood to a maximum chip length of 50 mm. The woodchips were then screened on a 10-mm sieve to remove any dust and smaller particles that might result in the filters clogging prematurely. The size distribution of the woodchip filter media by weight was: 10-14 mm: 23 %; 14-20 mm: 43 %; 20-28 mm: 22 %; and 28-50 mm: 12 %. The porosity of the packed reactors, determined using woodchip at the same moisture content as the woodchip used in the filter columns and calculated on a volume basis by saturating a column with water, was 29 %.

Figure 3.1 (a) The laboratory units and (b) diagram of the laboratory-unit supporting the 1m high columns (dimensions in mm)



The eighteen filters were divided into two sets of nine. There were three replicate filters of three depths in each of the two sets: 0.5 m, 1 m, and 1.5 m. Single-leaf corrugated CorriPipe™ was used to house the woodchip. The diameter of each experimental filter was 0.3 m and 0.355 m to the inside and outside of the corrugations, respectively. The majority (88 %) of the woodchips were less than 28 mm. This, coupled with the uneven interior wall of the filter column, avoided the potential for preferential flow and short-circuiting of the influent due to wall effects. A steel mesh was attached to the base of the filters to hold the woodchip in place, and a plastic container was placed under the base of each unit to collect the treated effluent.

Fresh DSW was used to seed the units with micro-organisms. This was poured on the surface of the filters over a 24-hour period. The influent DSW used during the study consisted of dried manure, collected from a dairy farm, dried in an oven for 24 hours at 100 °C, and mixed with water using a blender to ensure consistency. The first set of nine columns (S1) was loaded at a SS concentration of 10,000 mg L^{-1} (1 % DM) and the second set (S2) was loaded at a SS concentration of 30,000 mg L^{-1} (3 % DM). S1 corresponds to the legal upper limit of SS for soiled water at 1 % DM (SI 610 of 2010). However, influent unfiltered total nitrogen (TN_T) concentrations were low for S1, with an average concentration of 235 mg L^{-1}. S2 had an average influent TN_T concentration of 519 mg L^{-1}, which is close to the average for DSW found in a farm survey (Minogue et al., 2010). The higher level of SS loading would also provide for a worst-case scenario with regard to clogging. Influent was made up twice daily and stored in 10 L plastic containers.

The laboratory scale study used a reconstituted DSW. Table 3.1 compares the concentration of nutrients in the DSW used in this study to fresh DSW and synthetic DSW. The table serves to highlight the variable nature of the concentration of nutrients in DSW between studies. Influent concentrations of COD, SS, TN, NO_3-N and nitrite-N (NO_2-N) for this study are similar to other studies using fresh DSW. The low concentrations of NH_4-N and PO_4-P in the DSW used in this study are the most notably different parameters from other studies.

Table 3.1 Comparison of water quality parameters for synthetic DSW, fresh DSW and the reconstituted DSW used in this study

Reference	Type	COD	TN	NH_4-N	SS	NO_3-N	NO_2-N	PO_4-P
					mg L^{-1}			
Crumby et al., 1999	Fresh DSW	13,383	825	457	1§			415
Healy et al., 2007b	Synthetic	2,921	176	85	353	9		23
Martínez-Suller et al., 2010	Fresh DSW		351	32	12,000	0	0.3	
Minogue et al., 2010	Fresh DSW		587	212	5,000			
This study (1 % dry matter)	Reconstituted DSW	12,162	235	3.69	10,000	0	0	4.01
This study (3 % dry matter)	Reconstituted DSW	34322	547	0.98	30,000	0.54	0	5.08
Wood et al., 2007	Fresh DSW	6,690	540	366	6,144			

§ unit of figure %

The HLR was 28 L m^{-2} d^{-1} for both sets of filters, and DSW was applied in equal volumes of 0.67 L three times daily, seven days-a-week. The HLR was chosen based on a study by Minogue et al. (2010), who conducted a survey on the concentrations and volumes of DSW produced on Irish farms. This study found that the average volume of DSW produced per cow is 30 L m^{-2} d^{-1}. An intermittent feeding cycle was chosen over a continuous feed cycle to encourage the movement of air throughout the filter. A plastic container was used to hold the influent and it was applied by hand. The influent wastewater was agitated before application to the filters to ensure a homogeneous mixture. The filters were operated for 277 days for S1 and 197 days for S2.

A 100-ml sub-sample of effluent was taken for analysis three times weekly. Water samples were analysed within 24 hours of collection. Samples were passed through 1.4-µm Whatman filter paper to obtain the filtered fraction. The following water quality parameters were measured: SS, unfiltered COD (COD_T), filtered COD (COD_F), unfiltered TN (TN_T), and filtered TN (TN_F). Filtered samples were analysed for NH_4-N, NO_2-N and total oxidised nitrogen (TON). A Konelab 20 nutrient analyser (Fisher Scientific, Walthan, Massachusetts) was used to measure the nutrients. All tests were carried out in accordance with standard methods (APHA-AWWA-WEF, 1995). NO_3-N was calculated by subtracting NO_2-N from TON. Particulate N (PN) was calculated by subtracting TN_F from TN_T. Dissolved organic N (DON) was calculated by subtracting dissolved mineral N (NH_4-N + TON) from $TN_{F.}$

Removal of nutrients and other water quality parameters was calculated as the influent concentration minus the effluent concentration, expressed as a percent of the influent concentration. Descriptive statistics were used to characterise influent and effluent concentrations and removal rates. Percent removal data were analysed using ANOVA in a two-factorial design to test the effect of filter depth and influent SS concentration on filter performance.

3.3 Results and discussion

The woodchip filters achieved substantial removal of nutrients (Tables 3.2 and 3.3). At both concentrations of SS, there was almost complete removal of SS (>99 %), indicating that woodchip is an effective physical filter medium for trapping DSW solids. Concentrations of SS in the effluent decreased over time as the SS built up within the filters (Figure 3.2 and 3.3). The effect of filter depth on the concentration of SS in the effluent was not statistically significant (P>0.05), suggesting that the majority of the filtration process occurred in the uppermost part of the filters. There was no significant effect of SS concentration in the influent (P>0.05), indicating that woodchip filters are equally effective across this range of SS concentrations.

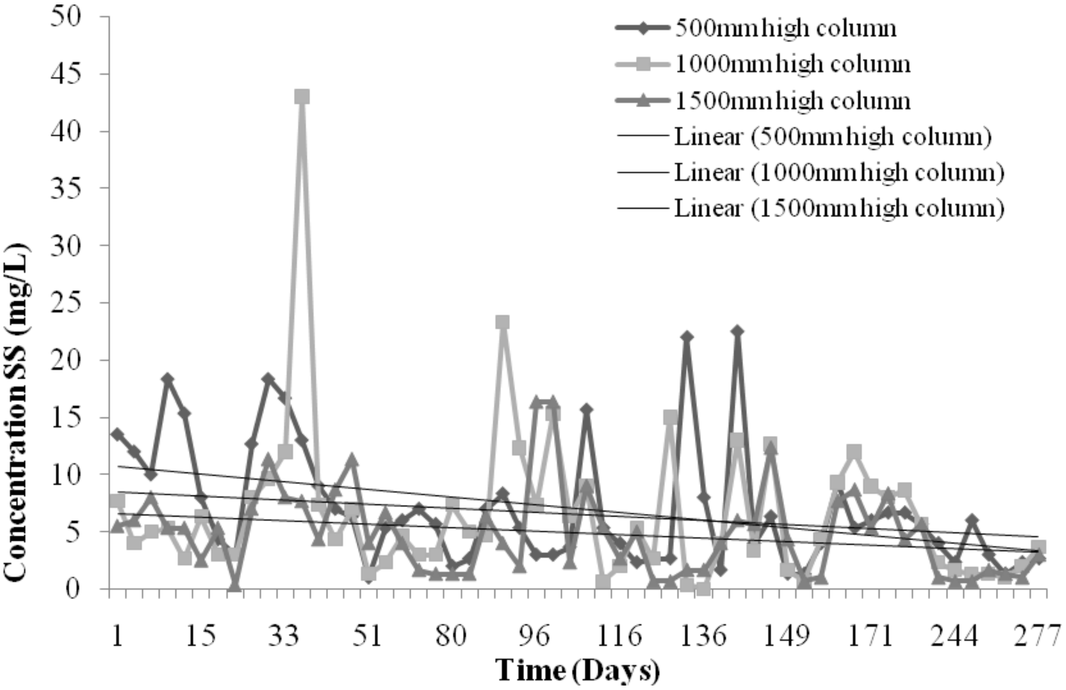


Figure 3.2 Average concentration of SS (mg L^{-1}) in the woodchip filter effluent from the three woodchip filter column heights for S1

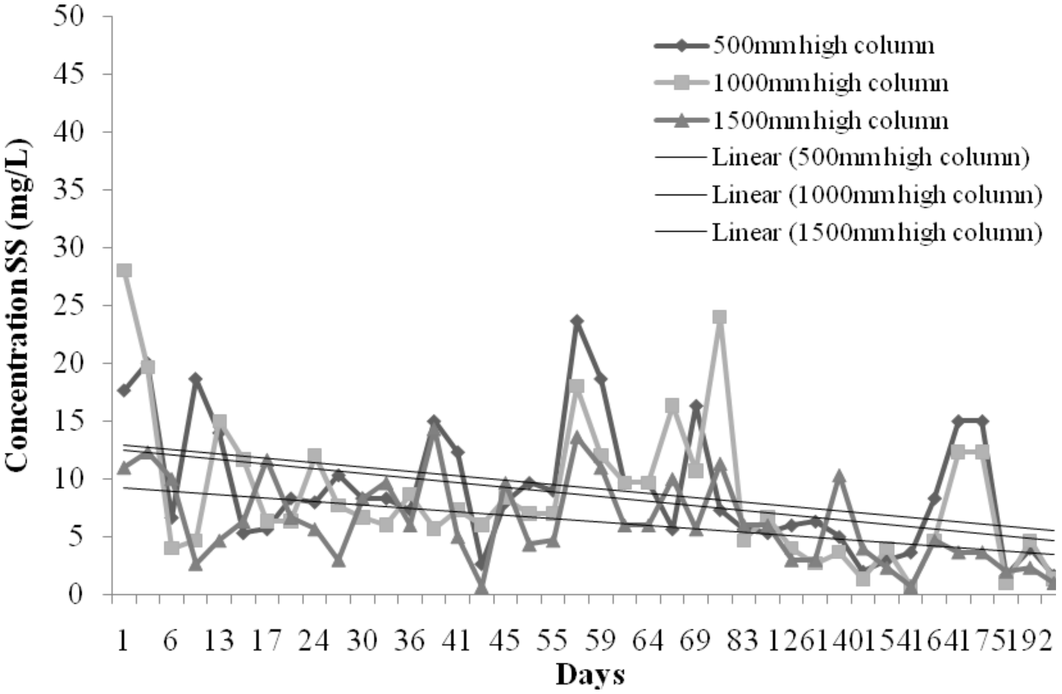


Figure 3.3 Average concentration of SS (mg L^{-1}) in the woodchip filter effluent from the three woodchip filter column heights for S2

After 128 days, a washout of solids occurred in one of the 0.5-m-deep filters in S1. This indicates that some SS found a pathway through the pores of the filter medium and washed out at the base of the column. However, it only occurred in one filter column and did not re-occur during the remaining part of the study, suggesting that periodic washouts of SS are not likely to be a major problem.

After 197 days of operation, the build-up of solids on the surface of the filters loaded at the higher rate of SS (840 g m^{-2} d^{-1}) meant that it was no longer possible to continue loading the filters. This suggests that the surface layer of the filter may need to be replaced periodically with fresh woodchip. The 1.0 m and 1.5 m-deep filters loaded at the lower concentration of SS were still functioning at the end of the study. From visual inspection, there was little indication that breakdown of the woodchip occurred during the study. This suggests that the filters have the capacity to treat DSW for at least 277 days without degradation of the filter medium.

Table 3.2 Water quality parameters for wood-chip filter influent and effluent loaded at 1 % SS (S1) over a period of 277 days. Standard deviations shown in brackets.

	Influent	Effluent					
		0.5 m		1.0 m		1.5 m	
	Average mg L^{-1}	Average mg L^{-1}	Decrease %	Average mg L^{-1}	Decrease %	Average mg L^{-1}	Decrease %
COD_T	12162 (1899)	532 (164)	96	526 (115)	96	518 (152)	96
COD_F	2047 (659)	496 (163)	76	523 (89)	74	484 (139)	76
TN_T	235 (56)	27 (12)	88	24 (10)	90	19 (9)	92
PN	96	6	93	7	93	3	97
TN_F	139 (65)	21 (8)	85	16 (4)	88	16 (4)	88
DON	135	9	93	6	93	8	91
NH_4-N	3.69 (0.49)	7.15 (4.56)	- 48	6.54 (4.01)	- 44	5.97(3.58)	- 38
NO_2-N	0.00 (0.00)	0.52 (0.94)	- 100	0.61 (0.98)	- 100	0.26 (0.39)	- 100
NO_3-N	0.00 (0.00)	4.07 (3.97)	- 100	3.20 (4.54)	- 100	1.92 (2.90)	- 100
Mineral N	3.69	11.74	- 69	10.36	- 64	8.15	- 55
PO_4-P	4.01 (1.24)	8.00 (4.86)	- 50	7.76 (3.70)	- 48	6.39 (2.02)	- 37.3
SS	10000	7 (5)	100	7 (7)	100	5(4)	100

Table 3.3 Water quality parameters for wood-chip filter influent and effluent loaded at 3 % SS (S2) over a period of 197[a] days. Standard deviations shown in brackets.

	Influent	Effluent					
		0.5 m		1.0 m		1.5 m	
	Average mg L^{-1}	Average mg L^{-1}	Decrease %	Average mg L^{-1}	Decrease %	Average mg L^{-1}	Decrease %
COD_T	34322 (4995)	795 (160)	98	999 (161)	97	941 (145)	97
COD_F	1794 (128)	779 (165)	57	943 (179)	47	929 (152)	48
TN_T	547 (97)	40 (10)	93	43 (11)	92	40 (12)	93
PN	353	3	99	2	99	2	100
TN_F	194 (60)	37 (9)	81	41 (13)	79	38 (10)	80
DON	192.27	28.08	85	31.14	64	28.87	55
NH_4-N	0.98 (0.06)	6.69 (4.33)	- 85	6.90 (4.49)	- 86	7.27 (4.68)	- 87
NO_2-N	0.00 (0.00)	0.13 (0.17)	- 100	0.08 (0.13)	- 100	0.09 (0.10)	- 100
NO_3-N	0.54 (0.15)	2.23 (2.25)	- 76	2.44 (3.22)	- 78	1.76 (2.19)	- 69
Mineral N	1.52	9.05	- 83	9.43	- 84	9.11	- 83
PO_4-P	5.08 (0.91)	13.63 (5.70)	- 63	16.02 (6.41)	- 68	16.32 (6.59)	- 69
SS	30000	9 (6)	100	9 (6)	100	6 (4)	100

[a] Clogging occurred after 197 days of operation

Total COD concentrations in the influent averaged 12,162 ± 1,899 mg L^{-1} for S1 and 34,322 ± 4,995 mg L^{-1} for S2. The percentage removal of COD_T for all three depths for S1 was 96 %. For S2, percentage removals in the 0.5 m-deep, 1.0 m-deep and 1.5 m-deep filters were 98 %, 97 % and 97 %, respectively. Much of the COD_T in the influent was associated with the particulate fraction; COD_F accounted for only 16 % of COD_T for S1 and 5 % for S2. It is, therefore, likely that physical filtration accounts for the majority of the COD_T removal, consistent with the decrease in SS. The effect of filter depth on COD_T removal was not significant ($P>0.05$), suggesting that most of the treatment process occurred in the upper (< 0.5 m) part of the filters. As the filters were aerobic, oxidation of organic compounds was also a possible mechanism for the observed decrease in COD.

Woodchip filters removed 88 % to 92 % of the TN_T for all column depths in S1, and 92 % to 93 % for all depths in S2. Total N removal increased significantly with filter depth ($P<0.001$), indicating that some removal occurs deeper than 0.5 m, but differences between depths were never more than 4 %. Particulate N accounted for 41 % of the influent TN_T for S1 and 65 % for S2. Particulate N removals of 88 % to 97 % were observed for S1, and 99 % to 100 % for S2. Along with the observed decrease in SS, these results suggest that physical filtration is an important process in removing TN_T.

Woodchip filters removed 85 % to 88 % of the TN_F for all filter depths in S1, and 79 % to 81 % for all depths in S2. Influent DON was 135 ± 65 mg L^{-1} for S1 and 192 ± 60 mg L^{-1} for S2, and accounted for 97 % of TN_F in S1 and 99 % in S2. The woodchip filters removed 85 % to 88 % of the DON for all filter depths in S1, and 79 % to 81 % for all depths in S2. Dissolved organic N may have been mineralised to NH_4 which, in turn, may have been nitrified to NO_3. There was an observed increase in NH_4 (an average of 43 % across all filter columns for S1 and 86 % for S2) and NO_3 concentrations in the effluent (Figure 3.4 and 3.5). However, this increase was only sufficient to account for a small proportion of the observed decrease in DON (0.05 %). Therefore, sorption of DON onto the filter medium or mineralisation followed by biological uptake were likely the dominant mechanisms of DON removal. Depth did not significantly affect TN_F removal (P>0.05), again indicating that filtration occurred in, at most, the top 0.5 m depth of the filter. This result is in keeping with the findings of similar work carried out by Vinten et al. (2006), who found little influence of the depth of woodchips on the reduction of nutrient concentrations in effluent from a woodchip corral in Scotland.

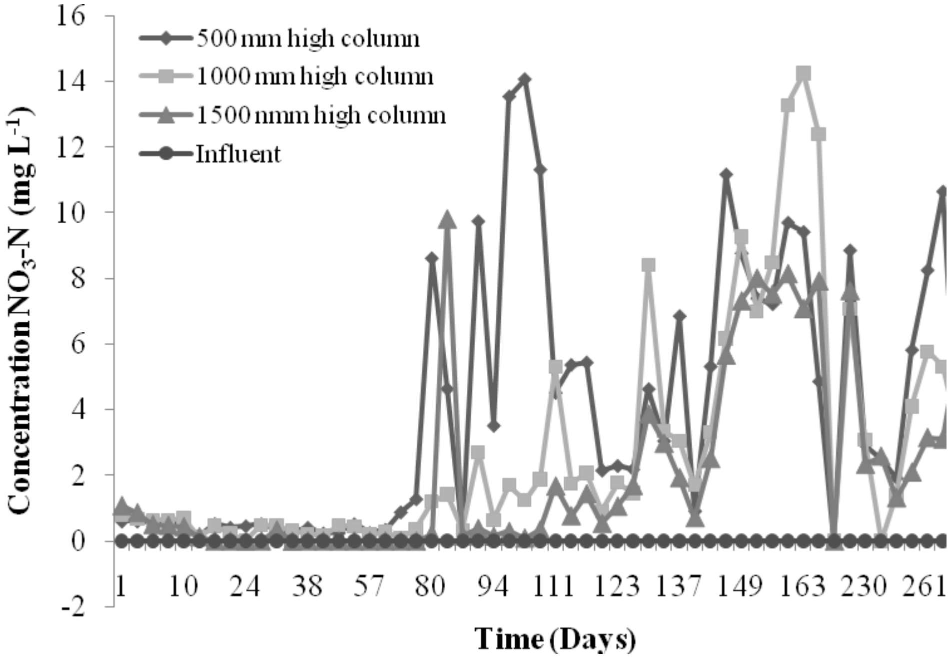


Figure 3.4 Average concentration of NO_3-N (mg L^{-1}) in the influent and the effluent from the three woodchip filter column heights for S1

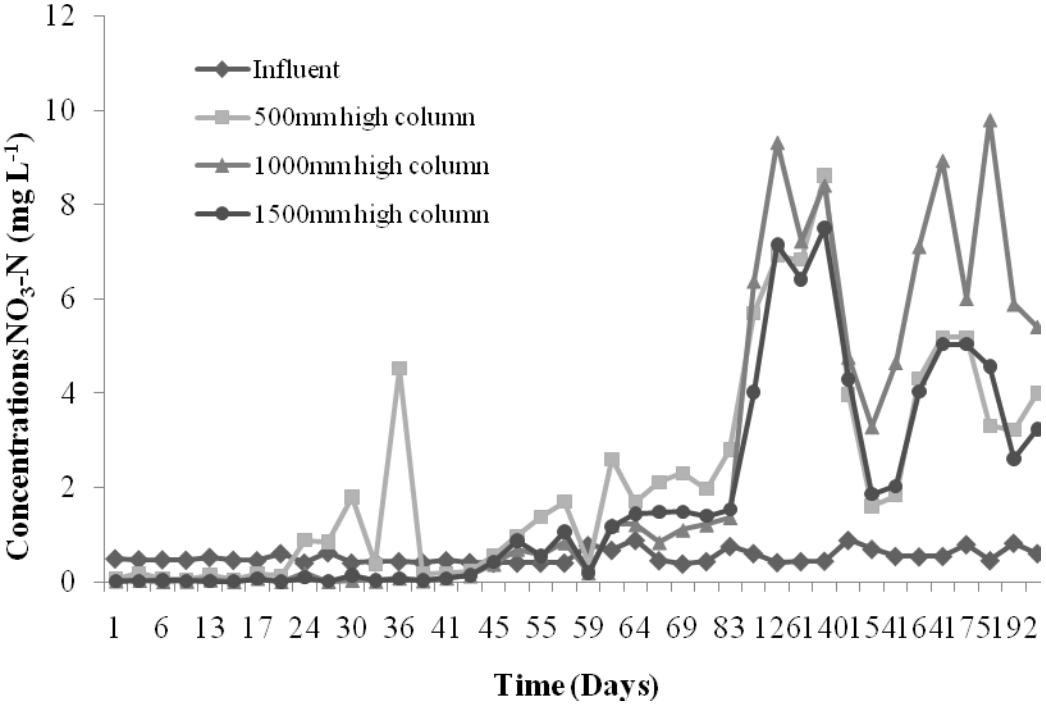


Figure 3.5 Average concentration of NO_3-N (mg L^{-1}) in the influent and the effluent from the three woodchip filter column heights for S2

The concentration of NH_4-N in the influent was substantially lower than would typically be expected for DSW. Minogue et al. (2010) measured an average value of 212 ± 206 mg L^{-1} as part of a farm study that looked at DSW on 60 farms around Ireland. In the present study, average values of 3.7 ± 0.5 mg L^{-1} for S1 and 1 ± 0.1 mg L^{-1} for S2 were measured. The low levels of NH_4-N in the influent are most likely due to the drying down of the fresh manure, leading to NH_3 loss via volatilisation. Nitrogen in the reconstituted DSW consisted mostly of organic N (98 % in S1 and 99 % in S2). Further investigation is required to examine the effect of the higher NH_4-N concentration of fresh DSW on filter performance.

The concentrations of NO_3-N in the effluent were still within the maximum allowable concentration (MAC) of 50 mg NO_3 L^{-1} for discharge to a receiving water body (WHO, 2006) (Tables 3.2 and 3.3). It should be noted that, on occasion, the concentrations were above the MAC. Considering the aerobic nature of the filters, it is unlikely that any significant denitrification occurred. However, monitoring of N emissions from the top of the filters would have to be carried out to rule out this possibility conclusively.

Influent PO_4-P concentrations were 3.49 ± 1.26 µg L^{-1} for S1 and 5.08 ± 0.91 µg L^{-1} for S2 (Tables 3.2 and 3.3). Concentrations of PO_4-P in the effluent were higher with an average increase of 56 % for S1 and 63 % for S2. However, concentrations were still very low with means of less than 20 µg L^{-1}, which is the critical concentration for lake eutrophication (He et al., 2006). In an aerobic system, organic P can be biologically degraded to PO_4-P (Guillen-Jimenez et al., 2000). This may explain the slight increase in PO_4-P concentration in the effluent.

3.4 Sizing of a farm-scale filter

Under a HLR of 28 L m^{-2} d^{-1}, laboratory-scale filters were capable of significant nutrient removal over at least 277 days. Bearing in mind the washout of SS after 128 days from one of the 0.5 m-deep filters, it is proposed that a woodchip depth of 1.0 m would be more suitable as it would provide increased pore space and a longer flow path for retention of SS. Minogue et al. (2010) found that the average amount of DSW generated by a dairy cow in Ireland is 30 L d^{-1}. Based on this figure and a HLR of 30 L m^{-2} d^{-1}, an area of 1 m^2 would be required per cow. At 1 m depth, this would give 1 m^3 of woodchip per cow. Therefore, a 1 m-deep filter pad of 100 m^2 area should be adequate to treat the DSW generated by a 100-cow dairy herd.

3.5 Summary

Analysis of woodchip filters operating at three different depths and two different influent loading rates for durations of up to 277 days showed that they were capable of significantly decreasing the concentration of SS, organic matter and nutrients from DSW.

The main conclusions from this study are:

- At both concentrations of SS, there was almost complete removal of SS (>99%) and the removal of COD_T ranged from 97 % to 98 %.
- Woodchip filters removed 89 % to 93 % of the TN_T and 79 to 88 % of the TN_F.
- Physical filtration was the main mechanism for the removal of nutrients. Sorption onto the filter medium and biological uptake were other possible removal mechanisms. As the filters were aerobic, mineralisation and nitrification were also active processes.
- For the purposes of a farm-scale filter, a 1 m-deep woodchip filter with an area of 100 m^2 appears to be sufficient to treat DSW from a 100-cow dairy herd.

Chapter 4

On-farm treatment of dairy soiled water using aerobic woodchip filters

Overview

The findings of the laboratory-based study provided the design guidelines for the construction of the farm-scale woodchip filters detailed in this chapter. The findings of this chapter are published in Water Research.

4.1 Introduction

Application of DSW to the land has long been the most common method of disposal employed by farmers (Martínez-Suller et al., 2010). However, when DSW is land applied at rates that exceed the nutrient requirements of the pasture, it can create a number of problems, the most significant threat being the loss of P and N in runoff (Silva et al., 1999; Regan et al., 2010) and subsurface leaching of N and P, depending on the soil type (Knudsen et al., 2006). In order to reduce costs and labour requirements, simple low-maintenance systems utilising natural processes are preferable for the treatment of waste streams on dairy farms. Constructed wetlands and FWSP have been investigated for the treatment of agricultural wastewaters (Hickey et al., 1989; Mason, 1997; Mantovi et al., 2003; Dunne et al., 2005; Wood et al., 2007).

This chapter will assess the performance of woodchip filters under normal farm conditions. Three replicated woodchip filter pads were constructed on a research farm at Teagasc, Moorepark Research Centre in South West Ireland. Each filter was capable of treating DSW generated by 100 cows. The filters were operational for eleven months and filter performance was tested by monitoring influent and effluent waters for nutrients, SS and COD. An economic appraisal of filter construction and operation was made and management options for woodchip effluent were considered.

4.2 Materials and methods

Three replicate farm-scale filter pads were constructed at the Teagasc Animal and Grassland Research and Innovation Centre, Moorepark, Co. Cork, Ireland (coordinates 52.163561,-8.263435) (Figure 4.1). The farm filters were operated for a study period of eleven months, from October 2009 to August 2010, inclusive. Each filter pad was constructed to the same specifications. The filter pads had a footprint of 12 m x 12 m, a depth of 1 m, and a top surface area of 100 m^2 (Figure 4.2). The base of the filters was sloped at 1:10 towards a centre line which contained a 101.6 mm-diameter perforated pipe to collect effluent after it passed through the filter. The perforated collection pipe, running half the length of the base, was sloped 1:20 downwards towards a single deepest point (Figure 4.3). All the effluent exited the base of the filter at this point. A 0.5 mm-thick plastic waterproof membrane, overlain by a felt protective cover to protect it from abrasion and tearing, was placed directly on top of the soil surface on which the units rested. The base of each pad was then filled with round washed limestone (25.4 to 50.8 mm in size) to make a level surface up to ground level.

Figure 4.1 Overview of the three farm-scale filters, as constructed

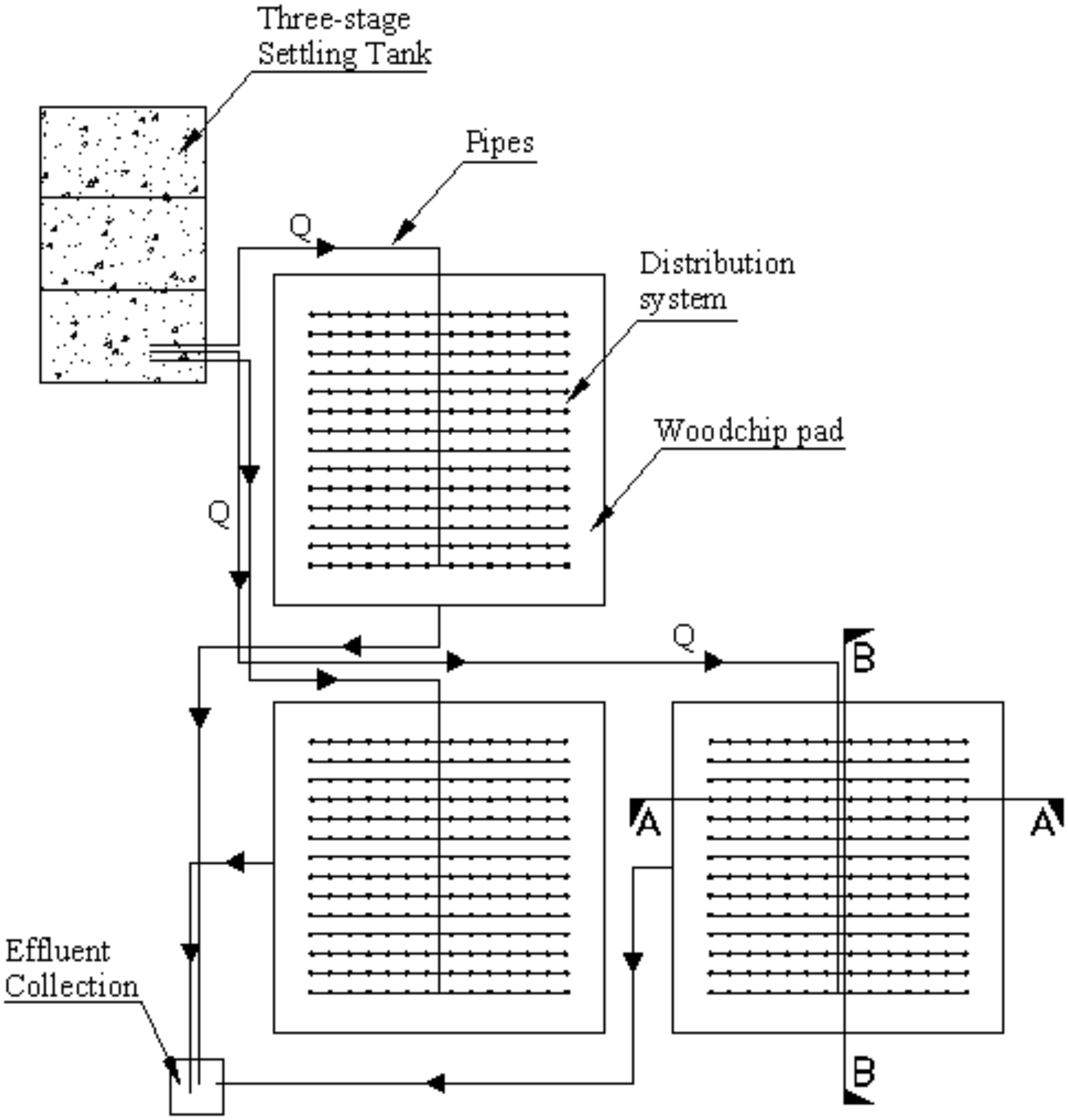


Figure 4.2 Schematic plan view of three farm scale woodchip filters.

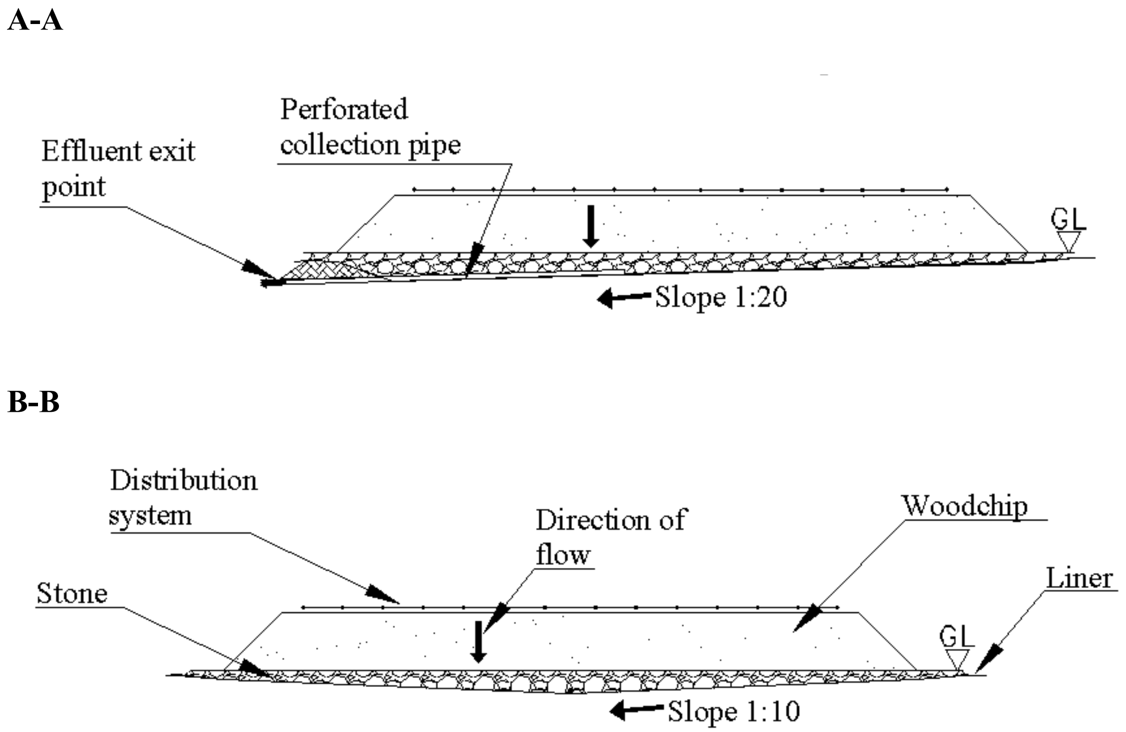


Figure 4.3 Schemeatic side view of three farm scale woodchip filters

Sitka Spruce (*Picea sitchensi (Bong.) Carr.)* thinnings, with the bark intact, were chipped onsite and placed directly on top of the stone layer. The size distribution of the woodchip filter media by weight, calculated as the percentage retained on each sieve, was: 28 mm: 9.11 %; 20 mm: 2.74 %; 14 mm 28.58 %; 10 mm: 29.45 %; and on the base: 30.11 %. The stone base extended out past the edge of the woodchip to allow for the movement of air underneath the base of the woodchip filter. This was to avoid the development of anaerobic conditions and the potential for denitrification.

A wastewater distribution system, consisting of 38.1 mm-diameter plastic pipes placed on top of the woodchip, was constructed to ensure an even distribution of the effluent over the surface of the woodchip (Figure 4.1). Distribution pipes were perforated by drilling 4 mm-diameter holes at 0.7 m-spacing on one side of the pipe. These holes were distributed evenly across the top of the filters with each exit hole delivering DSW to an area of approximately 0.49 m^2. The exit holes faced upwards to facilitate ease of cleaning, when necessary, and so that an even distribution of the effluent could be visually assessed by observing the spurts of water from each hole. Lateral distribution pipes were closed off with a screw stop-end. These could be opened occasionally to allow access to the pipe to clear any build-up of solids that might restrict flow.

The distribution system for each filter pad was connected to a separate submersible pump (Pedrollo, Tamworth UK) positioned in the final chamber of a 3-chamber DSW tank. A HLR of 30 L $m^{-2}d^{-1}$ DSW was applied to the filters. This was applied in equal volumes of 750 L, four times daily. Taking in to account head losses in the pipe, the number of bends in the pipe, and the flow curve for the pump, the time to deliver 750 L to each pad was adjusted accordingly to range from 582 s to 898 s. Effluent from all three filter pads was collected in a single tank and a submersible pump was used to pump the effluent to a lagoon on the farm. A 100-ml water sample, obtained from the pipe discharging into the collection tank, was taken from each pad separately for analysis twice weekly. Influent samples were taken, twice weekly, close to the location of the pumps delivering DSW to the filters. Samples were frozen immediately and tested within a period of 14 days. The following water quality parameters were measured: SS (filtered through 1.4 μm paper and dried overnight at 103 – 105 ºC); COD_T and COD_F (dichromate method); TN_T and TN_F (persulfate method). After filtering through a 1.4 μm filter paper, the following parameters were analysed using a Konelab 20 nutrient analyser (Fisher Scientific, Wathan, Massachusetts): NH_4-N, NO_2-N, TON and PO_4-P. Nitrate N was calculated by subtracting NO_2-N from TON. Dissolved organic N was calculated by subtracting TON and NH_4-N from TN_F. Particulate N was calculated by subtracting TN_F from TN_T. All tests were carried out in accordance with standard methods (APHA-AWWA-WEF, 1995).

A P adsorption isotherm test was carried out on the wood used in the farm-scale woodchip filter. Solutions containing four known concentrations of PO_4-P were made up: 21.51, 46.06, 61.4 and 92.13 mg PO_4-P L^{-1}. Approximately 5 g of wood was added to a container and was mixed with 115 ml of each solution concentration. Each mixture was then shaken for 24 hours using an end-over-end mixer. The solids were separated from the mixture using a centrifuge and tested for PO_4-P. The data obtained was then modelled using a suitably fitting adsorption isotherm (Langmuir or Freundlich).

The decrease in the concentration of nutrients and other water quality parameters was calculated as the influent concentration minus the effluent concentration, expressed as a percent of the influent concentration.

4.3 Results and discussion

4.3.1 Organic carbon and SS removal

Influent COD_T concentrations averaged 5,750 ± 1,441 mg L^{-1} and the filters achieved a 66 % decrease on the influent concentration to produce an effluent that had a concentration of 1,961 ± 251 mg L^{-1} (Table 4.1). Much of the influent COD_T was associated with the particulate fraction, with COD_F accounting for only 30 % of COD_T. While there was a 66 % decrease in COD_T, there was only a 43 % decrease in COD_F, indicating that the filters were less effective at decreasing the soluble COD fraction. This fraction likely consists of soluble organic matter. Therefore, it is likely that physical filtration is the primary removal mechanism for COD_T. The aerobic nature of the filters would suggest that oxidation of organic compounds may also contribute to the decrease in concentrations of COD_T and COD_F.

The woodchip filters achieved an average decrease in the concentration of SS of 86 %, decreasing the concentration from an influent value of 602 ± 303 mg L^{-1} to 84 ± 19 mg L^{-1} (Table 4.1). From the start of operation, the filters achieved good decreases in the concentration of SS. The laboratory study (Chapter 3) found that the ability of woodchip filters to remove SS improved over time. In that study, the woodchip used had been de-barked and passed through a 10 mm-diameter sieve; therefore, the gradual build-up of SS in the pore space served to steadily increase the ability of the woodchip to remove

SS. The presence of bark and smaller woodchip particles in this study possibly resulted in the immediate impact on SS concentrations.

Table 4.1 Chemical characteristics of influent DSW and average effluent concentration from three woodchip filter pads. Standard deviations are shown in brackets.

Parameter	Influent		Effluent		Decrease
	mg L^{-1}				%
COD_T	5,750	(1,441)	1961	(251)	66
COD_F	1,744	(488)	987	(133)	43
TN_T	357	(100)	153	(24)	57
Particulate N	140	(65)	64	(41)	54
TN_F	217	(64)	74	(16)	58
Dissolved Org N	202.15	(63)	64.80	(25)	68
NH_4-N	134	(45)	37	(10)	72
NO_2-N	1.66	(2)	4.69	(2)	-182
NO_3-N	12.88	(10)	22.46	(8)	-74
Mineral N	14.54	(10)	27.15	(17)	-87
Org N	207.43	(77)	91.64	(45)	56
PO_4-P	36.01	(17)	24.70	(3)	31
SS	602	(303)	84	(19)	86

4.3.2 Nitrogen conversion

An average influent TN_T concentration of 357 ± 100 mg L^{-1} was decreased by 57 % by the woodchip filters to give an effluent concentration of 153 ± 24 mg L^{-1} (Table 4.1). This compares favourably with another pilot-scale, employing horizontal flow over a stack of plastic sheets, which achieved TN_T decreases in DSW of between 56 and 76 % (Clifford et al., 2010). Particulate N accounted for 39 % of TN_T and was decreased by 54 % to 64 ± 4 mg L^{-1} in the effluent. The large decrease in PN was consistent with the assumption that physical filtration was the primary removal mechanism.

The filters removed, on average, 58 % of the influent TN_F from 217 ± 64 mg L^{-1} giving an effluent concentration of 74 ± 16 mg L^{-1}. Dissolved organic N accounted for 31 % of the influent TN_F with the filters decreasing the DON concentration by 60 % to 26.85 ± 28 mg L^{-1}. The most likely mechanism for decreasing the concentration of DON was mineralisation to NH_4-N. However, sorption onto the filter medium and biological uptake could also have contributed to the decrease of DON.

Influent concentrations of NH_4-N averaged 134 ± 45 mg L^{-1} and this concentration was decreased by, on average, 72 % to 37 ± 10 mg L^{-1} (Table 4.1). The influent concentration fluctuated over the duration of the study (Figure 4.4). The effluent concentrations reflected these fluctuations, which would suggest that the average rate of decrease of 72 % was close to the maximum rate achievable by the filters (Figure 4.4).

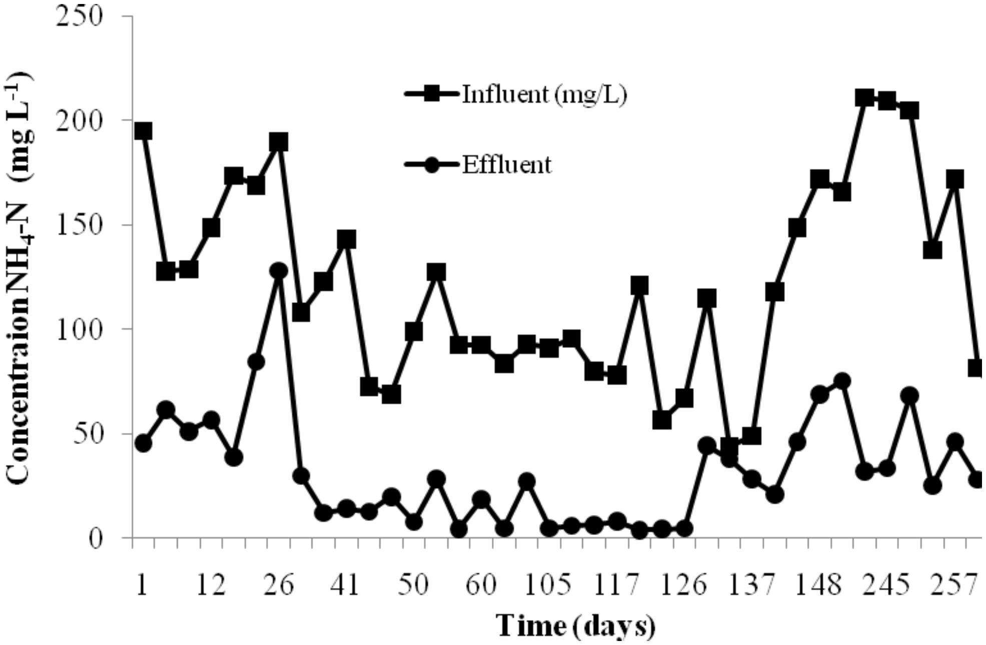


Figure 4.4 Comparison of the influent and effluent concentration (mg L^{-1}) of NH$_4$-N. Each point on the effluent line is the mean of three replicates.

Under aerobic conditions, nitrification is a likely mechanism for decreasing the concentration of NH$_4$-N. This hypothesis is supported by the concurrent increase in NO$_3$-N and decrease in NH$_4$-N in the effluent (Figure 4.5). There was a 74 % increase in the concentration of NO$_3$-N in the effluent from a concentration of 12.88 ± 10 mg L^{-1} to 22.46 ± 8 mg L^{-1} (Table 4.1). However, the relatively small absolute increase in NO$_3$-N concentration of the effluent (9.58 mg L^{-1}), relative to the decrease in NH$_4$-N (96 mg L^{-1}) would suggest that NH$_4$-N was also removed by another mechanism. Ammonium-N may have been adsorbed onto the woodchip (Wahab et al., 2010). Some denitrification may also have occurred within the filter, leading to a loss of N in gaseous form as N$_2$, N$_2$O, or NO$_x$. The NH$_4$-N could have been volatilized to NH$_3$. Further investigation into the emission of gases from the filter would be required to investigate this.

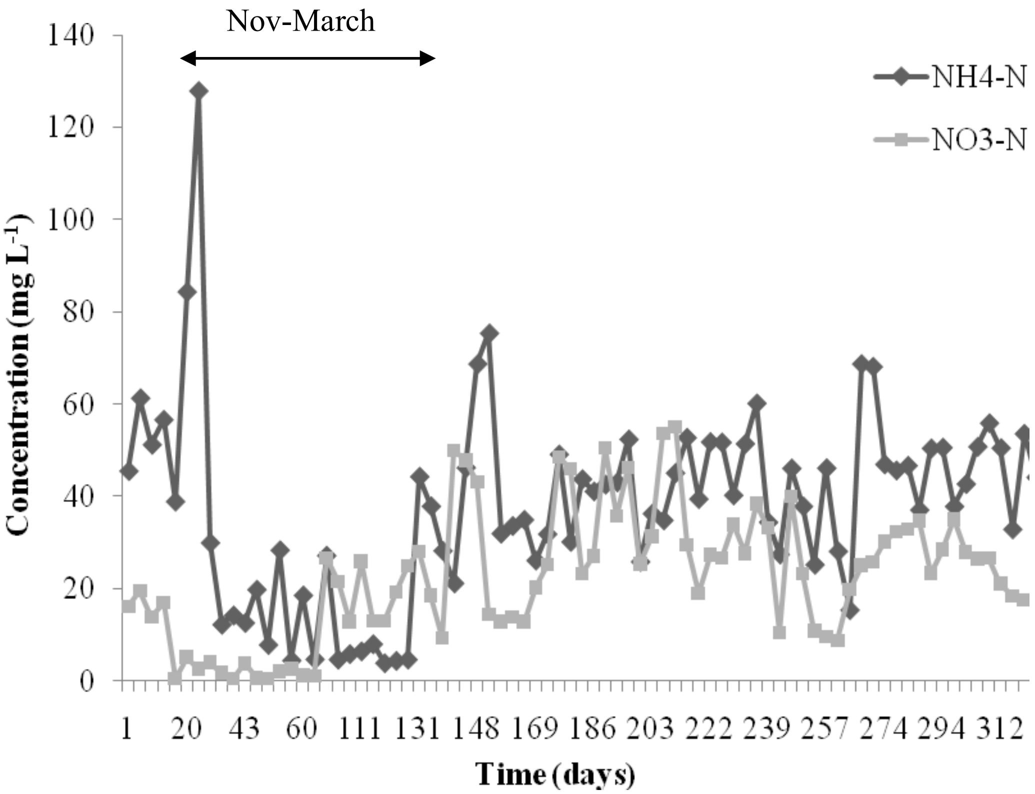


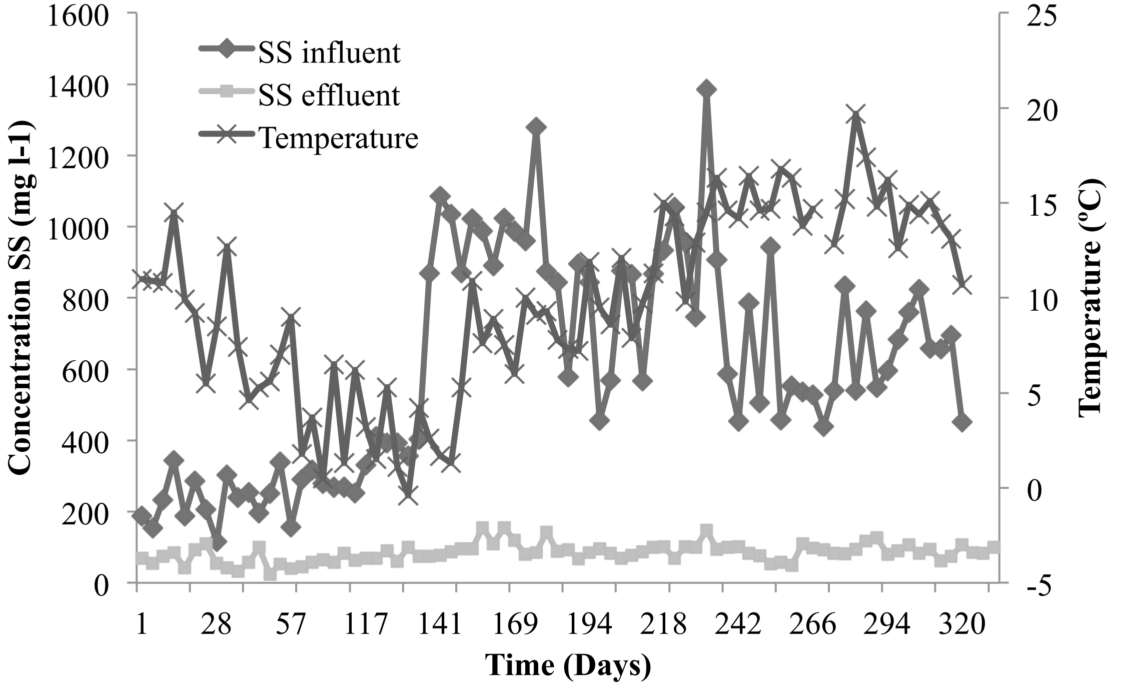
Figure 4.5 Comparison of effluent concentrations of NH_4-N and NO_3-N. Each point on the effluent line is the mean of three replicates.

4.3.3 Phosphorus retention

An average influent concentration of 36.01 ± 17 mg L^{-1} was recorded for PO_4-P. This decreased by 31 % to an average effluent concentration of 24.7 ± 3 mg L^{-1} (Table 4.1). This is a similar decrease to the decrease of 35 % achieved by Morgan and Martin (2008) in a study investigating DSW treatment using an ecological treatment system of aerobic and anaerobic reactors and subsurface wetlands. Using the Langmuir isotherm, the maximum mass of P adsorbed per mass of wood was calculated to be 1,958 mg P kg^{-1} woodchip. Phosphorus adsorption rates for wood are not widely recorded. Comparing the P adsorption capacity of woodchip with the effectiveness of sand to adsorb P, woodchip demonstrated a greater P adsorption capacity. Healy et al. (2010) recorded a value of 85 mg P kg^{-1} for sand. This would suggest that the woodchip could continue to adsorb P over a longer time period before all the potential P adsorption sites become exhausted.

4.3.4 Impact of seasonal variations and influent concentrations on the data

A comparison of the graphs of SS, COD_T, TN_T and PO_4-P indicate that all the parameters follow a similar trend (Figure 4.6 and 4.7). There is an increase in the influent concentration of all four parameters over the duration of the study period. This coincides with seasonal variations in temperature for all parameters, as highlighted by Martínez-Suller et al. (2010) with concentrations of N fractions lowest in the winter (November – March; Days 17 to 134) and highest in the summer (May – August; Days 197 – 320) (Figure 4.6 and 4.7). The low concentration of nutrients is likely to correspond with the lower number of cows being milked during the winter months (Minogue et al., 2010). The majority of the herd on the farm where the study was carried out were calved in the spring and therefore not milked during the winter months. There was no influence of rainfall as the holding yard for the cows was a closed yard. Effluent concentrations for all four parameters increased with the influent concentrations, albeit to a lesser degree, as indicated by the lower slope of the fitted regression line for effluent data. This was particularly so for SS. There was considerably less fluctuation in concentrations of the effluent compared to the influent. This would suggest that the woodchip filters are capable of producing a relatively consistent effluent concentration despite increasing and/or fluctuating influent concentrations. This is consistent with the findings of a laboratory study (Chapter 3) in which SS, COD_T and TN_T concentration in the influent did not have a significant effect on the performance of woodchip filters.



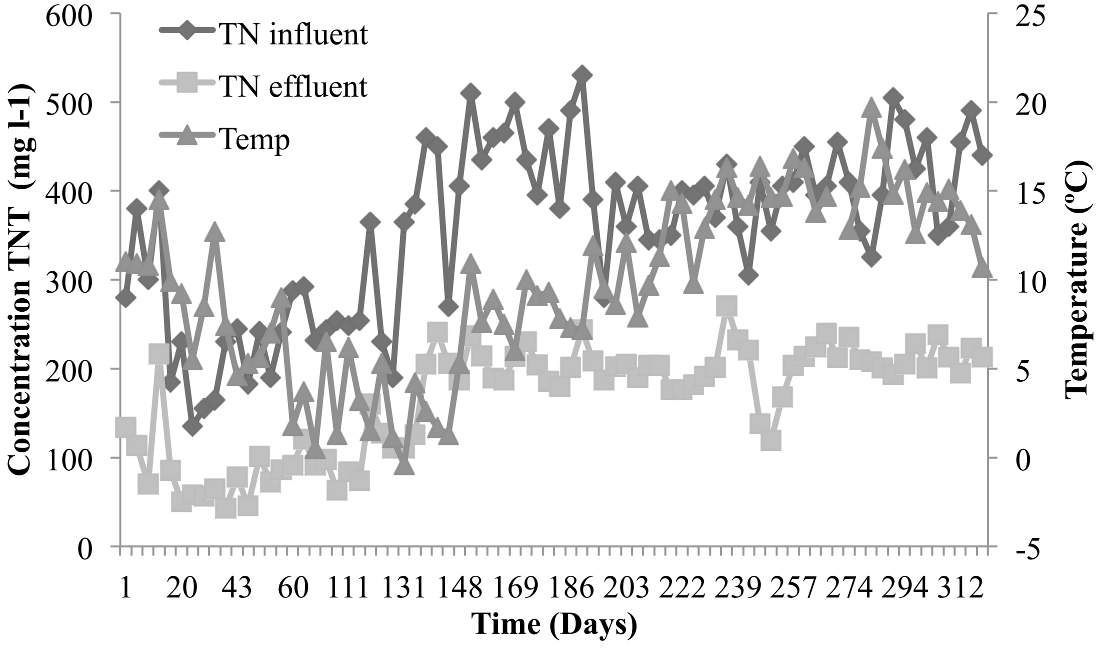
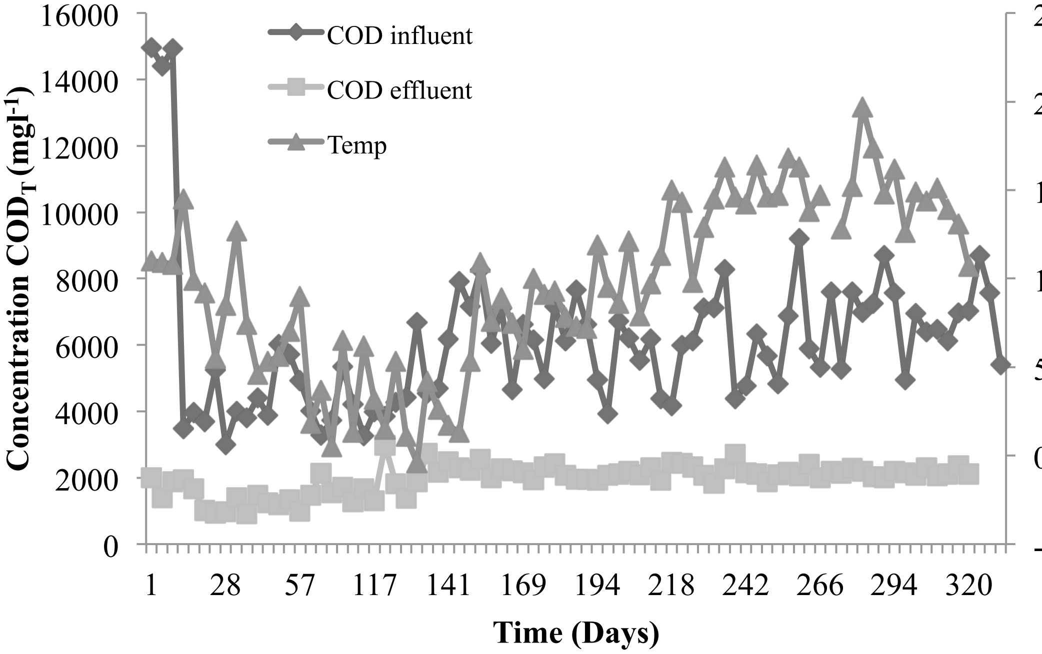


Figure 4.6 Graphs of the influent and effluent concentration (mg L^{-1}) of SS (top) and TN_T (bottom) to highlight increasing trend in influent concentrations and consistent effluents concentration. Mean daily temperature values (ºC) are also presented to demonstrate the effect of temperature on the influent concentrations for these parameters.



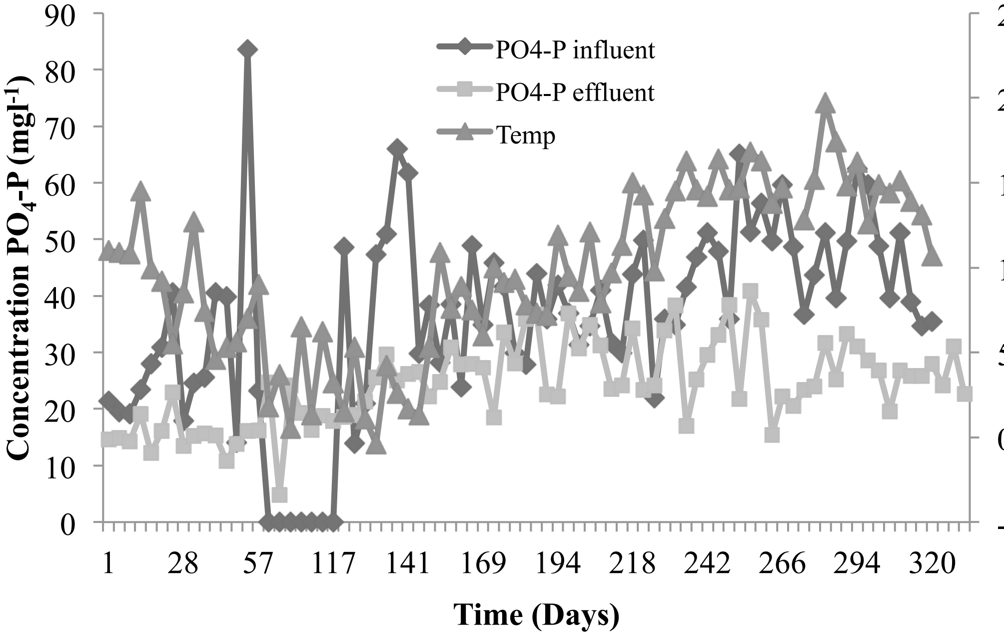


Figure 4.7 Graphs of the influent and effluent concentration (mg L^{-1}) of COD_T (top) and PO_4-P (bottom) to highlight increasing trend in influent concentrations and consistent effluents concentration. Mean daily temperature values (ºC) are also presented to demonstrate the effect of temperature on the influent concentrations for these parameters.

4.3.5 Economic appraisal of woodchip filter construction and operation

Presented in Table 4.2 are the estimated capital, operational and recurring costs associated with the construction and operation of an aerobic woodchip filter to treat DSW under current Irish conditions. The figures presented are based on the construction of three replicated farm-scale filters, and are presented for guidance purposes only. Calculations are presented for the costs associated with 1m^3 of woodchip, which would provide treatment for one cow on the basis that wash water generated per cow is approximately 30 L d^{-1} (Minogue et al., 2010). Capital costs involved in the construction of farm-scale filters include: use of a digger to dig out the filter base, a plastic liner to capture the effluent at the filter base, washed stone to make a level base for the woodchip; and pipes to deliver influent soiled water and to collect the treated effluent at the base of the filter.

Table 4.2 Estimated capital, operational and recurring costs associated with the construction and operation of an aerobic woodchip filter to treat dairy soiled water

No. cows	Q (L m^{-2} d^{-1})	Woodchip[a] (m^3)	Costs € Capital	Recurring[b]	Operational[c]	Total
1	30	1	33	25.48	0.7181	59
50	1500	60	1642	1274	35.905	2952
100	3000	120	3284	2548	71.81	5904
200	6000	240	6568	5096	143.62	11808

[a] Including woodchip around the edges of the filter extending out 1 m and inclined at 45°

[b] Woodchip to be replaced when excessive ponding occurs on the surface of the filter

[c] Based on the average of three pumps (0.75 kW) at different distances and head losses used in this study operating for between 4.53 and 6.98 hrs per week for a year at 16 c per unit of electricity (ESB, 2009)

The woodchips constitute the only recurring cost associated with the filters. Woodchip prices used in this paper are based on the cost of hiring a contractor to chip the wood on-site in June 2009. Costs associated with getting woodchip delivered on-farm may differ depending upon factors such as the distance of the farm from the woodchip supply base and moisture content of the woodchip. Moisture content can alter the weight of the woodchips and the price accordingly, if purchased on a per tonne basis. Woodchip would need replacing when ponding occurs on the surface of the filter, indicating that the pore space within the filter medium has reached capacity. Estimates suggest that this may occur after 2 to 3 yr of operation and would depend on the concentration of SS in the DSW being applied to the filter. If the build-up of SS extends throughout the entire depth of the woodchip, then all the woodchip would need to be replaced. If SS build-up is restricted to the upper portion of the woodchip, then only this portion of the woodchip would need to be replaced.

On-farm management practises should be considered prior to selection of the pump to deliver DSW to the filters and installation of the distribution system. Pump running costs depend upon: the water volumes generated, the head loss in the pipe delivering DSW to the filters, and distance from the holding tank to the woodchip filter pad. Ideally, the holding tank will consist of at least two compartments: the first compartment for the settlement of larger SS particles and the final compartment housing the pump to deliver DSW to the filter for treatment.

The operational costs calculated in Table 4.2 are based on the average of three replicated woodchip filters, each a different distance from the holding tank (between 4 and 20 m) and with different associated head losses, using 0.75 kW pumps operated, four times daily, for between 582 to 898 s. The unit cost of electricity of EUR16 cent is based on figures relevant as of 1st October 2009 (ESB, 2009).

4.3.6 Management options for woodchip effluent

Two management options may be employed to re-use the final effluent from the woodchip filters. Given the large volumes of fresh water used daily on farms to clean down the holding yard and milking parlour, the effluent could be recycled to wash down the holding yard. An alternative management option would be to apply the effluent to the land. The high concentration of plant available nutrients and low SS concentration would suggest it has potential to benefit plant growth and soil fertility without the traditional problems associated with the land spreading of fresh DSW.

The low concentration of SS in the effluent means that, if land applied, the potential for surface sealing of the soil is decreased. The potential for runoff is lowered and the infiltration ability of effluent into the soil profile is increased. The lower concentration of solids reduces problems such as clogging of pipes and aids the delivery of the effluent to distant fields for targeted irrigation via rotating arms (Peterson and Sommer, 2007).

The concentrations of NO_3-N in the effluent are just above the maximum allowable concentration for discharge to a receiving water body of 50 mg NO_3 L^{-1} (WHO, 2006). If the effluent from the woodchip filters was to be applied to the land, consideration would have to be given to the timing of application to avoid any potential leaching or runoff to nearby receiving water courses. If applied at a time when plant uptake is at its highest, this form of N would be very beneficial for plant growth. Ammonium N is also easily utilised by plants (von Wirén et al., 1997), and this form of N is not susceptible to leaching due to its positive charge that attracts it to negatively charged soil and clay particles (Miller and Cramer, 2005). Organic N is not immediately plant available, but, in soil, it acts as a slow release fertiliser and mineralises to NH_4-N, therefore becoming plant available (Zaman et al., 1999). It is not very mobile in soil, so application and timing rates would be determined based on the NO_3-N concentration of the effluent from the woodchip filters. Further investigation into the other fractions of P present in the effluent from the woodchips would be required to determine the potential for long-term build-up of P in the soil matrix.

If the effluent were to be reused as a flush down water in the holding yard of the milking parlour, the concentration of microbes in the effluent would have to be considered. This would determine the part of the farmyard on which this effluent is most suitable for use. Potable water is usually recommended for washing down the holding yard and milking parlour (ADF, 2008). A minimal maintenance and simple tertiary treatment system such as a sand filter, may be used to polish the effluent. Using the treated effluent to wash down the holding yard would mean a reduction in the on-farm consumption of fresh water. The potential increase in concentration of NO_3-N each time the water was cycled through the system, due to mineralisation and nitrification, would lead to a very nitrate-enriched effluent. As has already been outlined, this could be a very effective fertiliser but care would also be needed with application rates and timing to minimise the risk of nitrate leaching.

Solids from the DSW are trapped in the matrix of the woodchip filter. Spent filter chips could be composted or used in bioenergy production (Garcia et al., 2009). The woodchip provides long-term storage for the solids fraction and the working life of a woodchip filter is estimated to be around two to three years.

4.4 Conclusions

The main conclusions from this study are:

- This farm-scale filter study confirmed the effectiveness of woodchip filters to treat DSW under normal operational conditions;
- The results of the farm scale filter prove the laboratory results at a commercial scale;
- Analysis of three farm-scale woodchip filters operating for a duration of 11 months shows that they were capable of decreasing the SS, COD, TN and PO_4-P concentrations of fresh DSW by 86, 66, 57 and 31 %, respectively;

- Physical filtration was the principal mechanism of decreasing influent nutrient concentrations in the filters. Mineralisation, nitrification and biological degradation were active processes within the filters. Sorption and biological uptake on the filter media also contributed to decreasing nutrient concentrations;
- Woodchip filters are capable of producing an effluent that is consistent in SS and nutrient concentration despite fluctuations in influent concentration;
- Effluent from the filters may be applied to the land. The woodchip filter decreases the influent SS, and the resulting effluent contains nutrients, such as NO_3-N, NH_4-N and PO_4-P, that are readily plant available. The decrease in the concentration of SS in the effluent means that infiltration of DSW into the soil should be enhanced, delivering nutrients to the plant root system and decreasing potential for ammonia volatilisation. These characteristics of the effluent should improve the fertiliser value of nutrients in DSW; and
- There is the potential to reuse the effluent to wash down the holding yard of a milking parlour. Potable water is generally recommended for washing down all areas of a farmyard. Therefore, a further tertiary treatment is presented in Chapter 5 to examine the potential of two types of sand filter – single layer and stratified - to further clarify the effluent.

Chapter 5

Comparison of single-layer and stratified sand filters for the treatment of effluent from a farm-scale woodchip filter

Overview

In this chapter, the effectiveness of two types of sand filters, single-layer and stratified, are compared in their ability to treat effluent from farm-scale woodchip filters. Biomass accumulation in the upper layers of both types of filters, after an 82-day operating period, is also investigated.

5.1 Introduction

Single-pass SFs have been employed as a tertiary treatment system to polish several types of wastewaters (Leverenz et al., 2009; Healy et al., 2010). Their ability to reduce the concentration of various water quality parameters, including N and P, is well documented (Nakhla and Farooq, 2002; Healy et al., 2006). Sand filters are also noted for their ability to reduce the concentration of pathogenic bacteria and micro-organisms (Bahgat et al., 1998; Stevik et al., 2004). However, operational problems still exist. These are primarily associated with clogging within the matrix of the sand and the finite ability of the SF to remove P (Campos et al., 2002; Rodgers et al., 2005).

As part of this study, two commonly used SFs were constructed at laboratory-scale and investigated for their ability to polish effluent from farm-scale woodchip filters (Figure 5.1). The use of a SF is proposed as a final step in the overall treatment of DSW. After passing through a woodchip filter followed by further treatment in a SF, it is proposed that the effluent could then be used to wash down a holding yard and milking parlour. Some form of disinfection may be necessary to further reduce the concentration of coliforms to alleviate the potential for contamination of milking equipment and to raise the standard of the effluent to that of potable water.

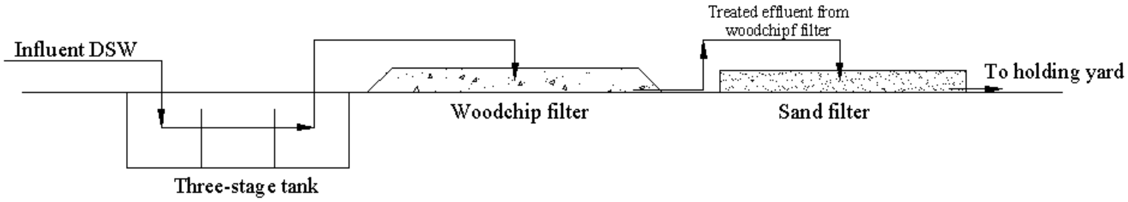


Figure 5.1 Overview of the layout of the farm treatment system consisting of a woodchip filter followed by a sand filter

5.2 Mechanisms of clogging

Surface clogging may be due to a number of causes. Accumulation of particulate matter and microorganisms - present in the influent wastewater - on surfaces as biofilms are believed to be the cause of surface sealing (Bouwer et al., 2000). In this process, hydrated extracellular polymers (exopolymers) as well as cells accumulate on the upper layers of the sand media and give rise to a reduction in permeability (Schwager and Boller, 1997). Siegrist and Boyle (1987) found an accumulation of organic matter in the upper sand layer, and hypothesised that it may have undergone humification and gradually filled the pore space, reducing the permeability. Sand filter clogging is believed to be a surface phenomenon, but the depth of clogging depends on the organic loading rate (OLR) and the size of the filter media (Rodgers et al., 2004). Leverenz et al. (2009) used an unsaturated flow model coupled with a reactive transport model (HYDRUS-CW2D) to determine the parameters affecting surface clogging and identified HLR, COD concentration, filter dosing frequency and time of operation as being significant. The concentration of TSS was also found to impact clogging in SFs. The influent COD concentration for this SF study was higher than most other studies using SFs to treat wastewater that had undergone at least primary treatment (Table 5.1).

Table 5.1 Average chemical characteristics (mg L^{-1}) of effluent from the woodchip filter used in this study over a period eleven months (n=78) compared with influent characteristic of other SF studies

Reference	Influent type	HLR	NO_3-N	NH_4-N	TN	PO_4-P	TSS	COD
		L m^{-2} d^{-1}	mg L^{-1}					
This study	DSW after woodchip filter	20	25.9	42.3	163	27.27	84	1991
Gill et al., 2009	Septic tank effluent[a]	28	0.8	16.2	20.7	3.14		492.6
Nakhala & Farooq, 2003	Secondary municipal effluent	0.15-0.38[b]	0.4		3.2	0.6	14	41
Rodgers et al., 2004	Aerobic biofilm treatment effluent	75	126.1	39.5		36.9	106	127.5
Rodgers et al., 2005	Synthetic DSW	20	2	50	120	30	265	1340
Rolland et al., 2009	Synthetic septic tank effluent	30[d]		56.4		8.9	86	462
Torrens et al., 2009a	FWSP effluent	0.15-80[c]	0.5	12		2.4	44	140

[a] concentrations given in g/d

[b] m/h

[c] m/d

[d] cm m^{-2} d^{-1}

Physical and chemical mechanisms responsible for clogging, such as the field-saturated hydraulic conductivity (K_{fs}) and the organic matter content of the media, may be used to quantify the extent of biofilm build-up within a filter. In an intermittent SF, loaded with synthetic wastewater resembling DSW and operated for a period of 806 days, Rodgers et al. (2004) quantified the extent of biofilm build-up by dismantling the filter and measuring the K_{fs} in 0.02 m-depth increments from the surface of the filter. The reduction of K_{fs} appeared to extend deep into the sand filter and only returned to a K_{fs} of virgin sand (packed to the same density as in the sand filter) at a depth of 0.165 m below the filter surface. Rodgers et al. (2004) also used loss on ignition (LOI; BSI, 1990) to give an indication of biomass distribution within the SF and found similar trends to the K_{fs} measurements.

5.3 Materials and methods

Two types of SFs were compared at laboratory-scale (n=3): (1) stratified SFs and (2) single-layer SFs (Figure 5.2). Each stratified SF was 1 m deep and each single-layer SF was 0.9 m deep. A 0.25 m-deep layer of distribution stone (6 - 10 mm in size), placed at the top of the stratified SF, was underlain by a 0.2 m-deep layer of coarse sand (D_{10}, 0.5 - 1.0 mm). Beneath this, a 0.075 m-deep layer of washed stone (6 - 10 mm in size) separated the coarse sand from a 0.1 m-deep layer of medium sand (D_{10}, 0.4 - 0.8 mm). Another 0.075 m-deep layer of 6 – 10 mm washed stone overlaid a 0.2 m-deep layer of fine sand (D_{10}, 0.2 – 0.63 mm). The bottom layer of sand was underlain by a 0.1 m-deep layer of washed stone (10 mm in size). In each single-layer SF, a 0.1 m-deep distribution layer (6 -10 mm in size) overlay a 0.7 m-deep layer of sand (D_{10}, 0.2 – 0.63 mm). This was underlain by a 0.1 m-deep layer of washed stone (6-10 mm in size). Double-leaf CorriPipe™, 0.3 m in diameter, was used to contain the sand. A steel mesh was attached to the base of the filters to hold the sand column in place, and a plastic container was placed under the base of each SF to collect the treated effluent.

Each SF was instrumented with an access tube (type ATL1, Delta-T Devices Ltd., Cambridge, UK) to allow volumetric water content to be measured at various depths. A probe (type PR1/6d-02, Delta-T Devices Ltd., Cambridge, UK) was inserted into the access tube and readings taken using a voltmeter (type HR2 Delta-T Devices

Ltd., Cambridge, UK). These readings were then converted into m^3 m^{-3} using the manufacturer's calibration curve.

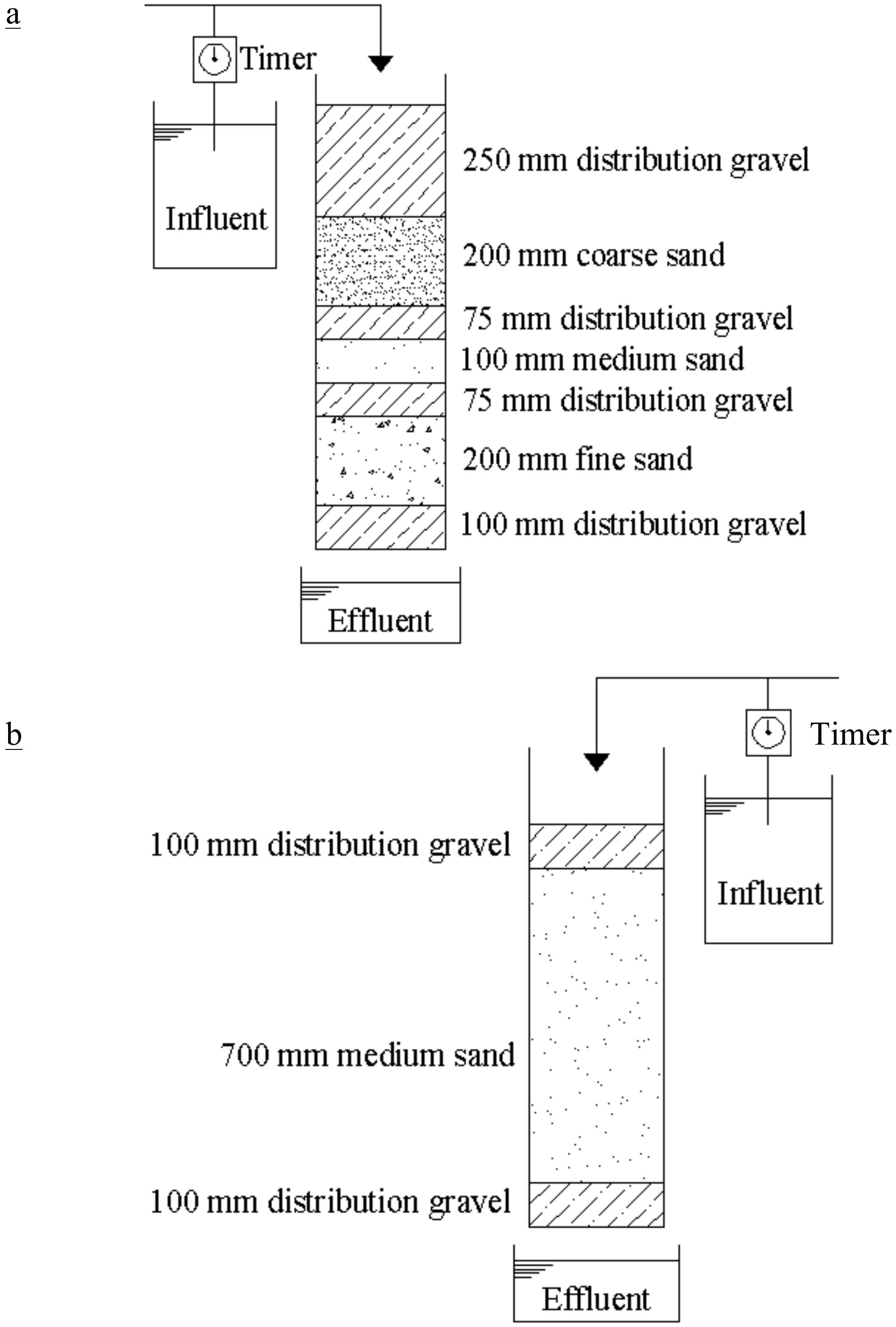


Figure 5.2 The stratified sand filter (a) and single-layer sand (b) filter used in the study showing depths of each layer

Figure 5.3 Sand filters as constructed – three replicate

Effluent from a woodchip filter treating fresh DSW was collected every three days, stored in a tank, and loaded onto the SFs at a HLR of 20 L m^{-2} d^{-1}. It was pumped onto the surface all six SFs every two hours using a peristaltic pump (Masterflex L/S 16, Illinois, USA) delivering 118 ml per dose via a spiral distribution manifold, positioned on the surface of each SF. The total study duration was 82 days.

5.3.1 Water quality parameters

Influent samples were taken, twice weekly, from the pipe discharging effluent from the woodchip filter. A 50-ml water sample was collected from the base of each filter for analysis twice weekly. Samples were frozen immediately and tested within a period of 14 days. A closed reflux method was used to test for COD_T and COD_F. Total N and TN_F were measured using the persulfate method. Suspended solids were measured by filtering a 10-ml sample through a filter paper (1.4 μm) and drying the solids captured and the filter paper for 24 hours at 103 – 105 °C. Filtered samples were measured for NH_4-N, NO_2-N, TON and PO_4-P using a Konelab 20 nutrient analyser (Fisher Scientific, Walthan, Massachusetts). Nitrate was calculated by subtracting NO_2-N from TON. Dissolved organic N was calculated by subtracting NO_2-N, NO_3-N and NH_4-N from TN_F. Particulate N was calculated by subtracting TN_F from TN_T. Inorganic N comprised of NH_4-N, NO_2-N and NO_3-N. Organic N was calculated by subtracting inorganic N from TN_T. All tests were carried out in accordance with standard methods (APHA-AWWA-WEF, 1995).

Removal of nutrients and other water quality parameters was calculated as the influent concentration minus the effluent concentration, expressed as a percent of the influent concentration. Descriptive statistics were used to characterise influent and effluent concentrations and removal rates. Percent removal data were analysed using ANOVA in a one-factorial design to test the effect of filter type on filter performance.

5.3.2 Tracer test

Average HRT within each SF was measured using a bromide (Br) tracer (Levenspiel, 1999). The tracer was made up to a concentration of 10 mg Br L^{-1} and applied to the filter in one dose using the peristaltic pump. Samples were collected daily over a 12-hour period approximately every 4 hours for 10 days from each of the six filters. The effluent containers were cleaned each time a sample was taken and the volume in each container at time of sampling was recorded.

5.3.3 Phosphorus adsorption test

A P adsorption isotherm test was carried out on the three sands used in the SFs. Each sand sample was washed in distilled water diluted with 10 % hydrochloric acid to eliminate the interference of native P concentration of the sand. Solutions containing four known concentrations of PO_4-P were made up: 21.51 mg PO_4-P L^{-1}, 46.06 mg

PO_4-P L^{-1}, 61.4 mg PO_4-P L^{-1} and 92.13 mg PO_4-P L^{-1}. Approximately 15 g of each type of sand - fine, medium and coarse - was added to a container and was mixed with 115 ml of each solution concentration. Each mixture was then shaken for 24 hours using an end-over-end mixer. The solids were separated from the mixture using a centrifuge and tested for PO_4-P. The data obtained was then modelled using a Langmuir isotherm.

5.3.4 Biomass experiments

After 82 days of operation, two columns from both sets of SFs were dismantled so that the build up of biomass within each filter could be quantified. Physical changes to a depth of 0.12 m below the surface of each SF were investigated by measuring K_{fs} (m s^{-1}) (constant-head method; BSI, 1990) and LOI (%) (BS 1377-3:1990; BSI, 1990). The amount of P that had adsorbed to the sand and its maximum adsorption capacity was measured using a Langmuir adsorption isotherm.

To measure the K_{fs}, an open-ended circular container, 0.05 m in diameter, was used to extract a sand core of height, l (Figure 5.4). Three replicate samples were taken from four layers: 0 - 0.03 m, 0.03 - 0.06 m, 0.06 - 0.09 m and 0.09 - 0.12 m, from one single-layer and one stratified SF. Water was supplied to the container and an overflow pipe maintained a constant head in the container, z. The flow rate (once constant flow rates were maintained), Q, was measured by calculating the time taken for a known volume of water to be collected. Taking the base of the open-ended container as datum, the following formula (from Darcy's Law) was then used to find values for K_{fs}:

$$Q = A\, K_{fs}\, i \qquad [5.1]$$

where A was the cross-sectional area of the container and i was the hydraulic gradient.

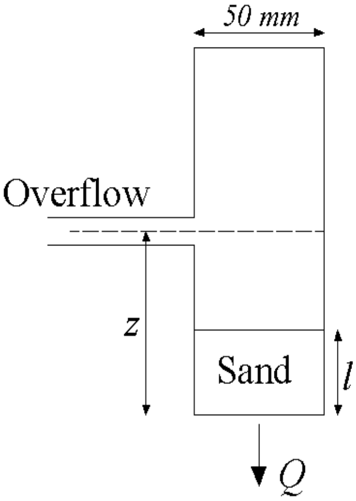


Figure 5.4 The experimental open-ended container used to calculate the field-saturated hydraulic conductivity test on different layers of sand from the single layer SF and the stratified SF

For determination of the mass LOI, replicated sand samples (n=3), taken at the same depth increments as the K_{fs} study, were dried at 50 °C until a constant weight was achieved, then ground down until they passed through a 425 μm sieve. The prepared samples were placed in a cool muffle furnace and then heated to 450 °C for over 3 hours. The LOI from the dismantled SFs were then compared with virgin sand samples. This gives an indication of the distribution of the biomass within a SF.

5.4 Results and discussion

5.4.1 Organic carbon and SS removal

Influent concentrations of COD_T were, on average, 1991 ± 296 mg L^{-1}. The single-layer SF decreased the influent concentration by 39 % to 1204 ± 270 mg L^{-1} (Table 5.2). The performance of the stratified SF was significantly better ($P<0.001$), achieving an average decrease of 56 %, resulting in an effluent concentration of 871 ± 121 mg L^{-1}. A study by Rodgers et al. (2005) found that, after 230 days, a stratified SF treating synthetic DSW at the same HLR achieved a removal rate of 96 %, decreasing an influent concentration of 1340 ± 285 mg L^{-1} to 60 ± 125 mg L^{-1}. However, the better performance achieved by Rodgers et al. (2005) may be a result of the enhanced straining effects of the medium. This was due to the higher deposition of organic materials, sediment and bacteria on the SF surface over a longer operational period (230 days versus 82 days in this study). An average influent COD_F concentration of 1073 ± 221 mg L^{-1} was measured and removal rates of 38 and 55 % were achieved by the single-layer and the stratified SF, respectively. The removal rates achieved by the stratified SF was significantly better ($P<0.001$) for both COD_T and COD_F. This would indicate that the stratified SFs were better at decreasing the soluble fraction of the influent as well as the fraction associated with influent SS. Therefore, both physical filtration and the oxidation of organic compounds may have contributed to the decrease in concentrations of COD_T and COD_F.

Influent SS concentrations were, on average, 84 ± 30 mg L^{-1} (Table 5.2). The single-layer SF achieved an average decrease of 52 %, giving an effluent concentration of 41 ± 8 mg L^{-1}. Effluent concentrations of 32 ± 6 mg L^{-1} were achieved by the stratified SF - a decrease of 62 % on the influent concentration and were significantly better than the decrease achieved by the single-layer SF ($P<0.001$). Straining is the main mechanism of removing SS in SFs with interception, impaction and adhesion also contributing to the overall reduction of solids in the effluent (Prochaska and Zouboulis, 2003).

5.4.2 Nitrogen conversion

Influent concentrations of TN_T ranged from 124 mg L^{-1} to 250 mg L^{-1} with a mean of 163 mg L^{-1}. The single-layer SF decreased the influent by, on average, 36 % to 104 ± 18 mg L^{-1} and the stratified SF by 57 % to 70 ± 21 mg L^{-1} ($P<0.001$) (Table 5.2). The influent TN_F concentration of 113 ± 25 mg L^{-1} was decreased by an average of 38 % for the single-layer SF to 61 ± 21 mg L^{-1} and by 41 % for the stratified SF to 59 ± 21 mg L^{-1} ($P>0.05$) (Table 5.2). Influent PN was, on average, 57 ± 45 mg L^{-1}. The stratified SF outperformed the single-layer SF, decreasing the influent concentration by 80 and 25 %, respectively (Table 5.2). Given its direct association with the SS concentration, it is most likely that the PN was reduced primarily by filtration and straining.

Table 5.2 Chemical characteristics of influent and average effluent concentration from three woodchip filter pads. Standard deviations are shown in brackets.

	Influent		Effluent					
			Single-layer			Stratified		
	mg L^{-1}		Average mg L^{-1}		Decrease %	Average mg L^{-1}		Decrease %
COD$_T$ **	1991	(296)	1204	(270)	39	871	(121)	56
COD$_F$**	1073	(221)	661	(162)	38	480	(51)	55
TN$_T$ **	163	(40)	104	(18)	36	70	(21)	57
Organic N	89	(42)	54	(15)	39	22	(19)	76
Inorganic N	74	(22)	48	(8)	35	43	(9)	42
P N	57	(45)	43	(16)	25	12	(9)	80
TN$_F$	113	(25)	61	(21)	38	59	(21)	41
DON	39	(25)	13	(16)	65	15	(18)	61
NH$_4$-N	42.3	(16.9)	23.5	(6.8)	34	20.7	(3.9)	41
NO$_2$-N	6.2	(5.1)	4.2	(2.1)	33	3.1	(1.7)	50
NO$_3$-N	25.9	(8.2)	18.9	(7.4)	27	24.9	(8.0)	4
Mineral N	32	(9)	24	(7)	24	19	(7)	40
PO$_4$-P**	27.27	(6.91)	11.41	(7.34)	58	7.08	(3.15)	74
SS**	84	(30)	41	(8)	52	32	(6)	62

(**) Decrease in effluent is significantly different between filter types

Organic N - at 89 ± 42 mg L^{-1} - accounted for, on average, 54 % of the influent TN_T concentration. The single-layer SF decreased the influent concentration by an average of 39 %, producing an effluent with an organic N concentration of 54 ± 15 mg L^{-1}. The stratified SF produced an effluent concentration of 22 ± 19 mg L^{-1} - an average decrease of 76 % (Table 5.2). The principal mechanisms of removing and transforming influent concentrations of organic N are filtration and mineralisation. Dissolved organic N in the influent was, on average, 39 ± 25 mg L^{-1} over the duration of the study. The single-layer SF outperformed the stratified SF and achieved a decrease of 65 % to produce an effluent concentration of 13 ± 16 mg L^{-1}. The stratified SF produced an effluent concentration of 15 ± 18 mg L^{-1}, which represented an overall decrease of 61 %. Mineralisation was the main transformation mechanism for decreasing the influent concentration of DON.

Influent inorganic N concentration was, on average, 74 ± 22 mg L^{-1} over the duration of the study. Of this, NH_4-N accounted for the largest fraction - at 57 % - of the influent inorganic N. The influent NH_4-N concentration decreased from 42 ± 17 mg L^{-1} to 24 ± 7 mg L^{-1} in the single-layer SF and to 21 ± 4 mg L^{-1} in the stratified SF, representing a decrease of 34 and 41 %, respectively ($P>0.05$) (Table 5.2). Both SFs are aerobic, therefore the principal mechanisms of decreasing the concentration of NH_4-N was nitrification. This hypothesis is usually reflected in an observed increase in the concentrations of NO_2-N and NO_3-N. However, by the end of this study, complete nitrification had not yet occurred (Figure 5.5 and 5.6). The single-layer SF decreased NO_2-N and NO_3-N by 33 and 27 % and the stratified SF by 50 and 4 %, respectively ($P>0.05$). The poor performance of the filters in relation to N removal may be due to the high OLR applied to the filters. In this study, an OLR of approximately 40 g COD_T m^{-2} d^{-1} was applied to the filters. This may have suppressed nitrification activity. US EPA guidelines (US EPA, 1980) recommend a maximum COD_T loading rate of approximately 10 g COD_T m^{-2} d^{-1}. Operating within this OLR, other studies achieved almost complete nitrification (Darby et al., 1996; Nichols et al., 1997; Rodgers et al., 2005).

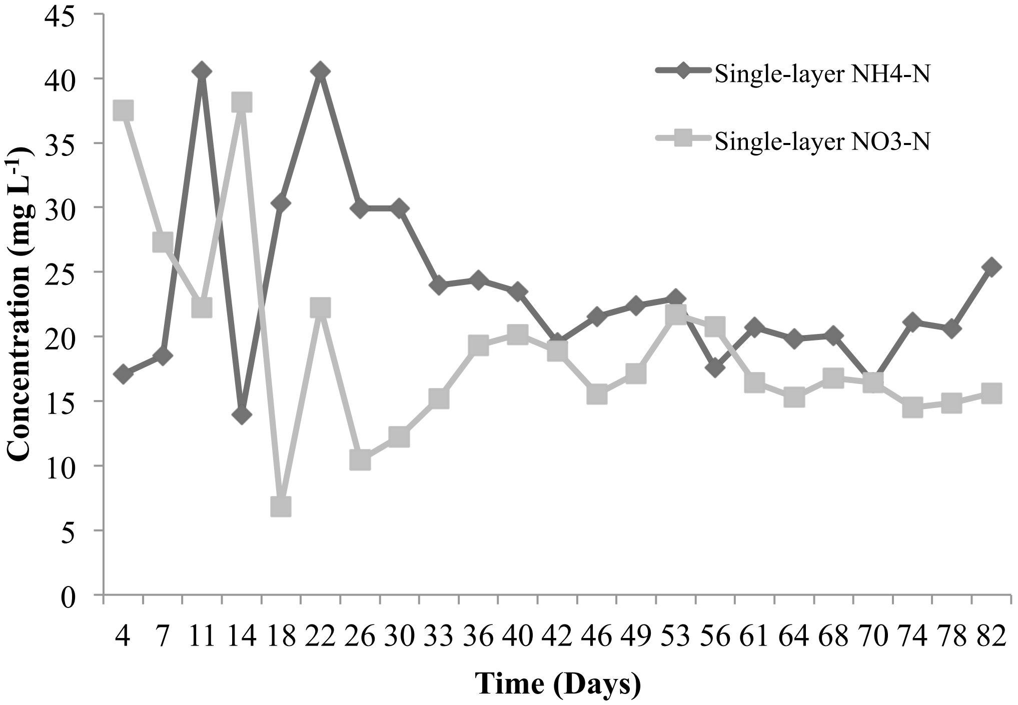


Figure 5.5 Comparison of the concentration of NH_4-N and NO_3-N in the effluent from the single-layer SF

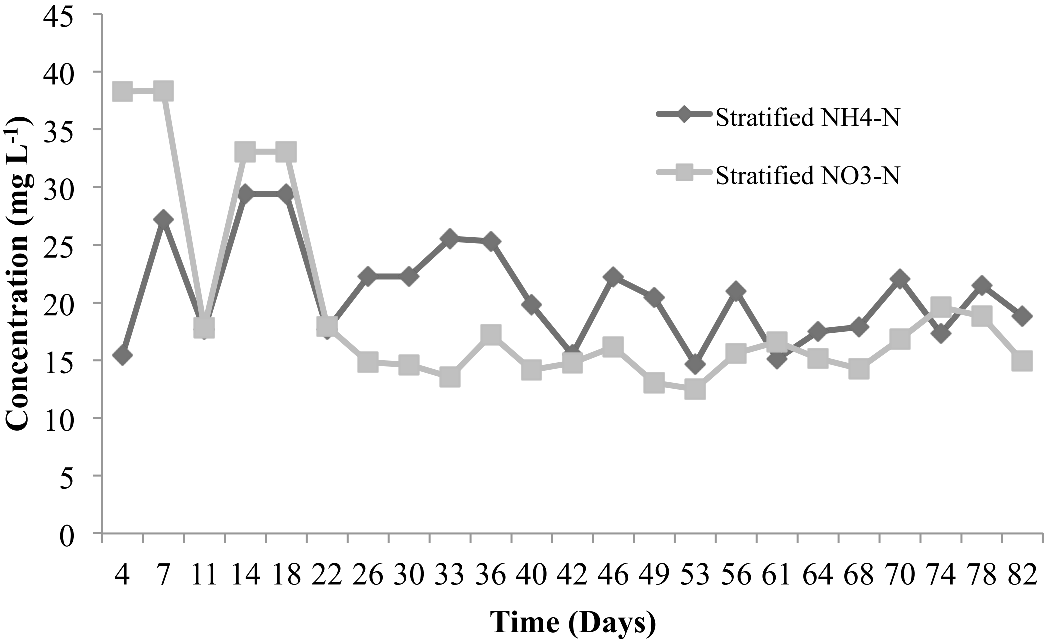


Figure 5.6 Comparison of the concentration of NH_4-N and NO_3-N in the effluent from the stratified SF

5.4.3 Phosphorus retention

The influent concentration of PO_4-P was, on average, 27.27 ± 6.91 mg L^{-1} (Table 5.1). The single-layer SF decreased the influent concentration by 58 % to an average effluent concentration of 11.41 ± 7.34 mg L^{-1}. The stratified SF achieved an average decrease of 74 %, producing an average effluent concentration of 7.08 ± 3.15 mg L^{-1} ($P<0.05$). For the single-layer SF, which consisted solely of medium sand (D_{10}, 0.4 – 0.8 mm), using the Langmuir isotherm, the maximum mass of P adsorbed per mass of sand was calculated to be 379 mg P kg^{-1} sand (Figure 5.7). The fine (D_{10}, 0.2 – 0.63 mm) and coarse sand (D_{10}, 0.5 – 1 mm) used in the stratified SF were calculated in a similar fashion (data not shown), and the maximum mass of P adsorbed per mass of sand was calculated as 759.19 mg P kg^{-1} for the fine sand and 1452.29 mg P kg^{-1} for the coarse sand. Although these maximum adsorption capacities are higher than other sands in Ireland – around 85 mg kg^{-1} (Healy et al., 2010) – they are still within the range for most sands (Foth and Ellis, 1997).

The combination of the three sands in the stratified SF resulted in an overall greater adsorption capacity, contributing to increased P removals. These results are consistent with other studies. Healy et al. (2010) used three media (crushed glass – 0.5 to 1.1 mm in size; sand – D_{10}, 0.15 mm; and a shallow podzolized soil sieved to less than 5 mm) in 0.65 m-deep filters to treat low-strength domestic wastewater. The respective P adsorption capacities of the filter media (measured using a Langmuir adsorption isotherm) were: 10.3, 85 and 1043 mg P kg^{-1}. Decreases of PO_4-P of 2.4, 4.3 and 100% were achieved in the glass, sand and soil filters. The average HRT affected the P retentions in these filters, as they ranged from 11.8 hours (glass) to 41.4 hours (soil).

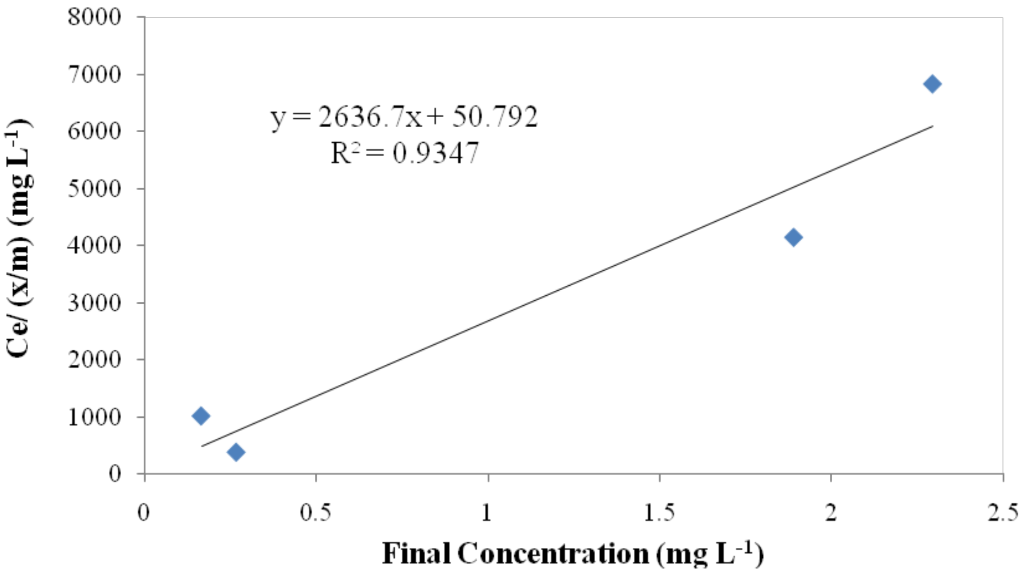


Figure 5.7 Langmuir isotherm for the medium sand used in the single-layer SF and in combination with two other sand types in the stratified SF

5.4.4 Biomass build-up

Results of the bromide tracer test showed that the breakthrough of the tracer occurred in the single-layer SF after 15.5 hours. After 82 days of operation, the mean HRT was 53.25 hours. Approximately 22 % of the Br applied was adsorbed by the filter media, which is consistent with other tracer tests on SFs (Rodgers et al., 2005). A Br tracer test was carried out on the stratified SFs, but no bromide was detected. This may have been due to the relatively few effluent water samples collected in the first two days – the time during which breakthrough and peak concentrations of Br would have been achieved.

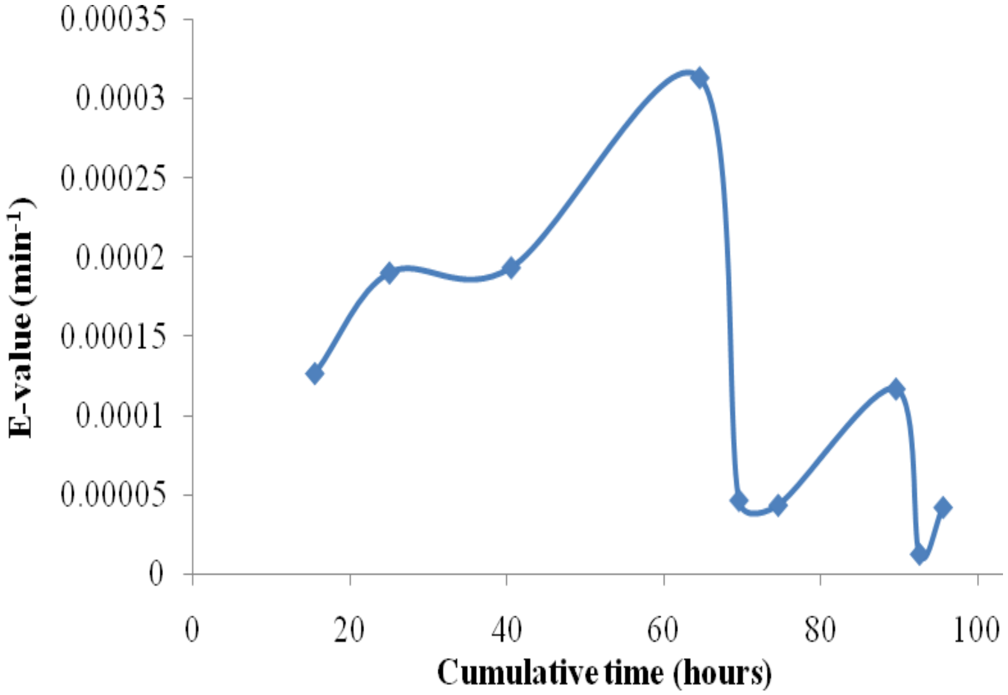


Figure 5.8 E-curve for a single-layer sand filter after 82 days of operation

Analysis of the volumetric water content of the single-layer SF to a depth of 0.6 m indicated there was no significant change with depth (Fig. 5.9). Rodgers et al. (2005) examined a stratified SF loaded for 342 days with synthetic DSW at a HLR of 20 L m^{-2} d^{-1} and a SS loading rate of between 5.2 and 12 g SS m^{-2} d^{-1} and found that the volumetric water content increased to a maximum value of approximately 40% at the filter surface. Comparatively, this study was only operational for 95 days at a SS loading rate of 1.7 g m^{-2} d^{-1}. Therefore, the volumetric water contents indicated that biofilm did not build-up in the filter media.

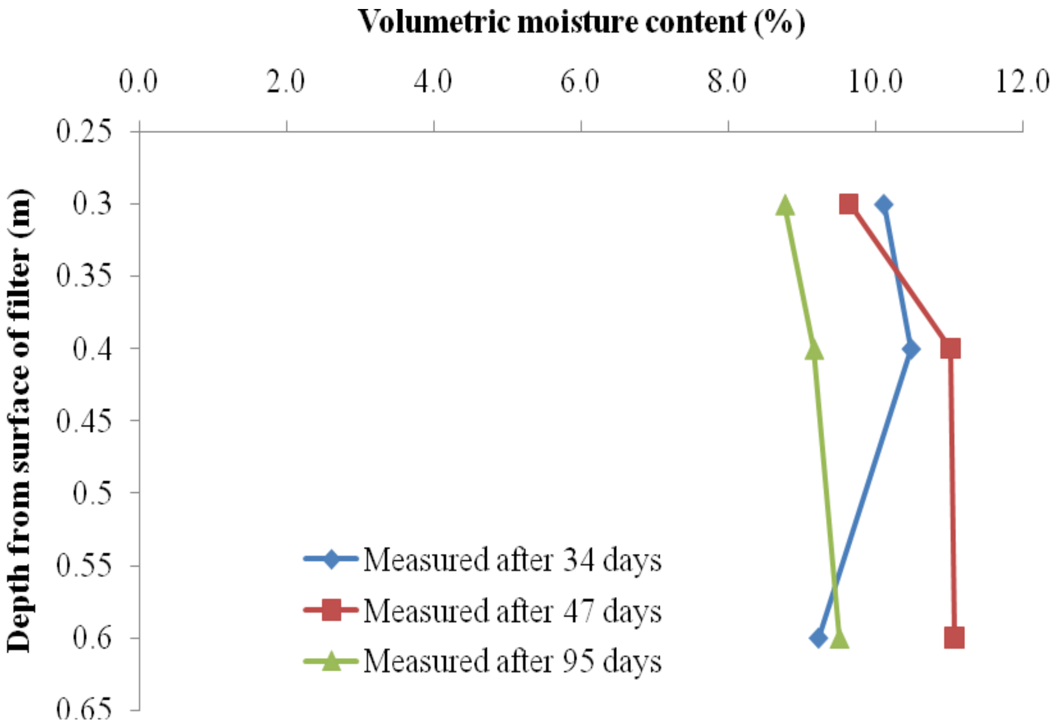


Figure 5.9 Volumetric water content measurements in a single-layer SF. Each point is an average of measurements taken on three different occasions (after 34, 47 and 95 days of operation) temperamental

Analysis of the LOI showed that most organic matter resided in the top 0.03 m in the stratified SF (Figure. 5.10). The LOI in this layer - at 0.38 ± 0.14 % - was more than four times the LOI of the virgin coarse sand (0.09 ± 0.045 %). For the single-layer SF, the LOI was greatest in the top layer at 0.52 ± 0.02 % (Figure 5.11). Loss on ignition in the 0.03 - 0.06 mm layer for the stratified SF was 0.19 ± 0.04 %, compared with 0.3 ± 0.07 % in the single-layer filter. This could suggest that biomass extends slightly deeper in the single-layer SF. Rodgers et al. (2004) measured maximum LOI values of approximately 2.3% in the uppermost layer of a stratified SF loaded at OLRs ranging from 6.5 to 76 g COD_T m^{-2} d^{-1} over an 806-day period. Immediately below the filter surface, LOI ranged from approximately 1% to 1.6% (Rodgers et al., 2004).

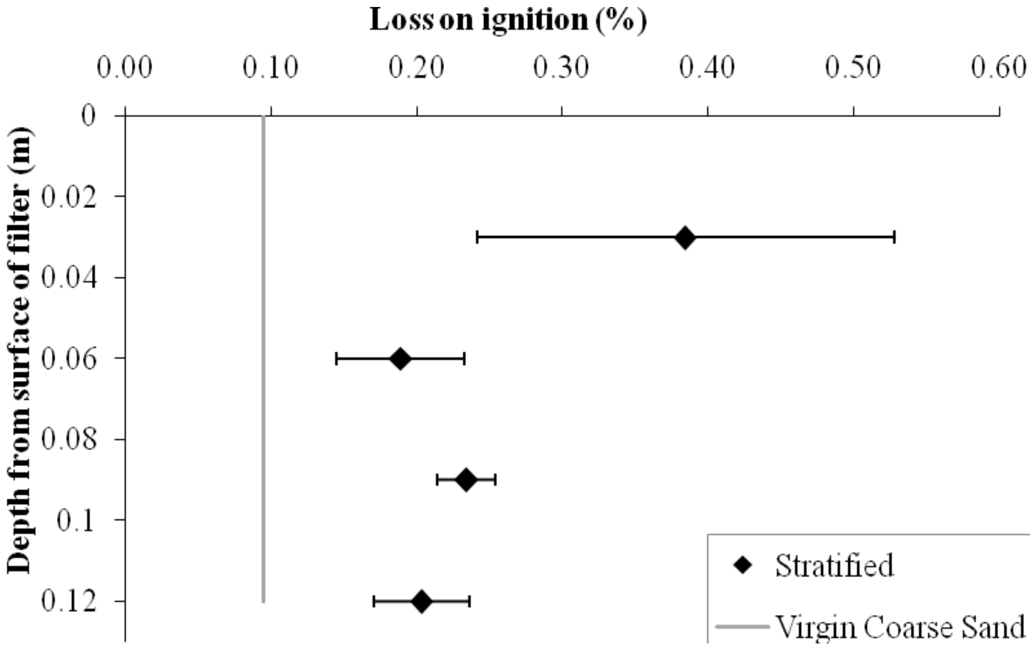


Figure 5.10 Mass loss on ignition in the upper layer of coarse sand of a laboratory-scale stratified sand filter

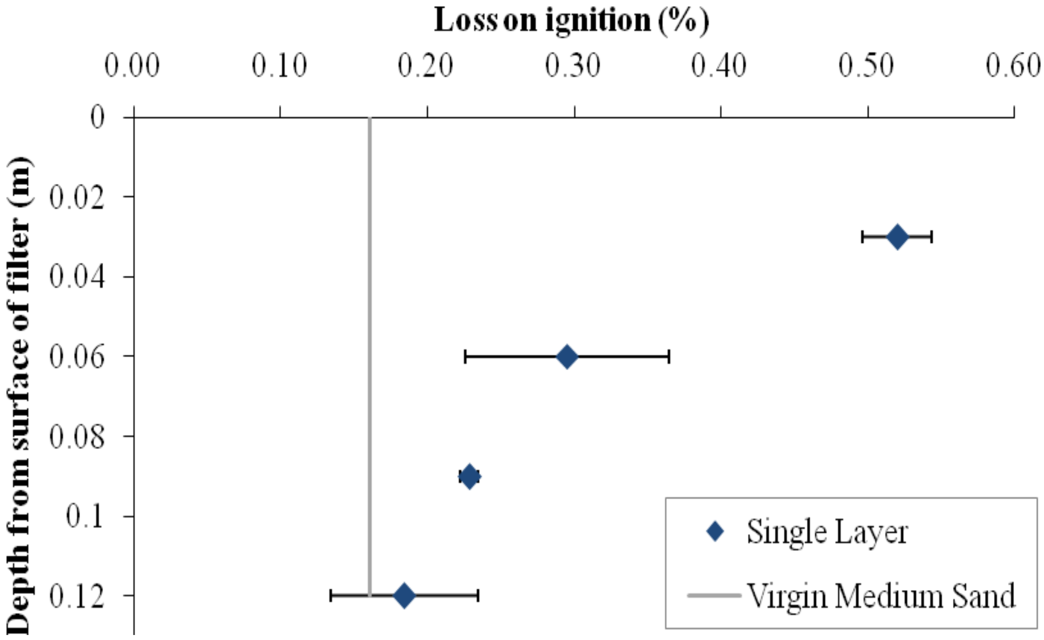


Figure 5.11 Mass loss on ignition in the upper layer of medium sand of a laboratory-scale single-layer sand filter

An investigation into the K_{fs} was carried out on two single-layer SFs (Figure 5.11). Measurements of K_{fs} for both filters indicated that some biofilm build-up occurred in the upper layer of the filter. In the 0 - 0.03 m layer, K_{fs} was, on average, $1.34 \times 10^{-4} \pm 4.23 \times 10^{-5}$ m s^{-1} and increased to $2.09 \times 10^{-4} \pm 7.05 \times 10^{-5}$ m s^{-1} in the 0.03 - 0.06 m layer, and to $2.3 \times 10^{-4} \pm 7.01 \times 10^{-5}$ m s^{-1} in the 0.06 - 0.09 m layer. Analysis of the single-layer SF, on which both LOI and K_{fs} were measured, suggests a correlation between measurements for K_{fs} and the build-up of biomass to a depth of 0.06 m in the single-layer SF. The decreasing LOI implies a decrease in the build-up of biomass on the filter medium to a depth of 0.12 m below the filter surface.

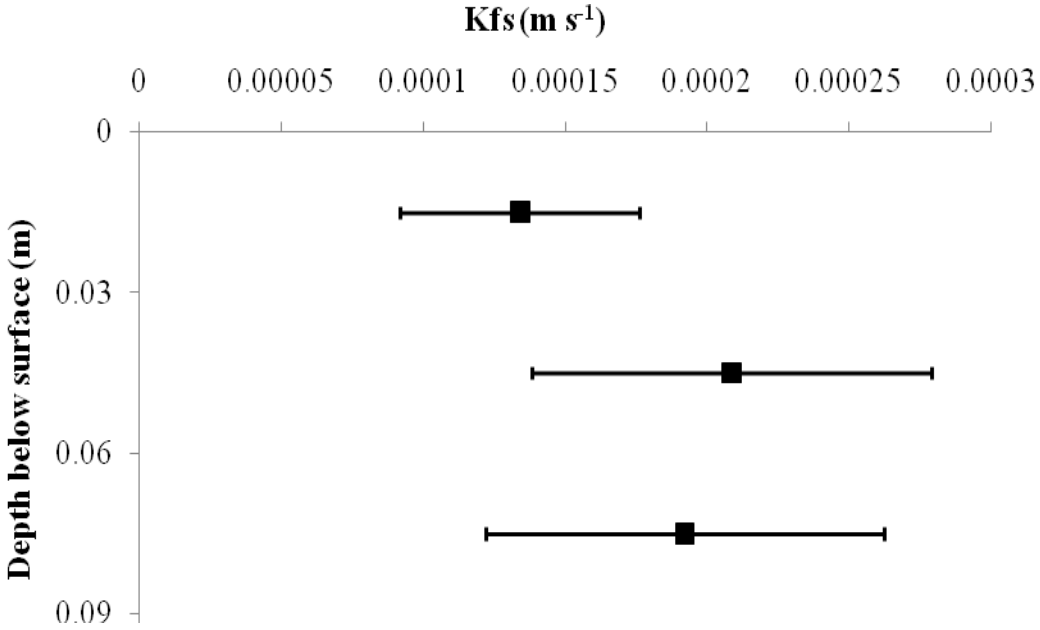


Figure 5.12 Field saturated hydraulic conductivity measurements for one single-layer SF column. Each point represents an average of three measurements from each depth

5.4.5 Microbial analysis

Samples of influent and effluent from all six SF's were taken on days 62 and 75 and analysed for TC. Influent values of $8.5 \times 10^6 \pm 7.1 \times 10^5$ CFU 100 mls^{-1} were measured. Both the single-layer SF and the stratified SF recorded similar rates of removal of 96 and 95 %, reducing the concentration of TC to 3.2 x 10^5 ± 1.6 x 10^5 CFU 100 mls^{-1} and 4.2 x 10^5 ± 13.2 x 10^5 CFU 100 mls^{-1}, respectively. Physical filtration and adsorption, or adhesion, are believed to be the principal mechanisms for removing pathogenic bacteria from wastewater in a SF (Stevik et al., 2004). Currently, little or no data is available regarding the concentration of microbes in water used to wash down the milking parlour and milking equipment. However, potable water is generally recommended for use (ADF, 2008). For a treated wastewater to reach a standard of potable water, no coliforms may be present. Therefore, some form of disinfection would be required to bring the treated effluent from the SF's to the standard of potable water.

5.5 Summary

The performance of a single-layer SF and a stratified SF, loaded at a HLR of 20 L m^{-2} d^{-1}, to polish effluent from a woodchip filter treating fresh DSW was investigated over an 82-day study period. The purpose of investigating two alternative SF designs was to propose a final tertiary treatment step as part of an overall on-farm system for the treatment of DSW. Both types of SFs were capable of decreasing the influent chemical characteristics. The single-layer SF decreased the influent concentration of COD_T, TN_T, NH_4-N, PO_4-P and SS by 39, 36, 34, 58 and 52 %, respectively. Influent concentrations of COD_T, TN_T, NH_4-N, PO_4-P and SS were decreased by 56, 57, 41, 74 and 62 % in the stratified SF.

Analysis of the distribution and build-up of biomass within the top layers of both SFs indicated that some biomass build-up had occurred. However, given the relatively short time period over which analyses was conducted, the build-up was only pronounced in the very top layers of both filters. Assessment of the ability of the SFs to remove coliforms from the influent wastewater indicated that both filters were capable of similar decreases in concentrations.

Both SFs appear to offer an effective method of achieving significant decreases in the concentration of organic matter, suspended sediment, nutrients and coliforms. If such a treatment system were to be incorporated at a full-scale, the cost of construction and operation would probably dictate the choice of one system over the other.

Chapter 6

Conclusions and Recommendations

Overview

The effectiveness of woodchip to act as a filter medium for the treatment of DSW was investigated in this study. Two sets of 0.5 m, 1 m and 1.5 m-deep laboratory-scale filters filled with de-barked Sitka spruce (*Picea sitchensis (Bong.) Carr* were used to treat DSW. One set of filters was loaded at 280 g SS m^{-2} d^{-1} and the other was loaded at 840 g SS m^{-2} d^{-1}. This experiment provided the design guidelines necessary for the construction of farm-scale woodchip filters. These filters, 100 m^2 in surface area and 1 m deep, tested the findings of the laboratory study under actual conditions at a working farm. Subsequent to this, two types of SF, a single-layer SF and a stratified SF, were investigated as a final tertiary treatment step as part of an overall on-farm system treating DSW. At a HLR of 20 L m^{-2} d^{-1}, the performance of these SFs was analysed over an 82-day period.

6.1 Main conclusions

The main conclusions from this study are as follows:

1. Woodchip shows potential as a filter medium for treating DSW. Woodchip filters are a low cost, minimal maintenance treatment system using a renewable resource that can be easily integrated into existing farm infrastructure.
2. For the laboratory-scale filters, average COD, SS and TN decreases of 95, 99 and 88 %, respectively, were achieved, and the effect of depth was negligible. The dominant treatment mechanism was physical filtration, but sorption and biological uptake also played a role. As the filters were aerobic, mineralisation and nitrification occurred.
3. The farm-scale filters had average COD, SS, NH_4-N, PO_4-P and TN reductions of 66, 86, 72, 31 and 57 %, respectively, giving effluent concentrations of 1,961 ± 251 mg L^{-1}, 84 ± 19 mg L^{-1}, 37 ± 10 mg L^{-1}, 24.7 ± mg L^{-1} and 153 ± 24 mg L^{-1}.

Effluent nutrient concentrations remained relatively stable over the study period, indicating the robustness of the filter.

4. Two options for the reuse of effluent from farm-scale woodchip filters were analysed: (i) *Effluent from the filters could be applied to land.* Woodchip filters remove the majority of the SS and the resulting effluent contains nutrient fractions that are readily plant available. (ii) *There is the potential to reuse the effluent to wash down the holding yard of milking parlours.* Potable water is generally recommended for washing down all areas of a farmyard. Therefore, SFs are proposed to further clarify the effluent and decrease the potential for microbial contamination of the holding yard.
5. Both types of SF investigated – a single-layer SF and a stratified SF -appear to offer an effective method of achieving good decreases in the concentration of organic matter, suspended sediment, nutrients and coliforms. If such a treatment system were to be incorporated at a full-scale, the cost of construction and operation would probably dictate the choice of one system over the other.

6.2 Further recommendations

- After 320 days, the farm-scale filter was still operational. Analysis of the farm-scale filter over a longer time period would determine the operating life of the filter.
- This study showed that a HLR of 20 L m^{-2} d^{-1} was capable of decreasing concentrations of nutrients in the effluent from the farm-scale filters. Increasing the HLR would result in a smaller footprint, would have lower construction costs and, therefore, would be worth investigating at laboratory-scale before construction of a full-scale SF.
- The release of GHG gases and NH_3 should be quantified so that a full N balance calculation may be completed

References

Achak M., Mandi L., Ouazzani N. (2009) Removal of organic pollutants and nutrients from olive mill wastewater by a sand filter. Journal of Environmental Management 90:2771-2779.

ADF (2008) Assured Dairy Farm Standards & Guidelines for Assessment. Edition 3.2:1.Scotland, UK.

Akratos C.S., Tsihrintzis V.A. (2007) Effect of temperature, HRT, vegetation and porous media on removal efficiency of pilot-scale horizontal subsurface flow constructed wetlands. Ecological Engineering 29:173-191.

APHA-AWWA-WEF (1995) Standard methods for the examination of water and wastewater. 19th edition. American Public Health Association. Washington, USA.

Arias C.A., Del Bubba M., Brix H. (2001) Phosphorus removal by sands for use as media in subsurface flow constructed reed beds. Water Research 35:1159-1168.

Auset M., Keller A.A., Brissaud F., Lazarova V. (2005) Intermittent filtration of bacteria and colloids in porous media. Water Resources Research 41:1-13.

Babatunde A.O., Zhao Y.Q., O'Neill M., O'Sullivan B. (2008) Constructed wetlands for environmental pollution control: A review of developments, research and practice in Ireland. Environment International 34:116-126.

Bahgat M., Dewedar A., Zayed A. (1999) Sand-filters used for wastewater treatment: buildup and distribution of microorganisms. Water Research 33:1949-1955.

Barkle G.F., Brown T.N., Painter D.J. (1999) Leaching of particulate organic carbon from land-applied dairy farm effluent. Soil Science 164:252-263.

Barkle G.F., Stenger R., Singleton P.L., Painter D.J. (2000) Effect of regular irrigation with dairy farm effluent on soil organic matter and soil microbial biomass. Australian Journal of Soil Research 38:1087-1097.

Bergsma T.T., Robertson G.P., Ostrom N.E. (2002) Atmospheric pollutants and trace gases: Influence of soil moisture and land use history on denitrification end-products. Journal of Environmental Quality 31:711-717.

Bhandral R., Bolan N.S., Saggar S., Hedley M.J. (2007) Nitrogen transformation and nitrous oxide emissions from various types of farm effluents. Nutrient Cycling in Agroecosystems 79:193-208.

Bolan N.S., Wong L., Adriano D.C. (2004) Nutrient removal from farm effluents. Bioresource Technology 94:251-260.

Bolan N.S., Laurenson S., Luo J., Sukias J. (2009) Integrated treatment of farm effluents in New Zealand's dairy operations. Bioresource Technology 100:5490-5497.

Bomo A.M., Stevik T.K., Hovi I., Hanssen J.F. (2004) Bacterial removal and protozoan grazing in biological sand filters. Journal of Environmental Quality 33:1041-1047.

Bouwer, E.J., Rijnaarts, H.H.M., Cunningham, A.B., Gerlach, R. (2000) Biofilms in porous media. pp. 123–158 *In* Bryers, J.D. (Ed.), Biofilms II: Process Analysis and Applications. Wiley, New York,

Buelna G., Dubé R., Turgeon N. (2008) Pig manure treatment by organic bed biofiltration. Desalination 231:297-304.

BS 1377: 3: 1990: 4. Determination by mass-loss on ignition. British standard method of test for soils for civil engineering purposes. Chemical and electro-chemical tests.

BS 1377: 5: 1990: 5. Determination of permeability by the constant-head method. British standard method of test for soils for civil engineering purposes. Compressibility, permeability and durability tests.

Cabrera and Gordillo (1995) Nitrogen release from land-applied animal manures. In: K. Steele, Editor, Animal Waste and the Land-Water Interface, CRC Lewis Publishers, Boca Raton, FL, pp. 393–404.

Cannon A.D., Gray K.R., Biddlestone A.J., Thayanithy K. (2000) SE--Structures and Environment: Pilot-Scale Development of a Bioreactor for the Treatment of Dairy Dirty Water. Journal of Agricultural Engineering Research 77:327-334.

Cameron K.C., Di H.J., McLaren R.G. (1997) Is soil an appropriate dumping ground for our wastes? Australian Journal of Soil Research 35:995-1035.

Campos L.C., Su M.F.J., Graham N.J.D., Smith S.R. (2002) Biomass development in slow sand filters. Water Research 36:4543-4551.

Carpenter S.R., Caraco N.F., Correll D.L., Howarth R.W., Sharpley A.N., Smith V.H. (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications 8:559-568.

Central Statistics Office (CSO) (2008) Farm structure survey 2007. Stationery Office, Dublin, Ireland.

Clifford E., Rodgers M., De Paor D. (2008) Dairy washwater treatment using a horizontal flow biofilm system. Water Science and Technology: 1879-1888.

Clifford E., Nielsen M., Sørensen K., Rodgers M. (2010) Nitrogen dynamics and removal in a horizontal flow biofilm reactor for wastewater treatment. Water Research 44:3819-3828.

Coillte. 2008. Available from www.coillte.ie [Accessed 16th May 2010].

Craggs R.J., Sukias J.P., Tanner C.T., Davies-Colley R.J. (2004) Advanced pond system for dairy-farm effluent treatment. New Zealand Journal of Agricultural Research 47:449-460.

Cronk J.K. (1996) Constructed wetlands to treat wastewater from dairy and swine operations: a review. Agriculture, Ecosystems & Environment 58:97-114.

Cumby T.R., Brewer A.J., Dimmock S.J. (1999) Dirty water from dairy farms, I: Biochemical characteristics. Bioresource Technology 67:155-160.

Csathó P., Sisák I., Radimszky L., Lushaj S., Spiegel H., Nikolova M.T., Nikolov N., Cermák P., Klir J., Astover A., Karklins A., Lazauskas S., Kopiński J., Hera C., Dumitru E., Manojlovic M., Bogdanovi D., Torma S., Leskošek M., Khristenko A. (2007) Agriculture as a source of phosphorus causing eutrophication in Central and Eastern Europe. Soil Use and Management 23:36-56.

CSO (2008) Farm structure survey 2007. Central Statistics Office, Stationery Office, Dublin, Ireland.

Department of Agriculture, Food and Fisheries (2010) Annual review and outlook for agriculture, food and fisheries 2008-2009. Department of Agriculture, Food and Fisheries, Dublin. 83 pp

Daly K., Jeffrey D., Tunney H. (2001) The effect of soil type on phosphorus sorption capacity and desorption dynamics in Irish grassland soils. Soil Use and Management 17:12-20.

Daniel T.C., Sharpley A.N., Lemunyon J.L. (1998) Agricultural phosphorus and eutrophication: A symposium overview. Journal of Environmental Quality 27:251-257

Darby, J., Tchobanoglous, G., Nor, M.A. (1996) Shallow intermittent sand filtration: performance evaluation, The Small Flows J. 2: 3–14.

Del Bubba M., Arias C.A., Brix H. (2003) Phosphorus adsorption maximum of sands for use as media in subsurface flow constructed reed beds as measured by the Langmuir isotherm. Water Research 37:3390-3400.

Demirel B., Yenigun O., Onay T.T. (2005) Anaerobic treatment of dairy wastewaters: A review. Process Biochemistry 40:2583-2595.

DOELG (2002). Making Ireland's Development Sustainable-Review, Assessment and Future Development. www.environ.ie 21st November 2010

Di H.J., Cameron K.C. (2000) Calculating nitrogen leaching losses and critical nitrogen application rates in dairy pasture systems using a semi-empirical model. New Zealand Journal of Agricultural Research 43:139 - 147.

Dou Z., Ramberg C.F., Toth J.D., Wang Y., Sharpley A.N., Boyd S.E., Chen C.R., Williams D., Xu Z.H. (2009) Phosphorus speciation and sorption-desorption characteristics in heavily manured soils. Soil Science Society of America Journal 73:93-101.

Dunne E.J., Culleton N., O'Donovan G., Harrington R., Daly K. (2005) Phosphorus retention and sorption by constructed wetland soils in Southeast Ireland. Water Research 39:4355-4362.

Eberhardt T.L., Min S.H., Han J.S. (2006) Phosphate removal by refined aspen wood fiber treated with carboxymethyl cellulose and ferrous chloride. Bioresource Technology 97:2371-2376.

Eghball B., Gilley J.E., Baltensperger D.D., Blumenthal J.M. (2002) Long-term manure and fertilizer application effects on phosphorus and nitrogen in runoff. Transactions of the American Society of Agricultural Engineers 45:687-694.

EC, 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. OJ L 327, 22.12.2000, p. 1–73

EC. (2008) Eurostat Regional Yearbook 2008. Office for Official Publications of the European Communities, Luxembourg.

EC. (2009) Agricultural statistics, Main results 2007-2008. Office for Official Publications of the European Communities, Luxembourg.

EEA. (2002) Environment Signals 2002, Report No. 9. European Environment Agency, Copenhagen.

EEC, 1991 Council Directive (91/271/EEC) of 12th December 1991 concerning the protection of waters caused by nitrates from agriculture sources. Official Journal of the European Communities L375/1. Brussels, Belgium.

Ellison M.E., Brett M.T. (2006) Particulate phosphorus bioavailability as a function of stream flow and land cover. Water Research 40:1258-1268.

EPA (2008) Ireland's Environment 2008. Environmental Protection Agency, Wexford, Ireland

EPA (2009) Code of practice wastewater treatment and disposal systems serving single houses (p.e. <10). Environmental Protection Agency, Wexford, Ireland

EPA (2010) Trends in NOx Emissions Nitrogen Oxides 1990-2008. Environmental Protection Agency, Wexford, Ireland

Erickson A.J., Gulliver J.S., Weiss P.T. (2007) Enhanced Sand Filtration for Storm Water Phosphorus Removal. Journal of Environmental Engineering 133:485-497.

ESB. 2009 http://www.esb.ie/esbcustomersupply/residential/energy_efficiency/what_is_1kwh.jsp Accessed 31/10/2010

Food and Agriculture Organisation (1996**)** Control of water pollution from agriculture Series title: FAO Irrigation and Drainage Papers. FAO, Rome

Foth H.D., Ellis B.G. (1997) 290 pp. Soil fertility. Chapter 7. 2nd edition. Lewis Publishers.

Fenton O., Healy M.G., Schulte R.P.O. (2008) A review of remediation and control systems for the treatment of agricultural waste water in Ireland to satisfy the requirements of the water framework directive. Biology and Environment 108:69-79.

Fuller, F., Beghin, J.C. (2004) China's growing market for dairy products. Iowa Ag Review, 10 (3): 10-11.

Garcia M.C., Szogi A.A., Vanotti M.B., Chastain J.P., Millner P.D. (2009) Enhanced solid-liquid separation of dairy manure with natural flocculants. Bioresource Technology 100:5417-5423.

Geohring L.D., McHugh O.V., Walter M.T., Steenhuis T.S., Akhtar M.S., Walter M.F. (2001) Phosphorus Transport Into Subsurface Drains By Macropores After Manure Applications: Implications for Best Manure Management Practices. Soil Science 166:896-909.

Gibert O., Pomierny S., Rowe I., Kalin R.M. (2008) Selection of organic substrates as potential reactive materials for use in a denitrification permeable reactive barrier (PRB). Bioresource Technology 99:7587-7596.

Gill L.W., O' Suilleabhain C., Misstear B.D.R., Johnston P.M. (2009) Comparison of stratified sand filters and percolation trenches for on-site wastewater treatment. Journal of Environmental Engineering 135:8-16.

Gottschall N., Boutin C., Crolla A., Kinsley C., Champagne P. (2007) The role of plants in the removal of nutrients at a constructed wetland treating agricultural (dairy) wastewater, Ontario, Canada. Ecological Engineering 29:154-163.

Greenan C.M., Moorman T.B., Kaspar T.C., Parkin T.B., Jaynes D.B. (2006) Comparing carbon substrates for denitrification of subsurface drainage water. Journal of Environmental Quality 35:824-829.

Guillen-Jimenez, E., Alvarez-Mateos, P., Romero-Guzman, F., Pereda-Marin, J., 2000. Bio-mineralization of organic matter in dairy wastewater, as affected by pH. The evolution of ammonium and phosphates. Wat. Res. 34, 1215-1224

Hall S.J., Matson P.A., Roth P.M. (1996) NO_x emissions from soil: Implications for air quality modeling in agricultural regions. Annual Review of Energy and the Environment 21:311-346.

Hammer, D.A. (1994) Guidelines for design, construction and operation of constructed wetlands for livestock wastewater treatment. In: P.J. DuBowy and R.P.

Reaves, Editors, Proceedings of a Workshop on Constructed Wetlands for Animal Waste Management. 155–181.

Hansen N.C., Daniel T.C., Sharpley A.N., Lemunyon J.L. (2002) The fate and transport of phosphorus in agricultural systems. Journal of Soil and Water Conservation 57:408-416.

Harrison R.B., Turner N.S., Hoyle J.A., Krejsl J., Tone D.D., Henry C.L., Isaksen P.J., Xue D. (2000) Treatment of septic effluent for fecal coliform and nitrogen in coarse-textured soils: Use of soil-only and sand filter systems. Water, Air, and Soil Pollution 124:205-215.

Hawke R.M., Summers S.A. (2006) Effects of land application of farm dairy effluent on soil properties: A literature review. New Zealand Journal of Agricultural Research 49:307-320.

He, Z. L.,Zhang, M. K., Stoffella, P. J., Yang, X. E., Banks, D. J. (2006). Phosphorus concentrations and loads in runoff water under crop production. Soil Science Society of America Journal 70: 1807-1816

Healy M.G., Rodgers M., Mulqueen J. (2006) Denitrification of a nitrate-rich synthetic wastewater using various wood-based media materials. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering 41:779-788.

Healy M.G., Rodgers M., Mulqueen J. (2007a) Treatment of dairy wastewater using constructed wetlands and intermittent sand filters. Bioresource Technology 98:2268-2281.

Healy M.G., Rodgers M., Mulqueen J. (2007b) Performance of a stratified sand filter in removal of chemical oxygen demand, total suspended solids and ammonia nitrogen from high-strength wastewaters. Journal of Environmental Management 83:409-415.

Healy, M.G., Burke, P., Rodgers, M. (2010) The use of laboratory sand, soil and crushed-glass filter columns for polishing domestic-strength synthetic wastewater that has undergone secondary treatment. Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering 45: 1635-1641.

Hickey C.W., Quinn J.M., Davies-Colley R.J. (1989) Effluent characteristics of dairy shed oxidation ponds and their potential impacts on rivers. New Zealand Journal of Marine and Freshwater Research 23:569 - 584.

Houlbrooke D.J., Horne D.J., Hedley M.J., Snow V.O., Hanly J.A. (2008) Land application of farm dairy effluent to a mole and pipe drained soil: Implications for nutrient enrichment of winter-spring drainage. Australian Journal of Soil Research 46:45-52.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kadlec, R.H., Knight, R. (1996) Treatment wetlands. CRC-Press, Boca Raton, Florida, USA,

Kadlec R.H., Tanner C.C., Hally V.M., Gibbs M.M. (2005) Nitrogen spiraling in subsurface-flow constructed wetlands: Implications for treatment response. Ecological Engineering 25:365-381.

Kadlec R.H. (2008) The effects of wetland vegetation and morphology on nitrogen processing. Ecological Engineering 33:126-141.

Kadlec R.H. (2009) Comparison of free water and horizontal subsurface treatment wetlands. Ecological Engineering 35:159-174.

Karthikeyan K.G., Tshabalala M.A., Wang D., Kalbasi M. (2004) Solution Chemistry Effects on Orthophosphate Adsorption by Cationized Solid Wood Residues. Environmental Science and Technology 38:904-911.

Kern J., Idler C., Carlow G. (2000) Removal of fecal coliforms and organic matter from dairy farm wastewater in a constructed wetland under changing climate conditions. Journal of Environmental Science and Health - Part A Toxic/Hazardous Substances and Environmental Engineering 35:1445-1461.

Kim D.-J., Lee D.-I., Keller J. (2006) Effect of temperature and free ammonia on nitrification and nitrite accumulation in landfill leachate and analysis of its nitrifying bacterial community by FISH. Bioresource Technology 97:459-468.

Kleinman P.J.A., Sharpley A.N. (2003) Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events. Journal of Environmental Quality 32:1072-1081.

Kleinman P.J.A., Sharpley A.N., Saporito L.S., Buda A.R., Bryant R.B. (2009) Application of manure to no-till soils: Phosphorus losses by sub-surface and surface pathways. Nutrient Cycling in Agroecosystems 84:215-227.

Knudsen M.T.K., Ib Sillebak; Berntsen, Jørgen; Petersen, Bjørn Molt and Kristensen, Erik Steen (2006) Estimated N leaching losses for organic and conventional farming in Denmark. Journal of Agricultural Science 144:135-149.

Kristiansen R., Cripps S.J. (1996) Waste management: Treatment of fish farm wastewater using sand filtration. Journal of Environmental Quality 25:545-551.

Lansing S.L., Martin J.F. (2006) Use of an ecological treatment system (ETS) for removal of nutrients from dairy wastewater. Ecological Engineering 28:235-245.

Lee D., Dillaha T., A, Sherrard J., H. (1989) Modeling phosphorus transport in grass buffer strips. Journal of Environmental Engineering 115:409-427.

Leverenz H.L., Tchobanoglous G., Darby J.L. (2009) Clogging in intermittently dosed sand filters used for wastewater treatment. Water Research 43:695-705.

Levenspiel, O. (1999) Chemical reaction engineering. 3rd edition. John Wiley & sons. New York.

Longhurst R.D., Roberts A.H.C., O'Connor M.B. (2000) Farm dairy effluent: A review of published data on chemical and physical characteristics in New Zealand. New Zealand Journal of Agricultural Research 43:7-14.

Luo J., Tillman R.W., Ball P.R. (1999) Factors regulating denitrification in a soil under pasture. Soil Biology and Biochemistry 31:913-927.

Majer Newman J., Clausen J.C., Neafsey J.A. (1999) Seasonal performance of a wetland constructed to process dairy milkhouse wastewater in Connecticut. Ecological Engineering 14:181-198.

Mander Ü., Lõhmus K., Teiter S., Mauring T., Nurk K., Augustin J. (2008) Gaseous fluxes in the nitrogen and carbon budgets of subsurface flow constructed wetlands. Science of the Total Environment 404:343-353.

Mantovi P., Marmiroli M., Maestri E., Tagliavini S., Piccinini S., Marmiroli N. (2003) Application of a horizontal subsurface flow constructed wetland on treatment of dairy parlor wastewater. Bioresource Technology 88:85-94.

Martínez-Suller L., Provolo G., Carton O.T., Brennan D., Kirwan L., Richards K.G. (2010) The composition of dirty water on dairy farms in Ireland. Irish Journal of Agricultural and Food Research 49:67-80.

Mason I.G. (1997) Performance of a facultative waste stabilization pond treating dairy shed wastewater. Transactions of the American Society of Agricultural Engineers 40:211-218.

Mawdsley J.L., Bardgett R.D., Merry R.J., Pain B.F., Theodorou M.K. (1995) Pathogens in livestock waste, their potential for movement through soil and environmental pollution. Applied Soil Ecology 2:1-15.

McDowell R.W., Wilcock R.J. (2007) Sources of sediment and phosphorus in stream flow of a highly productive dairy farmed catchment. Journal of Environmental Quality 36:540-548.

McGarvey J.A., Miller W.G., Zhang R., Ma Y., Mitloehner F. (2007) Bacterial population dynamics in dairy waste during aerobic and anaerobic treatment and subsequent storage. Applied and Environmental Microbiology 73:193-202.

McKay G., Poots V.J.P. (1980) Kinetics and diffusion processes in colour removal from effluent using wood as an adsorbent. Journal of Chemical Technology and Biotechnology 30:279-292.

Mikkelsen, R.L., and J.W. Gilliam. (1996) Animal waste management and edge of field losses. p. 57–68. In: K. Steele (ed.) Animal waste and the land–water interface. CRC–Lewis, Boca Raton, FL.

Miller, A. J., Cramer, M. D. (2005) Root nitrogen acquisition and assimilation. Plant and Soil, 274(1-2): 1-36.

Mingoue, D., Coughlan, F., Murphy, P., French, P., Bolger, T. (2010) Characterisation of soiled water on Irish dairy farms. BSAS/WPSA/Agricultural Research Forum Conference. Queen's University, Belfast. 12-14 April, 2010.

Morgan J.A., Martin J.F. (2008) Performance of an ecological treatment system at three strengths of dairy wastewater loading. Ecological Engineering 33:195-209.

Mosier A.R., Doran J.W., Freney J.R. (2002) Managing soil denitrification. Journal of Soil and Water Conservation 57:505-513.

Mulqueen, J, Rodgersm M., O'Leary, G., Carty, G. (2000). Wastewater treatment manuals – treatment systems for single houses. Environmental Protection Agency, Wexford, Ireland

Mulqueen J., Rodgers M., Scally P. (2004) Phosphorus transfer from soil to surface waters. Agricultural Water Management 68:91-105.

Nag A. (1995) Utilization of charred sawdust as an adsorbent of dyes, toxic salts and oil from water. Process Safety and Environmental Protection: Transactions of the Institution of Chemical Engineers, Part B 73:299-306.

Nakhla G., Farooq S. (2003) Simultaneous nitrification-denitrification in slow sand filters. Journal of Hazardous Materials 96:291-303.

Nguyen L.M. (2000) Organic matter composition, microbial biomass and microbial activity in gravel-bed constructed wetlands treating farm dairy wastewaters. Ecological Engineering 16:199-221.

Nichols D.J., Wolf D.C., Gross M.A., Rutledge E.M. (1997) Renovation of septic effluent in a stratified sand filter. ASTM Special Technical Publication 1324:235-247.

O'Driscoll K., Boyle L., French P., Hanlon A. (2008) The effect of out-wintering pad design on hoof health and locomotion score of dairy cows. Journal of Dairy Science 91:544-553.

OECD/FAO. (2009) Agricultural outlook 2009 – 2018. Available at: http://www.agri-outlook.org/dataoecd/2/31/43040036.pdf. (Verified 30 Nov.2010)

Owens J.D., Evans M.R., Thacker F.E. (1973) Aerobic treatment of piggery waste. Water Research 7:1745-1766.

Pachauri R.K., Reisinger A. (2007) IPCC Fourth Assessment Report: Climate Change 2007. Contribution of Working Groups I, II and III to the fourth assessment report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland. pp 104

Paredes D., Kuschk P., Mbwette T.S.A., Stange F., Müller R.A., Köser H. (2007) New aspects of microbial nitrogen transformations in the context of wastewater treatment - A review. Engineering in Life Sciences 7:13-25.

Peng Y., Zhu G. (2006) Biological nitrogen removal with nitrification and denitrification via nitrite pathway. Applied Microbiology and Biotechnology 73:15-26.

Petersen S.O., Sommer S.G., Béline F., Burton C., Dach J., Dourmad J.Y., Leip A., Misselbrook T., Nicholson F., Poulsen H.D., Provolo G., Sørensen P., Vinnerås B., Weiske A., Bernal M.P., Böhm R., Juhász C., Mihelic R. (2007) Recycling of livestock manure in a whole-farm perspective. Livestock Science 112:180-191.

Pidwirny, M. (2006). The Nitrogen Cycle. Fundamentals of Physical Geography, 2nd Edition. 18th November 2010.
http://www.physicalgeography.net/fundamentals/9s.html

Prochaska C.A., Zouboulis A.I. (2003) Performance of intermittently operated sand filters: A comparable study, treating wastewaters of different origins. Water, Air, and Soil Pollution 147:367-388.

Reed S.C., Brown D. (1995) Subsurface flow wetlands - A performance evaluation. Water Environment Research 67:244-248.

Reed, S.C., Crites, R.W., Middlebrooks, E.J. (1995) Natural systems for waste management and treatment. McGraw-Hill Professional; 1 edition New York. **P**p 428

Regan, J.T., Rodgers, M., Healy, M.G., Kirwan, L., Fenton, O. (2010) Determining phosphorus and sediment release rates from five Irish tillage soils. Journal of Environmental Quality 39:185-192.

Reynolds C.S., Davies P.S. (2001) Sources and bioavailability of phosphorus fractions in freshwaters: A British perspective. Biological Reviews of the Cambridge Philosophical Society 76:27-64.

Rice R.C. (1974) Soil Clogging during Infiltration of Secondary Effluent. Journal (Water Pollution Control Federation) 46:708-716.

Robertson W.D., Cherry J.A. (1995) In situ denitrification of septic system nitrate using reactive porous media barriers - Field trials. Ground Water 33:99-111.

Robertson W.D., Cherry J.A. (1997) Long-term performance of the Waterloo denitrification barrier. Land Contamination and Reclamation 5:183-188.

Robertson W.D., Blowes D.W., Ptacek C.J., Cherry J.A. (2000) Long-term performance of in situ reactive barriers for nitrate remediation. Ground Water 38:689-695.

Rodgers M., Mulqueen J., Healy M.G. (2004) Surface clogging in an intermittent stratified sand filter. Soil Science Society of America Journal 68:1827-1832.

Rodgers M., Healy M.G., Mulqueen J. (2005) Organic carbon removal and nitrification of high strength wastewaters using stratified sand filters. Water Research 39:3279-3286.

Rolland L., Molle P., Liénard A., Bouteldja F., Grasmick A. (2009) Influence of the physical and mechanical characteristics of sands on the hydraulic and biological behaviors of sand filters. Desalination 248:998-1007.

Ruane, E., Murphy, P., Clifford. E., O'Reilly, E., French. P., Rodgers. M. (In review) Treatment of dairy soiled water using a woodchip filter. Journal of Environmental Management

Russell J.M., Cooper R.N., Lindsey S.B. (1993) Soil denitrification rates at wastewater irrigation sites receiving primary-treated and anaerobically treated meat-processing effluent. Bioresource Technology 43:41-46.

Russell J.S., Middlebrooks E.J., Lewis R.F., Barth E.F. (1983) Lagoon effluent polishing with intermittent sand filters. Journal of Environmental Engineering 109:1333-1353.

Ryan, M., (1990) Properties of different grades of soiled water and strategies for safe disposal. Environmental Impact of Landspreading of Wastes. In: Proceedings of the Symposium Held at Johnstown Castle Centre for Soils and Environmental Research and Development, Co. Wexford, Ireland, May 30–31, 1990. pp. 43–58.

Saliling W.J.B., Westerman P.W., Losordo T.M. (2007) Wood chips and wheat straw as alternative biofilter media for denitrification reactors treating aquaculture and other wastewaters with high nitrate concentrations. Aquacultural Engineering 37:222-233.

Sarkar B., Chakrabarti P.P., Vijaykumar A., Kale V. (2006) Wastewater treatment in dairy industries - possibility of reuse. Desalination 195:141-152.

Sauer D.K., Boyle W.C., Otis R.J. (1976) Intermittent sand filtration of household wastewater. J.ENVIRONM.ENGNG DIV.ASCE 102:789-803.

Schaafsma J.A., Baldwin A.H., Streb C.A. (1999) An evaluation of a constructed wetland to treat wastewater from a dairy farm in Maryland, USA. Ecological Engineering 14:199-206.

Schelde K., De Jonge L.W., Kjaergaard C., Laegdsmand M., Rubæk G.H. (2006) Effects of manure application and plowing on transport of colloids and phosphorus to tile drains. Vadose Zone Journal 5:445-458.

Scherer M.M., Richter S., Valentine R.L., Alvarez P.J.J. (2000) Chemistry and microbiology of permeable reactive barriers for in situ groundwater clean up. Critical Reviews in Microbiology 26:221-264.

Schijven J.F., Bradford S.A., Yang S., Brown Jr G.E. (2004) Release of Cryptosporidium and Giardia from dairy cattle manure: Physical factors. Journal of Environmental Quality 33:1499-1508.

Schipper L., Vojvodic-Vukovic M. (1998) Nitrate removal from groundwater using a denitrification wall amended with sawdust: Field trial. Journal of Environmental Quality 27:664-668.

Schipper L.A., Vojvodic-Vukovic M. (2000) Nitrate removal from groundwater and denitrification rates in a porous treatment wall amended with sawdust. Ecological Engineering 14:269-278.

Schipper L.A., Vojvodic-Vukovic M. (2001) Five years of nitrate removal, denitrification and carbon dynamics in a denitrification wall. Water Research 35:3473-3477.

Schwager A., Boller M. (1997) Transport phenomena in intermittent filters. Water Science and Technology. pp. 13-20.

Shafqat M.N., Pierzynski G.M. (2010) Long-term effects of tillage and manure applications on soil phosphorus fractions. Communications in Soil Science and Plant Analysis 41:1084-1097.

Sharpley A.N. (1997) Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. Journal of Environmental Quality 26:1127-1132.

Siegrist R.L., Boyle W.C. (1987) Wastewater-induced soil clogging development. Journal of Environmental Engineering 113:550-566.

Silva R.G., Cameron K.C., Di H.J., Hendry T. (1999) A lysimeter study of the impact of cow urine, dairy shed effluent, and nitrogen fertiliser on nitrate leaching. Australian Journal of Soil Research 37:357-369.

Silva R.G., Cameron K.C., Di H.J., Jorgensen E.E. (2005) A lysimeter study to investigate the effect of dairy effluent and urea on cattle urine N losses, plant uptake and soil retention. Water, Air, and Soil Pollution 164:57-78.

Sims J.T., Edwards A.C., Schoumans O.F., Simard R.R. (2000) Integrating soil phosphorus testing into environmentally based agricultural management practices. Journal of Environmental Quality 29:60-71.

Singleton P.L., McLay C.D.A., Barkle G.F. (2001) Nitrogen leaching from soil lysimeters irrigated with dairy shed effluent and having managed drainage. Australian Journal of Soil Research 39:385-396.

Soares M.I.M., Braester C., Belkin S., Abeliovich A. (1991) Denitrification in laboratory sand columns: carbon regime, gas accumulation and hydraulic properties. Water Research 25:325-332.

Søvik A.K., Kløve B. (2005) Phosphorus retention processes in shell sand filter systems treating municipal wastewater. Ecological Engineering 25:168-182.

Soupir M.L., Mostaghimi S., Yagow E.R. (2006) Nutrient transport from livestock manure applied to pastureland using phosphorus-based management strategies. Journal of Environmental Quality 35:1269-1278.

Stevik T.K., Aa K., Ausland G., Hanssen J.F. (2004) Retention and removal of pathogenic bacteria in wastewater percolating through porous media: A review. Water Research 38:1355-1367.

Sukias J.P.S., Tanner C.C., Davies-Colley R.J., Nagels J.W., Wolters R. (2001) Algal abundance, organic matter, and physico-chemical characteristics of dairy farm facultative ponds: Implications for treatment performance. New Zealand Journal of Agricultural Research 44:279-296.

Tanner C.C., Clayton J.S., Upsdell M.P. (1995) Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands--II. Removal of nitrogen and phosphorus. Water Research 29:27-34.

Tchobanoglous, R.C.G. (1998). Small and Decentralized Wastewater Management Systems McGraw-Hill Science/Engineering/Math; 1 edition (April 2, 1998) Singapore.

Teagasc Forestry Development Unit. (2007) A road map for the farm forestry sector to 2015.

Toner P F, Bowman J J, Clabby K J, Lucey J, McGarrigle M L, Concannon C, Clenaghan P, Cunnningham P, Delaney J, O’Boyle S, MacCarthaigh M, Craig M and Quinn R (2005) Water Quality in Ireland 2001–03. Wexford, Ireland: Environmental Protection Agency. www.epa.ie. Dublin, Ireland: EPA Publications Office.

Toor G.S., Condron L.M., Di H.J., Cameron K.C., Sims J.T. (2004) Impact of farm-dairy effluent application on the amounts and forms of phosphorus loss by leaching from irrigated grassland. New Zealand Journal of Agricultural Research 47:479-490.

Torrens A., Molle P., Boutin C., Salgot M. (2009a) Impact of design and operation variables on the performance of vertical-flow constructed wetlands and intermittent sand filters treating pond effluent. Water Research 43:1851-1858.

Torrens A., Molle P., Boutin C., Salgot M. (2009b) Removal of bacterial and viral indicator in vertical flow constructed wetlands and intermittent sand filters. Desalination 246:169-178.

Toth J.D., Dou Z., Ferguson J.D., Galligan D.T., Ramberg C.F., Jr. (2006) Nitrogen- vs. Phosphorus-based Dairy Manure Applications to Field Crops: Nitrate and Phosphorus Leaching and Soil Phosphorus Accumulation. J Environ Qual 35:2302-2312.

Truu M., Juhanson J., Truu J. (2009) Microbial biomass, activity and community composition in constructed wetlands. Science of the Total Environment 407:3958-3971.

Tshabalala M.A., Tshabalala K.G., Karthikeyan D.W. (2004) Cationized milled pine bark as an adsorbent for orthophosphate anions. Journal of Applied Polymer Science 93:1577-1583.

Unwin R.J., Pain B.F., Whinham W.N. (1986) The effect of rate and time of application of nitrogen in cow slurry on grass cut for silage. Agricultural Wastes 15:253-268.

U.S. Environmental Protection Agency. (1993a) Manual nitrogen control. Office of research and development. Office of Water, Washington D.C.

U.S. Environmental Protection Agency. (1993b) Subsurface Flow Constructed Wetlands for Waste Water Treatment A Technology Assessment. Office of Water, Washington D.C.

U.S. Environmental Protection Agency. (1995) Handbook of Constructed Wetlands: General Considerations: Volume 1. USDA-Natural Resources Conservation Service and the US Environmental Protection Agency-Region III, in cooperation with the Pennsylvania Department of Environmental Resources

USEPA (1999) Wastewater Technology Fact Sheet Intermittent Sand Filters. Office of Water, Washington D.C.

Vadas P.A., Kleinman P.J.A., Sharpley A.N., Turner B.L. (2005) Relating soil phosphorus to dissolved phosphorus in runoff: A single extraction coefficient for water quality modeling. Journal of Environmental Quality 34:572-580.

Vinten A.J.A., Donnelly S., Ball B.C., Crawford C.E., Ritchie R.M., Parker J.P. (2006) A field trial to evaluate the pollution potential to ground and surface waters from woodchip corrals for overwintering livestock outdoors. Soil Use and Management 22:82-94.

Vohla C., Kõiv M., Bavor H.J., Chazarenc F., Mander Ü. (*In Press*) Filter materials for phosphorus removal from wastewater in treatment wetlands--A review. Ecological Engineering In Press, Corrected Proof.

Von Wirén N., Gazzarrini S., Frommer W.B. (1997) Regulation of mineral nitrogen uptake in plants. Plant and Soil. 196:191-199.

Wahab M.A., Jellali S., Jedidi N. (2010) Ammonium biosorption onto sawdust: FTIR analysis, kinetics and adsorption isotherms modeling. Bioresource Technology 101:5070-5075.

Wanko A., Mose R., Beck C. (2005) Biological processing capacities and biomass growth in waste water treatment by infiltration on two kinds of sand. Water, Air, and Soil Pollution 165:279-299.

Wang H., Magesan G.N., Bolan N.S. (2004) An overview of the environmental effects of land application of farm effluents. New Zealand Journal of Agricultural Research 47:389-403.

Water Environment Federation (1998) pp. 69–73. Biological and chemical systems for nutrient removal. Alexandria, VA.

WHO (2006) Guidelines for drinking-water quality, Recommendations. 1:3. WHO, Geneva, Switzerland.

Wilcock R.J., Betteridge K., Shearman D., Fowles C.R., Scarsbrook M.R., Thorrold B.S., Costall D. (2009) Riparian protection and on-farm best management practices for restoration of a lowland stream in an intensive dairy farming catchment: A case study. New Zealand Journal of Marine and Freshwater Research 43:803-818.

Withers P.J.A., Lord E.I. (2002) Agricultural nutrient inputs to rivers and groundwaters in the UK: Policy, environmental management and research needs. Science of the Total Environment 282-283:9-24.

Wood J., Fernandez G., Barker A., Gregory J., Cumby T. (2007) Efficiency of reed beds in treating dairy wastewater. Biosystems Engineering 98:455-469.

World Bank Group (1998) Pollution prevention and abatement handbook, 1998 : toward cleaner production / The World Bank Group in collaboration with United Nations Industrial Development Organization, United Nations Environment Programme: Nitrogen oxides. Washington DC, USA.

Xie Y., Biswas N., Bewtra J.K. (1999) Nitrification and denitrification in water and soil environments. International Journal of Environmental Studies 56:451-474.

Yates C.R., Prasher S.O. (2009) Phosphorus reduction from agricultural runoff in a pilot-scale surface-flow constructed wetland. Ecological Engineering 35:1693-1701.

Ying C., Umetsu K., Ihara I., Sakai Y., Yamashiro T. (2010) Simultaneous removal of organic matter and nitrogen from milking parlor wastewater by a magnetic activated sludge (MAS) process. Bioresource Technology 101:4349-4353.

Yu B., Zhang Y., Shukla A., Shukla S.S., Dorris K.L. (2001) The removal of heavy metals from aqueous solutions by sawdust adsorption - Removal of lead and comparison of its adsorption with copper. Journal of Hazardous Materials 84:83-94.

Zaman M., Di H.J., Cameron K.C. (1999) A field study of gross rates of N mineralization and nitrification and their relationships to microbial biomass and enzyme activities in soils treated with dairy effluent and ammonium fertilizer. Soil Use and Management 15:188-194.

Zaman M., Cameron K.C., Di H.J., Inubushi K. (2002) Changes in mineral N, microbial biomass and enzyme activities in different soil depths after surface applications of dairy shed effluent and chemical fertilizer. Nutrient Cycling in Agroecosystems 63:275-290.

Zebarth B.J., Paul J.W., Van Kleeck R. (1999) The effect of nitrogen management in agricultural production on water and air quality: Evaluation on a regional scale. Agriculture, Ecosystems and Environment 72:35-52.

Zhao L., Zhu W., Tong W. (2009) Clogging processes caused by biofilm growth and organic particle accumulation in lab-scale vertical flow constructed wetlands. Journal of Environmental Sciences 21:750-757.

Appendices

Appendix 1 – Results from the laboratory-scale woodchip filter experiment

Table A.1 Results for COD_T for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

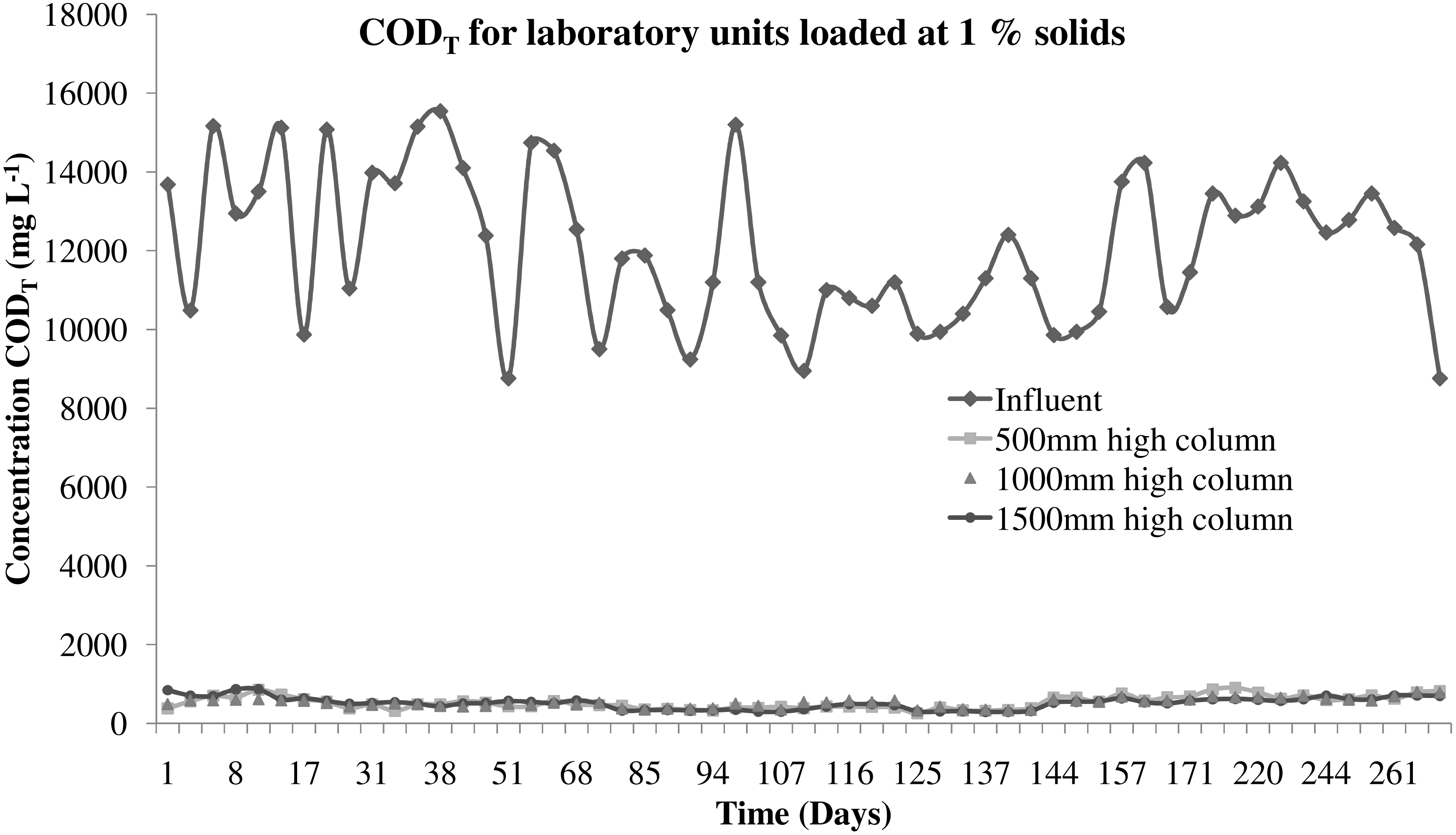
Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008	13680	382	380		381	445	457	572	491	1014	757	756	842
3	18/06/2008	10485	457	715	502	558	513	648	595	585	783	630		707
5	20/06/2008	15165		723	678	701	637	486	629	584	712	685	681	693
8	23/06/2008	12945	659	762	567	663	781	483	535	600	985	950	659	865
10	25/06/2008	13500	832	981	737	850	672	608	560	613	985	950	659	865
15	30/06/2008	15120	720	844	624	729	562	651	541	585	653	551		602
17	02/07/2008	9870	535	657	649	614	593	589	541	574	628	572	703	634
19	04/07/2008	15075	459	600	577	545	537	540	464	514	558	554	587	566
24	09/07/2008	11040	312	421	410	381	437	435	403	425	473	507	501	494
31	16/07/2008	13980	304	590	552	482	432	492	484	469	574	490	479	514
33	18/07/2008	13710	47	550	354	317	430	423	662	505	606	498	505	536
36	21/07/2008	15150	383	488	573	481	543	421	503	489	577	470	438	495
38	23/07/2008	15540	389	535	524	483	415	451	470	445	497	426	368	430
40	25/07/2008	14100	344	744	592	560	384	402	495	427	618	440	455	504
43	28/07/2008	12380	411	628	538	526	376	434	511	440	615	453	472	513
51	05/08/2008	8760	591	293	403	429	547	490	462	500	655	431	613	566
57	11/08/2008	14740	591	293	403	429	452	490	462	468	655	431		543
64	18/08/2008	14540	471	604	637	571	479	567	531	526	607	463	459	510
68	22/08/2008	12540	406	466	548	473	467	526	462	485	817	462	473	584
74	28/08/2008	9500	384	443	560	462	536	523	514	524	569	471	459	500
80	03/09/2008	11800	372	530		451	419	373	344	379	363	315	293	324
85	08/09/2008	11880	299	448	320	356	287	455	316	353	290	376	331	332
88	11/09/2008	10490	434	338	336	369	329	455	362	382	319	328	371	339
92	15/09/2008	9240	320	341	359	340	376	391	373	380	301	321	359	327
94	17/09/2008	11200	270	344	372	329	470	391	283	381	319	306	371	332
96	19/09/2008	15200	376	369	443	396	625	428	457	503	326	320	398	348
99	22/09/2008	11200	419	498	272	396	599	424	321	448	307	276	303	295

Table A.2 Results for COD_T for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
107	29/09/2008	9850	461	485	303	416	342	396	319	352	294	269	317	293
111	03/10/2008	8950	356	324	475	385	411	421	796	543	445	285	341	357
114	06/10/2008	11000	412	365	495	424	453	462	684	533	512	369	415	432
116	08/10/2008	10800	456	385	425	422	463	584	699	582	555	412	495	487
121	13/10/2008	10600	462	371	411	415	429	524	666	540	513	523	420	485
123	15/10/2008	11200	422	360	411	398	502	590	655	582	466	486	442	465
125	17/10/2008	9890	241	259	262	254	290	304	394	329	305	315	284	301
128	20/10/2008	9940	377	452	364	398	357	458	460	425	294	314	293	300
136	28/10/2008	10400	296	319	374	330	319	328	441	363	318	336	273	309
137	29/10/2008	11300	318	309	327	318	386	354	315	352	300	307	263	290
139	31/10/2008	12400	309	327	386	341	315	365	315	332	300	307	263	290
142	03/11/2008	11300	397	367	389	384	372	280	396	349	299	346	304	316
144	05/11/2008	9860	664	574	727	655	609	497	721	609	499	571	508	526
149	10/11/2008	9940	697	575	684	652	592	523	614	576	513	529	595	546
153	14/11/2008	10450	419	701	523	548	545	601	499	548	597	564	501	554
157	18/11/2008	13750	684	759	823	755	614	695	725	678	695	621	599	638
160	21/11/2008	14230	543	614	593	583	568	592	536	565	586	523	499	536
163	24/11/2008	10570	678	592	698	656	584	487	657	576	514	513	493	507
171	02/12/2008	11450	723	612	714	683	612	514	699	608	610	594	523	576
198	29/12/2008	13450	690	956	939	862	534	750	777	687	655	586	587	609
206	06/01/2009	12890	740	824	1142	902	560	771	667	666	674	609	576	620
220	20/01/2009	13120	604	723	1024	784	532	744	717	664	626	587	576	596
230	30/01/2009	14230	644	596	647	629	535	703	718	652	568	577	563	569
240	09/02/2009	13250	643	770	711	708	545	851	713	703	630	599	605	611
244	13/02/2009	12460	529	641	597	589	623	714	526	621	599	624	891	705
249	18/02/2009	12780	540	642	663	615	556	678	567	600	575	617	653	615
254	24/02/2009	13450	722	699	701	707	533	487	722	581	540	598	682	607

Table A.2 Results for COD_T for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
261	02/03/2009	12580	694	596	579	623	723	785	564	691	682	718	715	705
272	13/03/2009	12162	841	771	752	788	653	861	878	797	610	707	801	706
277	18/03/2009	8760	923	714	823	820	723	799	823	782	692	610	792	698



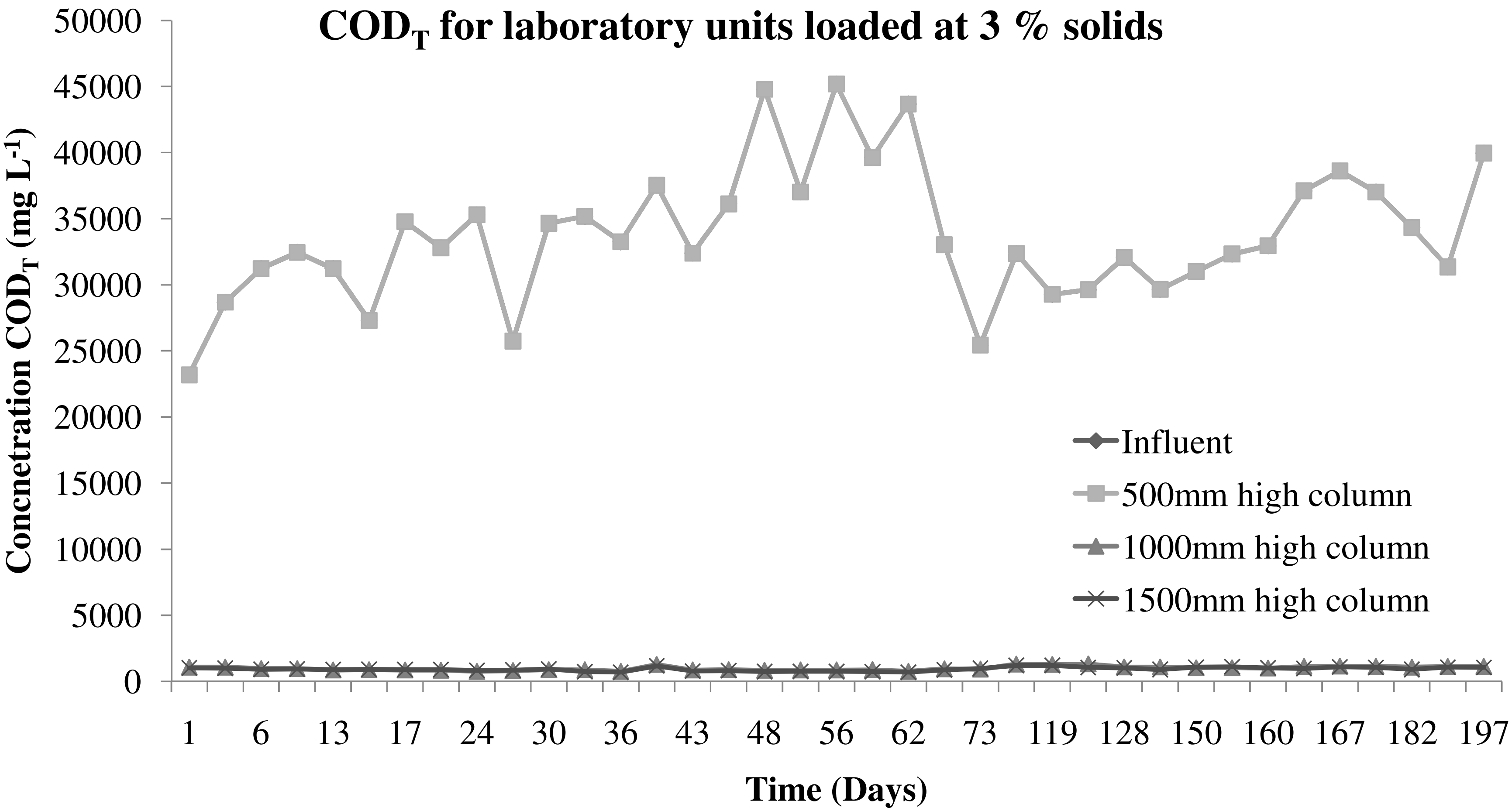
COD$_T$ for laboratory units loaded at 1 % solids
Concentration COD$_T$ (mg L^{-1})
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
1
8
17
31
38
51
68
85
94
107
116
125
137
144
157
171
220
244
261
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.3 Results for COD_T for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	23190	760	856	884	833	1130	1156	923	1070	1201	909	955	1022
3	05/09/2008	28680	908	914	958	927	1107	1224	899	1077	1134	855	1001	997
6	08/09/2008	31220	730	729	772	744	1056	1052	790	966	1025	831	884	913
9	11/09/2008	32460	690	717	841	749	1047	1025	843	972	1080	834	906	940
13	15/08/2008	31220	635	646	708	663	925	931	733	863	1000	796	884	893
15	17/08/2008	27300	630	629	708	656	982	961	728	890	1040	893	810	914
17	19/08/2008	34775	579	661	719	653	969	962	660	864	1053	759	870	894
20	22/08/2008	32800	625	592	718	645	921	968	658	849	1053	777	867	899
24	26/08/2008	35300	574	505	605	561	808	861	600	756	1000	704	810	838
27	29/08/2008	25750	537	570	654	587	857	916	690	821	971	743	872	862
30	02/10/2008	34650	596	549	647	597	962	1021	673	885	1101	819	874	931
34	06/10/2008	35175	692	663	699	685	1063	933	653	883	934	632	642	736
36	08/10/2008	33250	669	594	702	655	826	822	635	761	880	599	592	690
41	13/10/2008	37530	1148	1017	1198	1121	1447	1321	1068	1279	1498	1018	1022	1179
43	15/10/2008	32400	674	557	661	631	972	982	635	863	992	639	705	779
45	17/10/2008	36120	686	608	711	668	979	1102	596	892	1029	676	733	813
48	20/10/2008	44790	661	547	646	618	979	901	630	837	946	612	671	743
55	28/10/2008	37020	658	542	684	628	1016	929	638	861	941	644	677	754
56	29/10/2008	45180	717	672	690	693	1021	915	658	865	940	639	666	748
59	31/10/2008	39630	692	663	699	685	1063	933	653	883	934	632	642	736
62	03/11/2008	43680	669	594	702	655	826	822	635	761	880	599	592	690
64	05/11/2008	31750	1148	1017	1198	1121	1447	1321	1068	1279	1498	1018	1022	1179
66	07/11/2008	34125	926	1001	876	934	979	1011	986	992	1032	923	897	951
69	10/11/2008	33025	824	913	902	880	1001	965	897	954	962	875	807	881

Table A.4 Results for COD_T for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
73	14/11/2008	25450	921	724	1001	882	932	897	945	925	999	1007	945	984
83	24/11/2008	32375	1077	1005	1204	1095		1439	1175	1307	1454	1165	1038	1219
119	29/12/2008	29275	979	862	1024	955	1516	1314	996	1275	1370	1205	1055	1210
126	06/01/2009	29625	795	444	892	710	1366	1272	1324	1321	934	1155	1062	1050
128	08/01/2009	32075	865	784	903	851	1241	1143	877	1087	1174	984	908	1022
140	20/01/2009	29650	844	749	928	840	1301	1094	870	1088	923	921	869	904
150	30/01/2009	31000	723	841	821	795	1142	1011	929	1027	998	1101	1096	1065
154	03/02/2009	32325	803	766	888	819	1246	957	881	1028	1158	1130	1043	1110
160	09/02/2009	32950	798	823	875	832	1212	943	854	1003	1208	920	914	1014
164	13/02/2009	37110	695	723	841	753	1194	1263	972	1143	1021	918	978	972
167	16/02/2009	38610	914	900	1044	953	1340	1118	996	1151	1181	1108	983	1091
175	24/02/2009	37020	923	945	1001	956	1388	1062	983	1144	1189	1009	955	1051
182	02/03/2009	34320	954	1001	932	962	1210	985	1010	1068	875	901	942	906
192	13/03/2009	31350	970	992	1158	1040	1298	1098	1017	1138	1208	1036	987	1077
197	18/03/2009	39960	984	985	1001	990	1198	1101	1098	1132	1110	1042	990	1047



COD$_T$ for laboratory units loaded at 3 % solids
Concnetration COD$_T$ (mg L^{-1})
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
1
6
13
17
24
30
36
43
48
56
62
73
119
128
150
160
167
182
197
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.5 Results for COD_F for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008	1160					397	432	524	451				
3	18/06/2008	990					732	502	610	615				
10	25/06/2008	1160					640	513	547	567				
15	30/06/2008	1600	745	695	597	679	559	624	561	581	601	567		584
17	02/07/2008	2100	507	608	600	572	584	582	538	568	655	576	667	633
33	18/07/2008	1120	399	446	441	429	424	408	585	472	571	467	522	520
40	25/07/2008	1200	389	552	568	503	406	420	485	437	528	459	446	478
64	18/08/2008	1900	460	539	560	520	474	548	530	517	598	467	448	504
80	03/09/2008	1700	292	481		387	401	354	339	365	360	311	292	321
88	11/09/2008	1980	431	334	337	367	327	413	351	364	308	319	341	323
111	03/10/2008	1920	302	323	418	348	385	380	545	437	425	292	343	353
121	13/10/2008	2680	388	370	391	383	424	523	628	525	508		518	513
123	15/10/2008	2655	362	364	386	371	506	579	647	577	518	324	249	364
136	28/10/2008	2645	288	298	369	318	323	307	410	347	323	338	290	317
244	13/02/2009	2640	789	755	748	764	642	838	859	780	592	674	799	688
249	18/02/2009	2775	899	709	799	802	713	781	821	772	690	599	790	693

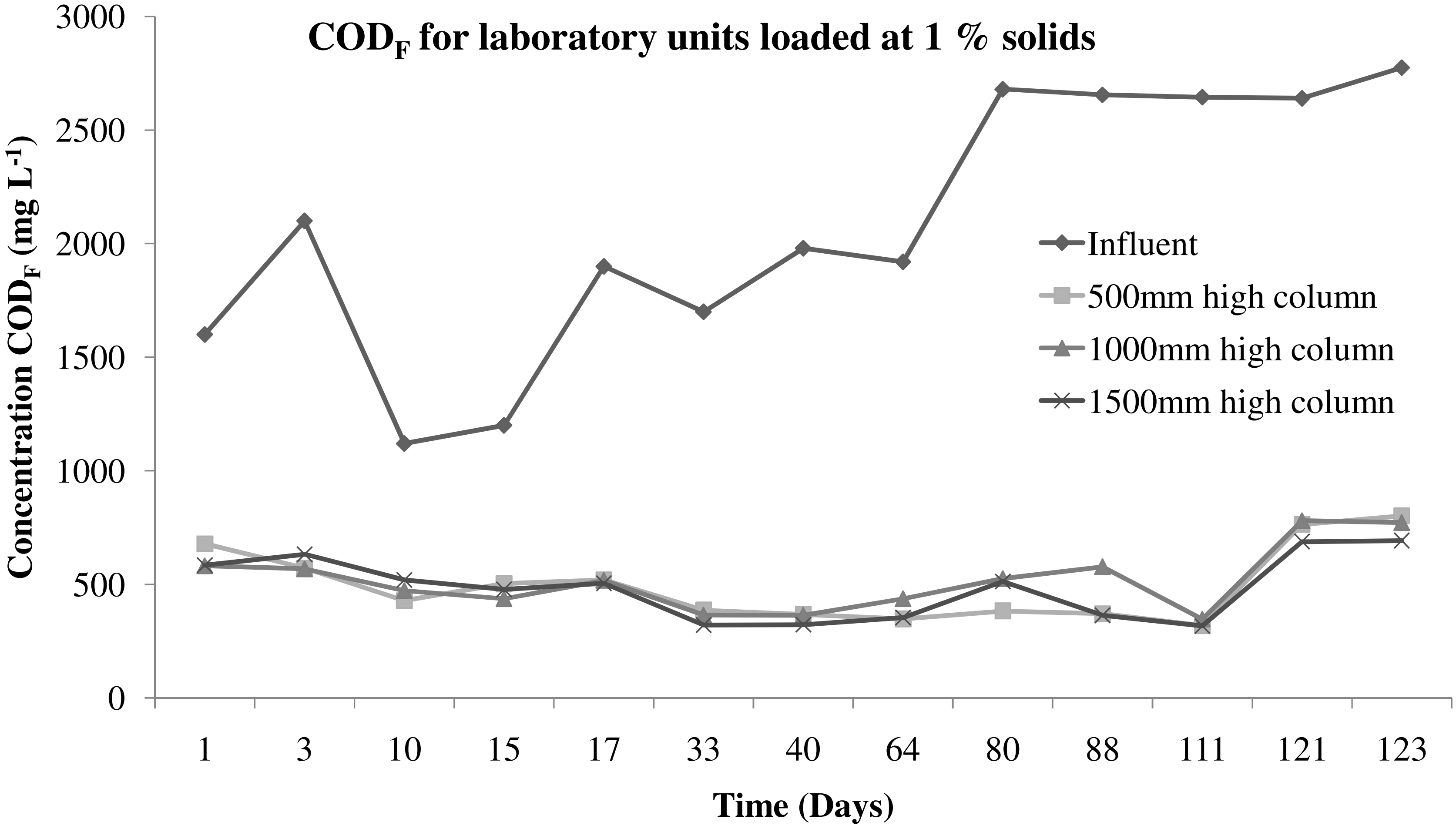

COD_F for laboratory units loaded at 1 % solids
Concentration COD_F (mg L^{-1})
3000
2500
2000
1500
1000
500
0
1
3
10
15
17
33
40
64
80
88
111
121
123
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.6 Results for COD_F for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	1700	702	804	837	781	1060	1132	935	1042	1023	932	980	978
9	11/09/2008	1715	606	677	768	684	928	960	793	894	950	829	870	883
13	15/09/2008	1715	510	595	687	597	871	879	725	825	950	812	835	866
30	02/10/2008	1655	468	516	617	534	887	943	715	848	1000	765	814	860
41	13/10/2008	1670	1116	999	1121	1079	1591	1029	962	1194	978	1016	1210	1068
43	15/10/2008	1680	600	569	632	600	901	948	698	849	928	692	714	778
55	28/10/2008	1710	613	548	655	605	966	910	663	846	925	672	667	755
62	03/11/2008	1680	594	587	689	623	935	822	650	802	848	631	612	697
83	24/11/2008	1700	1039	1004	1184	1076	1608	1445	1172	1408	1439	1131	1070	1213
119	29/12/2008	1665	893	863	1033	930	144	1268	1035	816	1351	1201	1073	1208
126	06/01/2009	1645	787	695	865	782	1305	1264	1274	1281	1147	1053	985	1062
128	08/01/2009	1670	695	759	860	771	1193	1075	872	1047	1123	980	907	1003
150	30/01/2009	1920	714	839	892	815	1021	936	941	966	871	923	899	898
154	03/02/2009	1930	693	753	972	806	1292	1123	1034	1150	1291	1149	1038	1159
164	13/02/2009	1880	629	714	832	725	1042	1161	937	1047	998	920	952	957
192	13/03/2009	2020	718	946	1133	932	1268	1122	983	1124	1212	936	966	1038
197	18/03/2009	1930	819	923	967	903	1007	998	1042	1016	989	934	984	969

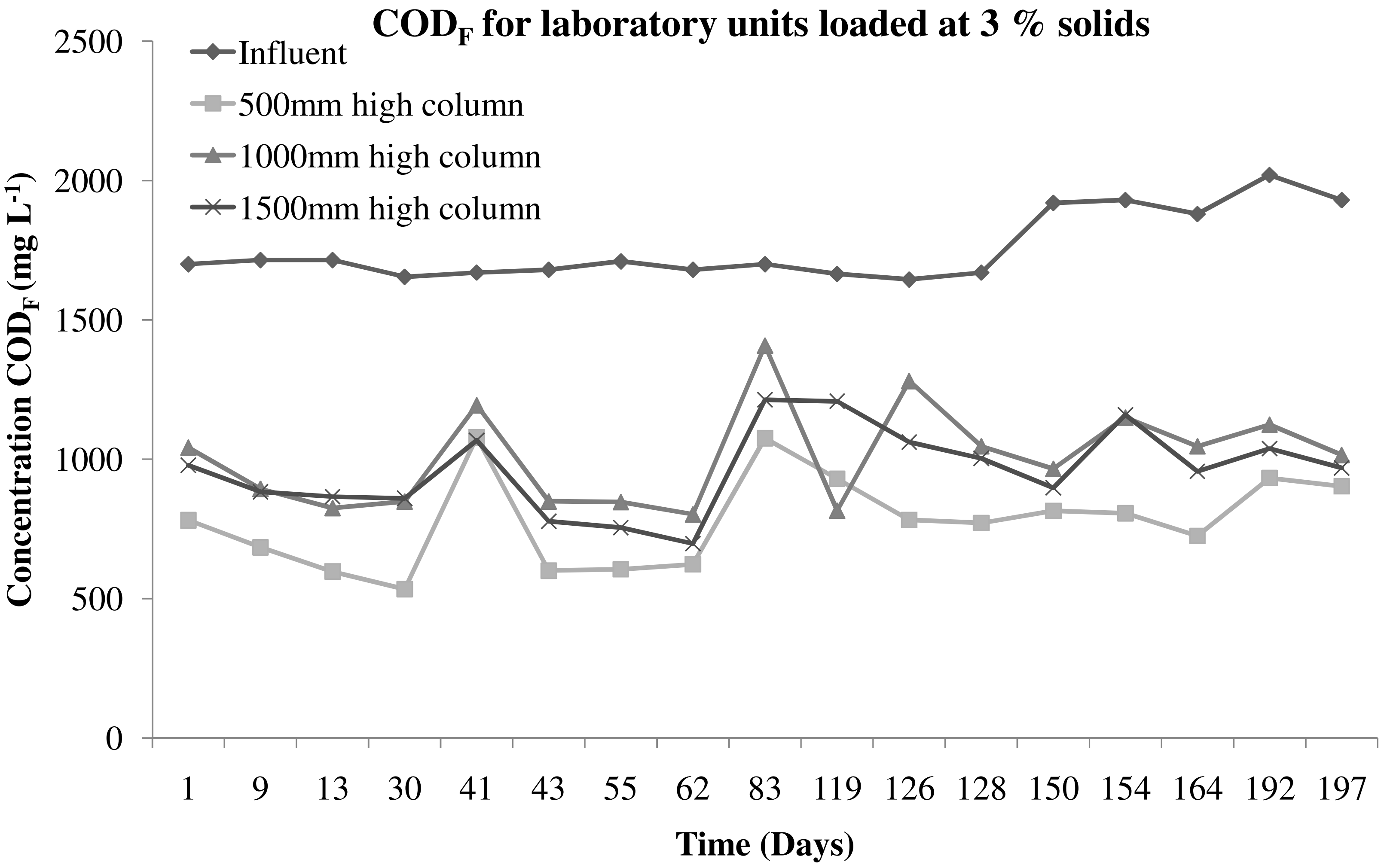
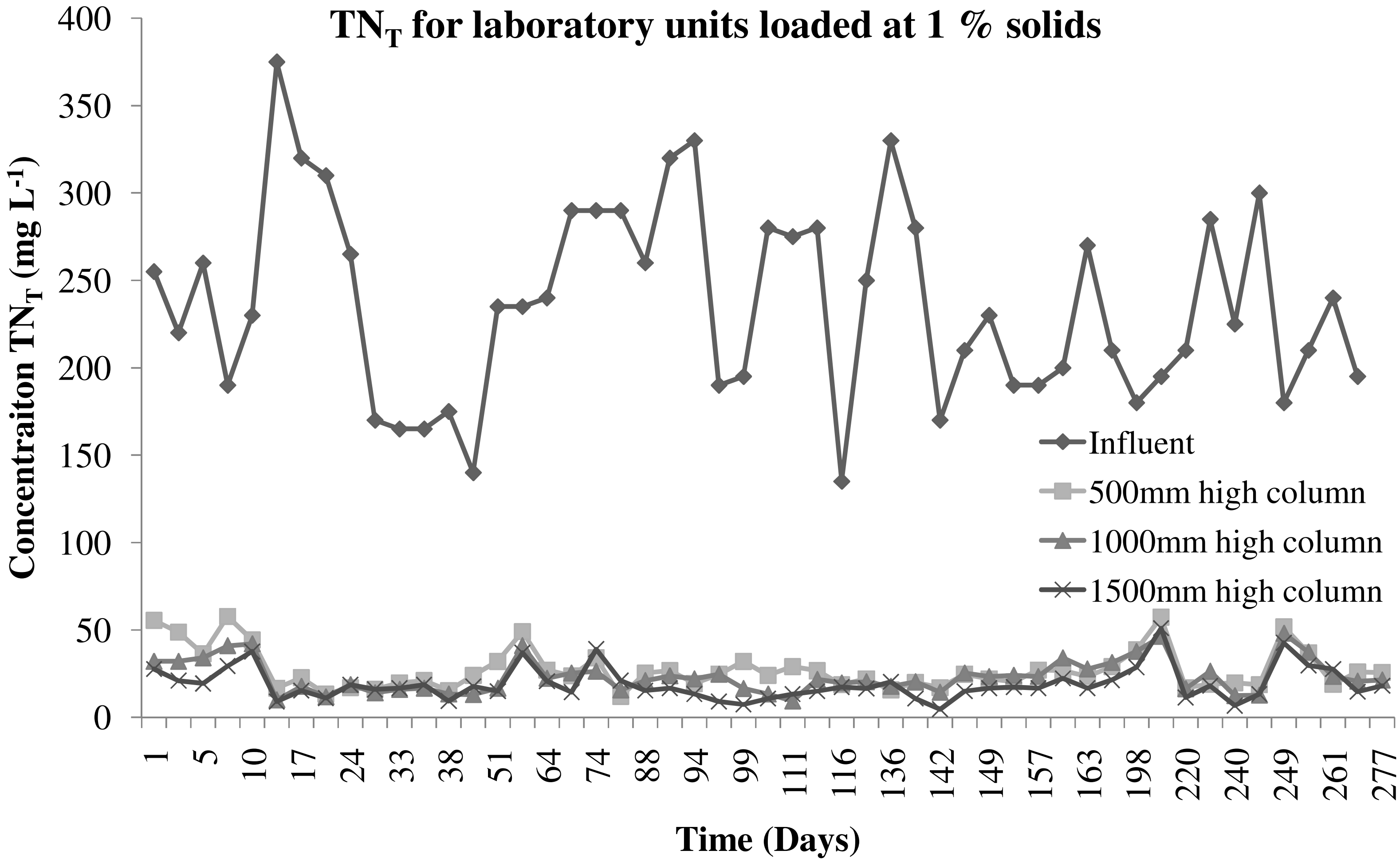

COD$_F$ for laboratory units loaded at 3 % solids
Influent
500mm high column
1000mm high column
1500mm high column
Concentration COD$_F$ (mg L^{-1})
2500
2000
1500
1000
500
0
1
9
13
30
41
43
55
62
83
119
126
128
150
154
164
192
197
Time (Days)

Table A.7 Results for TN_T for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008	255	49	62		56	29	36	31	32	30	31	22	28
3	18/06/2008	220	49	62	35	49	29	36	31	32	24	18		21
5	20/06/2008	260	30	41	38	36				34	21	17	20	19
8	23/06/2008	190	51	82	40	58				41	25	39	24	29
10	25/06/2008	230	39	48	46	44	41	46	39	42	30	44	39	38
15	30/06/2008	375	15	15	20	17	11	9	10	10	10	8		9
17	02/07/2008	320	26	18	24	23	16	20	17	18	15	15	16	15
19	04/07/2008	310	14	14	12	13	12	12	11	12	11	11	11	11
24	09/07/2008	265	14	18	19	17	18	17	21	19	16	27	13	19
31	16/07/2008	170	13	18	17	16	10	15	17	14	18	13	17	16
33	18/07/2008	165	19	19	21	20	13	12	23	16	18	14	18	17
36	21/07/2008	165	17	18	28	21	19	15	16	17	21	21	14	19
38	23/07/2008	175	13	15	18	15	12	15	13	13	8	9	11	9
40	25/07/2008	140	17	36	19	24	14	13	12	13	25	12	16	18
51	05/08/2008	235	24	35	37	32	19	16	15	17	20	13	12	15
57	11/08/2008	235	53	47	47	49	52	29	42	41	46	36	29	37
64	18/08/2008	240	27	29	25	27	20	22	25	22	26	19	17	21
68	22/08/2008	290	17	29	25	24	27	27	22	25	14	14	15	14
74	28/08/2008	290	40	29	33	34	26	27	26	26	67	28	22	39
85	08/09/2008	290	15	6	15	12	8	26	13	16	7	31	25	21
88	11/09/2008	260	47	19	10	25	20	31	12	21	12	13	21	15
92	15/09/2008	320	46	12	22	27	22	14	35	24	19	16	15	17
94	17/09/2008	330	14	22	22	19	36	15	15	22	18	13	9	13
96	19/09/2008	190	41	3	30	25	39	17	18	25	10	4	13	9
99	22/09/2008	195	27	62	7	32		20	13	17	10	7	5	7
107	29/09/2008	280	33	19	20	24	15	14	11	13	9	11	12	11
111	03/10/2008	275	24	27	36	29	10	7	11	9	26	5	9	13

Table A.8 Results for TN_T for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
114	06/10/2008	280	24	32	24	27	20	16	29	22	14	19	12	15
116	08/10/2008	135	18	17	21	19	17	18	24	20	17	20	15	17
121	13/10/2008	250	24	22	20	22	17	24	20	20	18		15	17
136	28/10/2008	330	10	18	19	16	11	18	24	18	23	25	13	20
137	29/10/2008	280	30	17	13	20	14	31	16	20	12	14	6	11
142	03/11/2008	170	18	14	19	17	14	15	14	14	5	5	4	5
144	05/11/2008	210	19	32	23	25	32	19	25	25	11	15	19	15
149	10/11/2008	230	18	29	19	22	24	25	21	23	14	19	17	17
153	14/11/2008	190	17	19	25	20	24	19	29	24	16	19	17	17
157	18/11/2008	190	21	29	31	27	17	29	24	23	14	17	19	17
160	21/11/2008	200	23	27	30	27	39	31	32	34	24	21	22	22
163	24/11/2008	270	17	29	24	23	31	25	27	28	19	14	17	17
171	02/12/2008	210	24	32	31	29	29	36	29	31	24	19	21	21
198	29/12/2008	180	36	41	39	39	39	37	37	38	33	25	28	29
206	06/01/2009	195	56	56	60	57	45	48	46	46	54	58	41	51
220	20/01/2009	210	14	19	18	17	10	23	16	16	11	14	9	11
230	30/01/2009	285	22	16	19	19	23	29	27	26	24	17	13	18
240	09/02/2009	225	26	20	13	20	12	13	12	12	7	6	7	7
244	13/02/2009	300	15	22	19	19	13	9	16	13	13	17	10	13
249	18/02/2009	180	47	54	54	52	50	49	45	48	32	38	58	43
254	24/02/2009	210	40	32	39	37	29	38	45	37	21	43	25	30
261	02/03/2009	240	18	17	22	19	24	25	21	23	26	30	27	28
272	13/03/2009	195	24	28	26	26	21	17	24	21	17	14	13	15
277	18/03/2009		23	28	26	26	21	24	19	21	19	17	18	18



TN_T for laboratory units loaded at 1 % solids
Concentraiton TN_T (mg L^{-1})
400
350
300
250
200
150
100
50
0
1
5
10
17
24
33
38
51
64
74
88
94
99
111
116
136
142
149
157
163
198
220
240
249
261
277
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.9 Results for TN_T for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	350	57	56	58	57	65	57	52	58	64	48	50	54
3	05/09/2008	480	60	79	70	70	62	66	38	55	59	47	60	55
6	08/09/2008	610	35	43	33	37	45	31	44	40	41	35	39	38
9	11/09/2008	650	49	39	37	42	40	27	31	33	39	34	33	35
13	15/08/2008	630	34	29	44	36	30	42	30	34	37	37	26	33
15	17/08/2008	420	35	33	36	35	35	39	32	35	38	30	33	34
17	19/08/2008	370	38	33	39	37	41	41	30	37	46	36	38	40
20	22/08/2008	735	36	29	34	33	43	31	26	33	38	36	32	35
24	26/08/2008	690	33	27	31	30	31	32	26	30	45	35	35	38
27	29/08/2008	510	37	40	35	37	45	52	40	46	49	38	37	41
30	02/10/2008	530	35	28	37	33	44	44	35	41	37	33	44	38
34	06/10/2008	540	59	62	61	61	73	69	52	65	62	52	59	58
36	08/10/2008	510	48	39	47	45	49	49	45	48	56	51	48	52
41	13/10/2008	750	40	45	48	44	41	38	34	38	46	36	65	49
43	15/10/2008	560	32	30	34	32	28	37	29	31	40	29	30	33
45	17/10/2008	480	38	41	52	44	51	49	42	47	43	39	45	42
48	20/10/2008	510	45	29	34	36	38	29	50	39	30	29	31	30
55	28/10/2008	520	51	37	46	45	48	43	36	42	50	42	38	43
56	29/10/2008	610	34	30	57	40	50	59	51	53	39	48	38	42
59	31/10/2008	570	42	36	50	43	44	40	29	38	37	31	33	34
62	03/11/2008	490	32	28	33	31	56	38	23	39	28	29	25	27
64	05/11/2008	500	30	26	31	29	31	34	33	33	30	25	27	27
66	07/11/2008	510	29	31	27	29	39	40	37	39	29	15	25	23
69	10/11/2008	630	31	37	33	34	40	39	41	40	27	21	29	26

Table A.10 Results for TN_T for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
73	14/11/2008	610	28	35	39	34	41	38	25	35	29	28	24	27
83	24/11/2008	530	31	40	40	37	43	38	41	41	42	39	41	41
119	29/12/2008	530	59	57	61	59	72	69	62	68	61	70	60	64
126	06/01/2009	560	51	48	49	49	54	59	42	52	41	49	46	45
128	08/01/2009	670	36	29	32	32	29	21	37	29	32	27	25	28
140	20/01/2009	650	39	42	51	44	39	49	42	43	29	51	47	42
150	30/01/2009	420	42	22	30	31	36	31	35	34	26	23	24	24
154	03/02/2009	410	42	39	51	44	47	37	29	38	51	56	49	52
160	09/02/2009	710	15	13	15	14	24	17	18	20	14	13	13	13
164	13/02/2009	610	43	35	36	38	42	38	47	42	51	39	48	46
167	16/02/2009	540	51	39	46	45	61	60	51	57	41	47	41	43
175	24/02/2009	550	47	35	41	41	50	30	39	40	28	26	26	27
182	02/03/2009	470	46	41	39	42	57	60	61	59	39	34	36	36
192	13/03/2009	450	58	54	58	57	64	61	70	65	67	67	69	68
197	18/03/2009	450	52	49	56	52	59	56	61	59	63	59	57	60

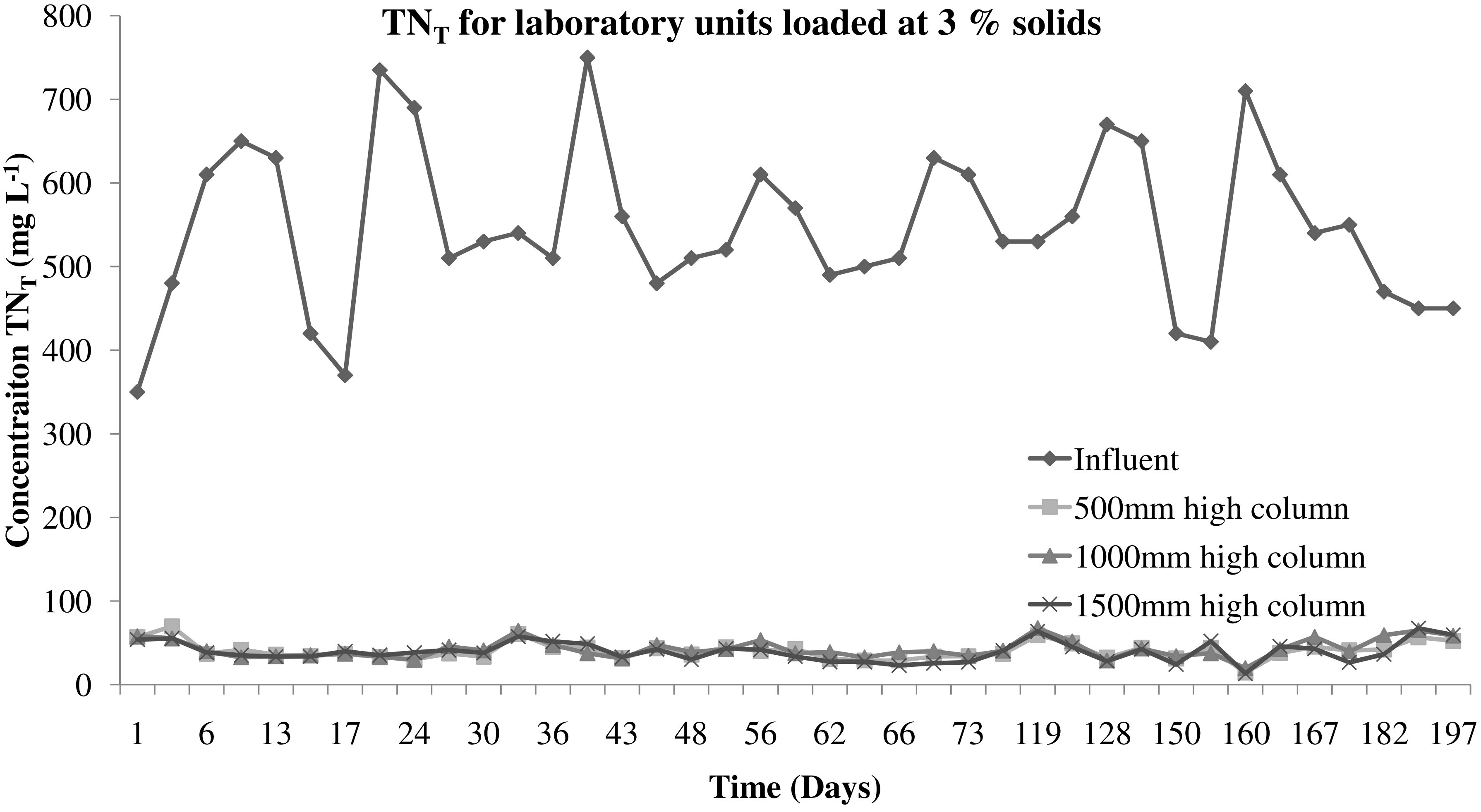
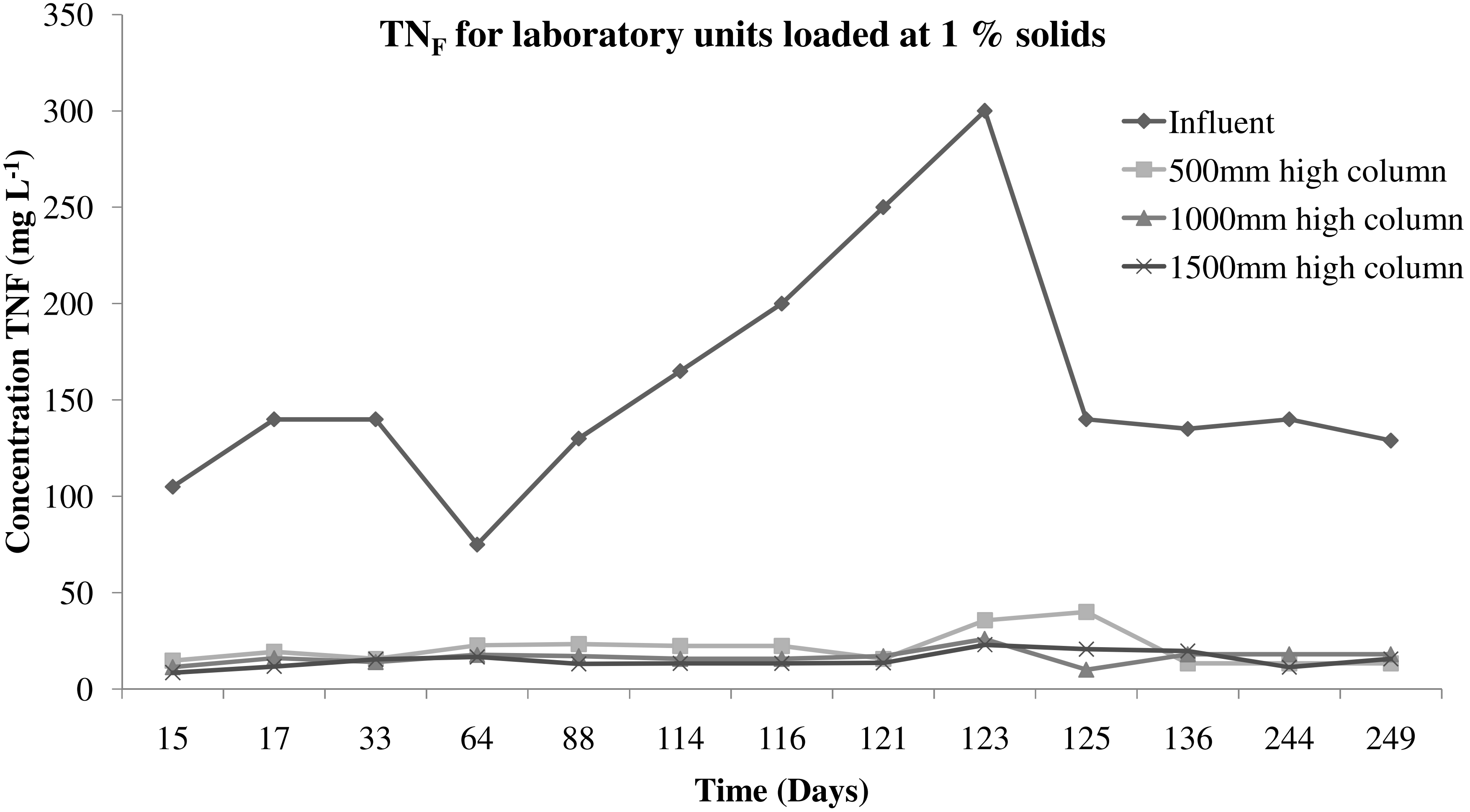

TN_T for laboratory units loaded at 3 % solids
Concentraiton TN_T (mg L^{-1})
800
700
600
500
400
300
200
100
0
1
6
13
17
24
30
36
43
48
56
62
66
73
119
128
150
160
167
182
197
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.11 Results for TN_F for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008										21	22		22
3	18/06/2008										22	19		21
10	25/06/2008	30									18	37	22	26
15	30/06/2008	52	13	17	14	15	10	7	17	11	7	10		9
17	02/07/2008	85	23	18	17	19	17	16	15	16	13	9	13	12
33	18/07/2008	105	16	16	15	16	13	11	18	14	17	13	16	15
64	18/08/2008	140	24	24	20	23	17	18	18	18	20	16	14	17
88	11/09/2008	140	41	11	18	23	16	13	22	17	13	14	12	13
114	06/10/2008	75	23	18	26	22	13	18	16	16	16	11	13	13
116	08/10/2008	130	23	18	26	22	13	18	16	16	16	11	13	13
121	13/10/2008	165	14	16	17	16	16	19	16	17	14		13	14
123	15/10/2008	200	41	40	26	36	25	27	26	26	24	21	24	23
125	17/10/2008	250	30	64	26	40	8	10	12	10	12	31	19	21
136	28/10/2008	300	12	15	13	13	11	17	26	18	21	24	14	20
244	13/02/2009	140	24	26	24	13	19	17	19	18	9	12	13	11
249	18/02/2009	135	20	26	24	13	19	21	18	18	17	15	15	16



TNF for laboratory units loaded at 1 % solids
Concentration TNF (mg L-1)
350
300
250
200
150
100
50
0
15
17
33
64
88
114
116
121
123
125
136
244
249
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.12 Results for TN_F for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	170	46	53	56	52	54	59	53	55	55	50	50	52
13	15/09/2008	210	34	30	34	33	34	32	35	34	35	35	23	31
24	26/09/2008	230	22	18	39	26	32	38	32	34	38	34	34	35
34	06/10/2008	190	58	43	46	49	53	57	48	53	60	51	45	52
41	13/10/2008	190	28	25	26	26	26	29	23	26	36	29	30	32
43	15/10/2008	200	35	35	50	40	45	42	35	41	40	35	43	39
45	17/10/2008	270	42	23	29	31	33	23	47	34	62	26	28	39
48	20/10/2008	210	39	26	32	32	40	25	39	35	52	31	29	37
55	28/10/2008	250	32	36	38	35	36	39	34	36	43	36	31	37
59	31/10/2008	180	33	35	39	36	42	46	31	40	40	32	33	35
62	03/11/2008	195	39	30	35	35	37	26	26	30	30	25	21	25
83	24/11/2008	210	27	28	27	27	27	26	24	26	24	25	20	23
119	29/12/2008	285	53	53	57	54	70	67	59	65	55	61	55	57
126	06/01/2009	225	49	43	45	46	49	56	39	48	37	42	41	40
128	08/01/2009	300	28	19	27	25	23	23	2	16	25	24	22	24
164	13/02/2009	180	32	29	31	31	41	32	41	38	47	36	41	41
167	16/02/2009	210	46	35	44	42	55	50	51	52	41	47	41	43
175	24/02/2009	240	42	34	39	38	39	32	35	35	32	27	30	30
182	02/03/2009	195	39	35	31	35	49	52	54	52	27	31	31	30
192	13/03/2009	285	46	51	52	50	60	65	62	62	60	52	63	58

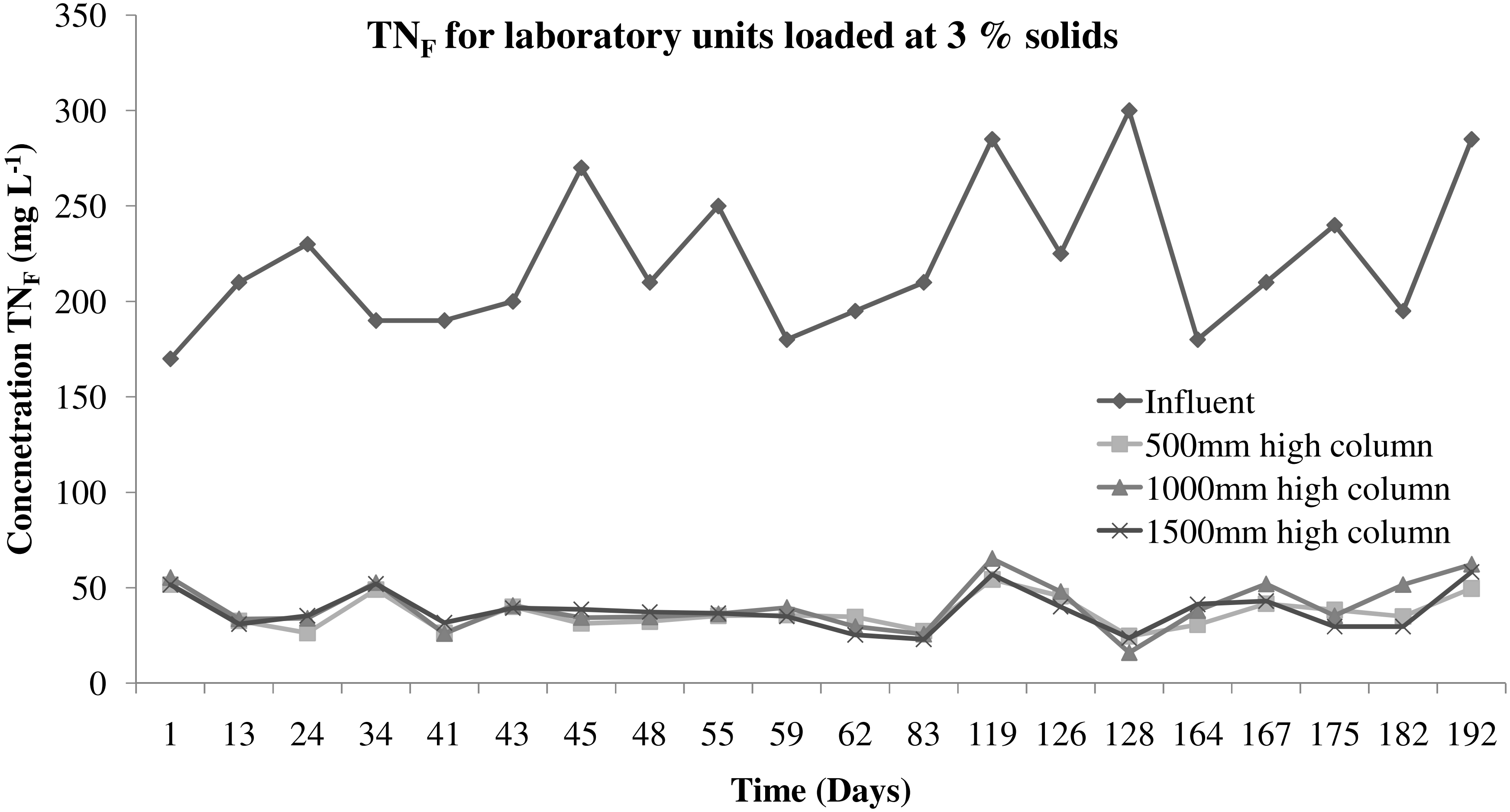

TN$_F$ for laboratory units loaded at 3 % solids
Concnetration TN$_F$ (mg L^{-1})
350
300
250
200
150
100
50
0
1
13
24
34
41
43
45
48
55
59
62
83
119
126
128
164
167
175
182
192
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.13 Results for NH_4-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008	3.5	5.1	4.55		4.83	0.85	1.54	1.66	1.35	10.52	4.47	2.27	5.75
3	18/06/2008	3.46	2.87	1.52	0.6	1.66	1.35	0.71	0.66	0.91	2.36	1.96		2.16
5	20/06/2008	3.69		0.69	0.49	0.59	0.68	0.62	0.78	0.69	2.72	2.69	2.25	2.55
8	23/06/2008	3.8	4.23	3.45	5.21	4.30	0.53	0.66	0.96	0.72	1.83	6.26	5.5	4.53
10	25/06/2008	3.68	3.23	1.1	10.05	4.79	1.94	1.99	2.32	2.08	5.29	10.09	6.67	7.35
15	30/06/2008	3.67	3.45	7.41	7.14	6.00	3.38	4.52	3.45	3.78	3.28	2.83		3.06
17	02/07/2008	3.82	12.24	2.57	2.06	5.62	4.1	3.48	3.23	3.60	1.94	11.66	2.93	5.51
19	04/07/2008	3.7	4.91	2.68	1.29	2.96	3.73	3.2	3.75	3.56	3.78	1.6	0.13	1.84
24	09/07/2008	3.78	6.91	6.35	8.99	7.42	6.1	5.58	9.79	7.16	6.8	4.11	6.36	5.76
31	16/07/2008	3.7	6.71	6.52	3.05	5.43	3.93	5.78	6.5	5.40	8.78	4.31	7.05	6.71
33	18/07/2008	3.7	8.28	6.71	5.79	6.93	6.14	5.97	9.12	7.08	6.15	4.62	8.07	6.28
36	21/07/2008	3.78	4.08	4.22	12.08	6.79	4.03	4.75	5.96	4.91	8.32	7.28	4.19	6.60
38	23/07/2008	3.69	3.26	9.41	5.75	6.14	3.74	5.1	4.67	4.50	4.14	1.81	0.98	2.31
40	25/07/2008	3.67	11.09	16	10.005	12.37	7.31	6.49	6.81	6.87	8.52	3.31	3.3	5.04
43	28/07/2008	3.42	39	21.42	18.59	26.34	28.11	20.69	18.73	22.51	25.43	18.36	11.44	18.41
51	05/08/2008	3.56	9.71	11.16	7.48	9.45	9.03	8.59	11.27	9.63	11.74	5.07	8.54	8.45
57	11/08/2008	3.46	4.08	4.22	12.08	6.79	4.03	4.75	5.96	4.91	8.32	7.28	4.19	6.60
64	18/08/2008	3.44	9.52	11.13	11.7	10.78	11.57	9.39	16	12.32	17.34	15.39	10.01	14.25
68	22/08/2008	3.44	7.7	7.23	12.52	9.15	15.7	5.36	12.61	11.22	5.8	5.34	7.47	6.20
74	28/08/2008	3.44	3.94	6.88	6.7	5.84	5.09	5.69	5.09	5.29	6.12	4.03	5.87	5.34
80	03/09/2008	3.43	5.4	18.37		11.89	3.98	1.05	1.37	2.13	1.15	0.71	0.52	0.79
85	08/09/2008	3.44	7.21	14.92	6.89	9.67	10.11	14.32	8.51	10.98	10.12	14.59	16.12	13.61
88	11/09/2008	3.43	6.84	17.82	7.69	10.78	5.91	15.29	8.41	9.87	6.11	16.59	19.13	13.94
92	15/09/2008	3.43	6.91	3.88	5.44	5.41	7.18	6.74	9.42	7.78	4.65	5.03	3.34	4.34
94	17/09/2008	3.43	3.52	9.31	9.42	7.42	13.83	8.57	5.24	9.21	3.56	5.74	6.67	5.32
96	19/09/2008	3.44	14.34	28.83	29.83	24.33	17.6	14.09	5.24	12.31	7.64	3.58	16.75	9.32
99	22/09/2008	3.47	11.49	6.04	7.95	8.49		13.56	6.78	10.17	6.34	3.52	3.16	4.34

Table A.14 Results for NH_4-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
107	29/09/2008	3.46	6.91	3.88	5.44	5.41	7.18	6.74	9.42	7.78	4.65	5.03	3.34	4.34
111	03/10/2008	2.17	6.22	5.05	4.97	5.41	8.2	5.86	23.81	12.62	8.46	4.67	3.17	5.43
114	06/10/2008	1.67	5.74	20.89	13.7	13.44	7.16	6.36	8.19	7.24	6.46	4.15	2.98	4.53
116	08/10/2008	1.96	9.61	5.83	4.35	6.60	5.09	6.21	7.19	6.16	4.78	6.53	2.63	4.65
121	13/10/2008	2.41	1.5	1.81	1.33	1.55	1.3	1.57	2.2	1.69	1.88		2.05	1.97
123	15/10/2008	2.82	7.03	6.74	6.42	6.73	5.26	5.19	4.89	5.11	3	4.96	1.89	3.28
125	17/10/2008	3.1	5.17	4.39	4.54	4.70	4.94	5.2	5.3	5.15	5.51	7.85	5.78	6.38
128	20/10/2008	3.68	5.74	6.16	4.53	5.48	8.12	16.97	15.55	13.55	7.3	8.88	9.38	8.52
136	28/10/2008	3.1	7.68	7.46	7.95	7.70	8.14	9.89	8.51	8.85	19.61	9.1	7.81	12.17
137	29/10/2008	3.44	22.23	9.04	7.37	12.88	9.43	7.94	7.33	8.23	5.33	6.33	3.82	5.16
139	31/10/2008	3.78		5.59	13.77	9.68	13.47		4.76	9.12	2.72	3.27	2.08	2.69
142	03/11/2008	3.68	2.97	4.68	11.56	6.40	4.42	3.17	4.3	3.96	3.15	2.74	2.19	2.69
144	05/11/2008	3.85	9.28	7.75	7.59	8.21	8.66	4.07	6.61	6.45	4.53	4.71	16.37	8.54
149	10/11/2008	3.6	9.32	9.45	6.97	8.58	8.42	9.01	6.29	7.91	5.42	7.32	9.14	7.29
153	14/11/2008	3.56	10.21	9.78	11.21	10.40	9.48	6.97	7.32	7.92	6.14	9.78	8.23	8.05
157	18/11/2008	2.65	7.21	6.49	5.23	6.31	6.19	7.82	9.14	7.72	8.73	9.25	10.14	9.37
160	21/11/2008	5.14	6.17	7.12	10.23	7.84	9.34	11.41	10.21	10.32	8.78	7.14	12.36	9.43
163	24/11/2008	3.54	8.17	9.42	10.14	9.24	11.32	12.12	9.82	11.09	9.97	7.23	14.14	10.45
171	02/12/2008	3.42	4.14	6.23	9.14	6.50	10.14	11.12	7.23	9.50	8.45	9.14	13.23	10.27
198	29/12/2008	4.52	4.66	5.28	4.92	4.95	6.93	6.25	6.49	6.56	6.14	4.94	3.8	4.96
206	06/01/2009	4.95	1.8	2.84	1.75	2.13	1.48	1.88	2.11	1.82	2.71	2.05	1.59	2.12
220	20/01/2009	3.95	4.01	3.97	3.77	3.92	2.99	3.14	4.23	3.45	5.14	4.97	4.72	4.94
230	30/01/2009	3.45	3.35	2.14	3.72	3.07	2.99	4.01	3.11	3.37	4.17	5.14	4.99	4.77
240	09/02/2009	4.65	3.01	3.25	4.01	3.42	2.76	2.58	3.27	2.87	4.01	3.13	2.92	3.35
244	13/02/2009	6.52	4.41	5.13	4.95	4.83	4.14	4.2	4.31	4.22	3.8	2.8	1.79	2.80
249	18/02/2009	5.62	6.47	7.58	5.34	6.46	5.8	5.8	5.97	5.86	4.43	4.25	3.22	3.97
254	24/02/2009	5.32	2.96	3.64	3.57	3.39	4.05	4.02	3.96	4.01	3.2	3.24	2.56	3.00

Table A.14 Results for NH_4-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
261	02/03/2009	3.95	1.257	1.743	2.094	1.70	1.983	2.134	1.994	2.04	2.454	2.123	1.825	2.13
272	13/03/2009	4.23	3.96	4.97	3.18	4.04	4.68	5.17	4.23	4.69	3.07	4.28	2.3	3.22
277	18/03/2009	5.23	4.23	4.32	3.99	4.18	2.14	3.15	2.99	2.76	3.2	4.14	3.23	3.52

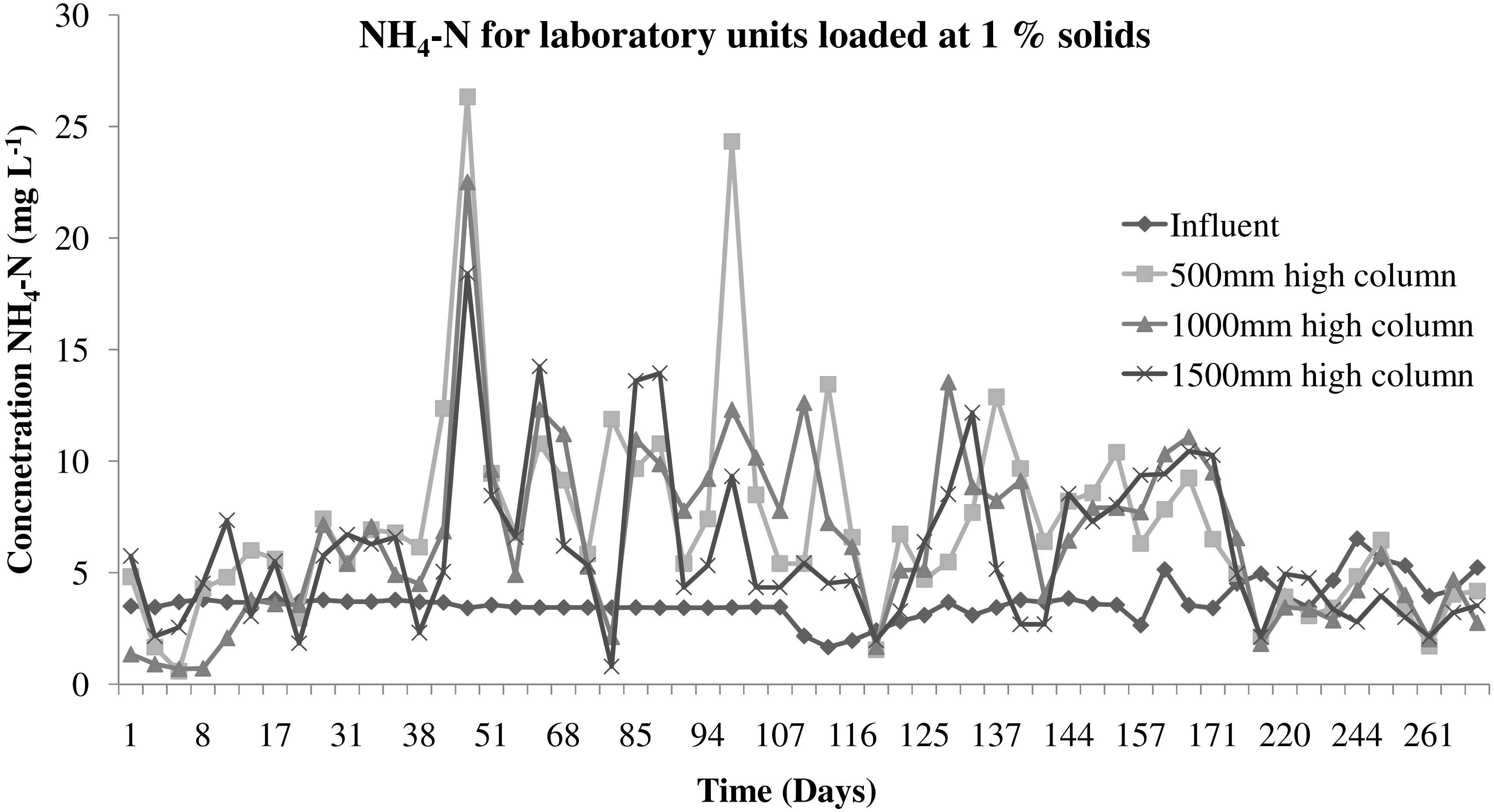

NH$_4$-N for laboratory units loaded at 1 % solids
Concnetration NH$_4$-N (mg L^{-1})
Time (Days)
0
5
10
15
20
25
30
1
8
17
31
38
51
68
85
94
107
116
125
137
144
157
171
220
244
261
Influent
500mm high column
1000mm high column
1500mm high column

Table A.15 Results for NH_4-N for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	0.9	4.62	3.04	4.3	3.99	7.78	6.03	3.82	5.88	8.23	11.68	11.51	10.47
3	05/09/2008	0.92	3.17	1.79	1.15	2.04	3.85	0.98	1.19	2.01	1.96	11.68	11.51	8.38
6	08/09/2008	0.91	6.12	5.19	6.49	5.93	5.58	3.96	3.28	4.27	4.44	6.23	6.33	5.67
9	11/09/2008	0.91	12.65	10.36	10.09	11.03	10.64	9.12	7.85	9.20	9.52	10.19	9.81	9.84
13	15/08/2008	0.91	2.4	2.02	2.78	2.40	3.11	2.45	2.41	2.66	2.46	3.29	3.24	3.00
15	17/08/2008	0.89	8.6	7.68	9.73	8.67	8.54	6.41	6.31	7.09	6.18	3.58	6.38	5.38
17	19/08/2008	0.89	8.92	8.84	10.78	9.51	12.52	14.01	9.52	12.02	13.85	12.43	13.93	13.40
20	22/08/2008	0.92	8.16	8.26	9.73	8.72	10.39	7.71	6.49	8.20	9.81	8.1	8.29	8.73
24	26/08/2008	0.96	5.28	3.94	4.73	4.65	5.82	4.07	3.47	4.45	8.82	4.77	4.46	6.02
27	29/08/2008	0.96	12.65	10.66	10.09	11.13	10.64	9.12	7.85	9.20	9.52	10.19	9.81	9.84
30	02/10/2008	0.96	18.93	12.17	12.68	14.59	16.98	16.74	16.93	16.88	20.64	12.36	11.78	14.93
34	06/10/2008	0.95	15.8	14.92	16.88	15.87	21.61	18.95	17.45	19.34	22.8	20.77	24.17	22.58
36	08/10/2008	1.01	25.57	14.1	12.3	17.32	21.71	12.04	10.25	14.67	15.25	19.35	15.02	16.54
38	10/10/2008	1.02	4.44		4.29	4.37		6.21	3.24	4.73	4.63	5.65	3.61	4.63
41	13/10/2008	0.98	2.42	2.52	2.33	2.42	3.34	2.49	1.95	2.59	4.95	3.15	2.54	3.55
43	15/10/2008	0.97	6.06	5.14	7.26	6.15	4.33	10.65	9.72	8.23	8.42	9.41	7.78	8.54
45	17/10/2008	0.97	11.56	11.33	7.18	10.02	8.17	6.68	6.46	7.10	7.46	5.76	5.36	6.19
48	20/10/2008	0.96	8.39	6.88	8.36	7.88	9.1	6.39	6.34	7.28	7.86	5.49	5.23	6.19
55	28/10/2008	0.97	5.05	2.78	2.58	3.47	3.48	3.07	5.21	3.92	5.18	6.72	3.56	5.15
56	29/10/2008	0.96	18.64	18.69	22	19.78	22.46	21.42	20.14	21.34	21.45	19.88	21.04	20.79
59	31/10/2008	0.96	16.09	3.37	3.4	7.62	5.98	4.21	3.33	4.51	5.58	4.26	3.37	4.40
62	03/11/2008	0.96	9.24	9.05	3.74	7.34	4.95	2.94	2.47	3.45	3.09	2.78	2.92	2.93
64	05/11/2008	0.96	4.68	4.51	5.5	4.90	7.68	5.98	6.5	6.72	6.42	6.61	5.27	6.10
66	07/11/2008	0.95	5.21	4.97	6.21	5.46	3.97	4.21	6.85	5.01	7.48	6.19	7.13	6.93

Table A.16 Results for NH_4-N for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
69	10/11/2008	1	5.32	4.72	5.92	5.32	6.23	6.97	7.01	6.74	6.92	7.14	5.39	6.48
73	14/11/2008	0.97	4.97	5.32	4.1	4.80	3.97	4.45	5.12	4.51	6.1	5.97	5.45	5.84
83	24/11/2008	0.95	5.32	4.97	5.41	5.23	3.24	4.56	5.42	4.41	6.97	4.99	5.14	5.70
119	29/12/2008	0.94	5.11	5.32	4.11	4.85	8.48	6.86	7.2	7.51	6.99	13.18	6.94	9.04
126	06/01/2009	0.95	2.27	1.79	1.97	2.01	3.35	4.27	3.83	3.82	3.71	6.43	3.85	4.66
128	08/01/2009	0.97	2.58	2.83	3.01	2.81	3.32	3.25	4.01	3.53	2.65	3.29	2.73	2.89
140	20/01/2009	1.01	4.23	4.14	3.92	4.10	4.91	4.71	3.39	4.34	4.01	3.79	4.14	3.98
150	30/01/2009	1.02	4.23	3.14	2.45	3.27	3.92	4.61	3.71	4.08	4.12	3.57	4.11	3.93
154	03/02/2009	1.07	3.95	3.66	3.76	3.79	6.4	4.2	4.03	4.88	4.37	5.57	4.18	4.71
160	09/02/2009	1.12	2.07	3.36	2.64	2.69	2.57	2.03	2.13	2.24	3.14	2.64	2.77	2.85
164	13/02/2009	1.1	6.79	5.72	7.47	6.66	8.41	7.6	7.57	7.86	6.3	8.41	6.34	7.02
167	16/02/2009	1.09	9.35	8.32	8.77	8.81	9.94	9.42	9.35	9.57	6.86	9.06	7.01	7.64
175	24/02/2009	1.18	9.35	8.32	8.77	8.81	9.94	9.42	9.35	9.57	6.86	9.06	7.01	7.64
182	02/03/2009	1.03	2.319	2.301	2.387	2.34	4.291	2.937	3.717	3.65	2.33	2.771	2.901	2.67
192	13/03/2009	0.97	2.31	3.61	4.13	3.35	4.33	4.47	4.2	4.33	2.73	3.15	3.33	3.07
197	18/03/2009	0.98	3.14	2.96	4.23	3.44	4.34	4.56	4.14	4.35	2.36	2.97	2.14	2.49

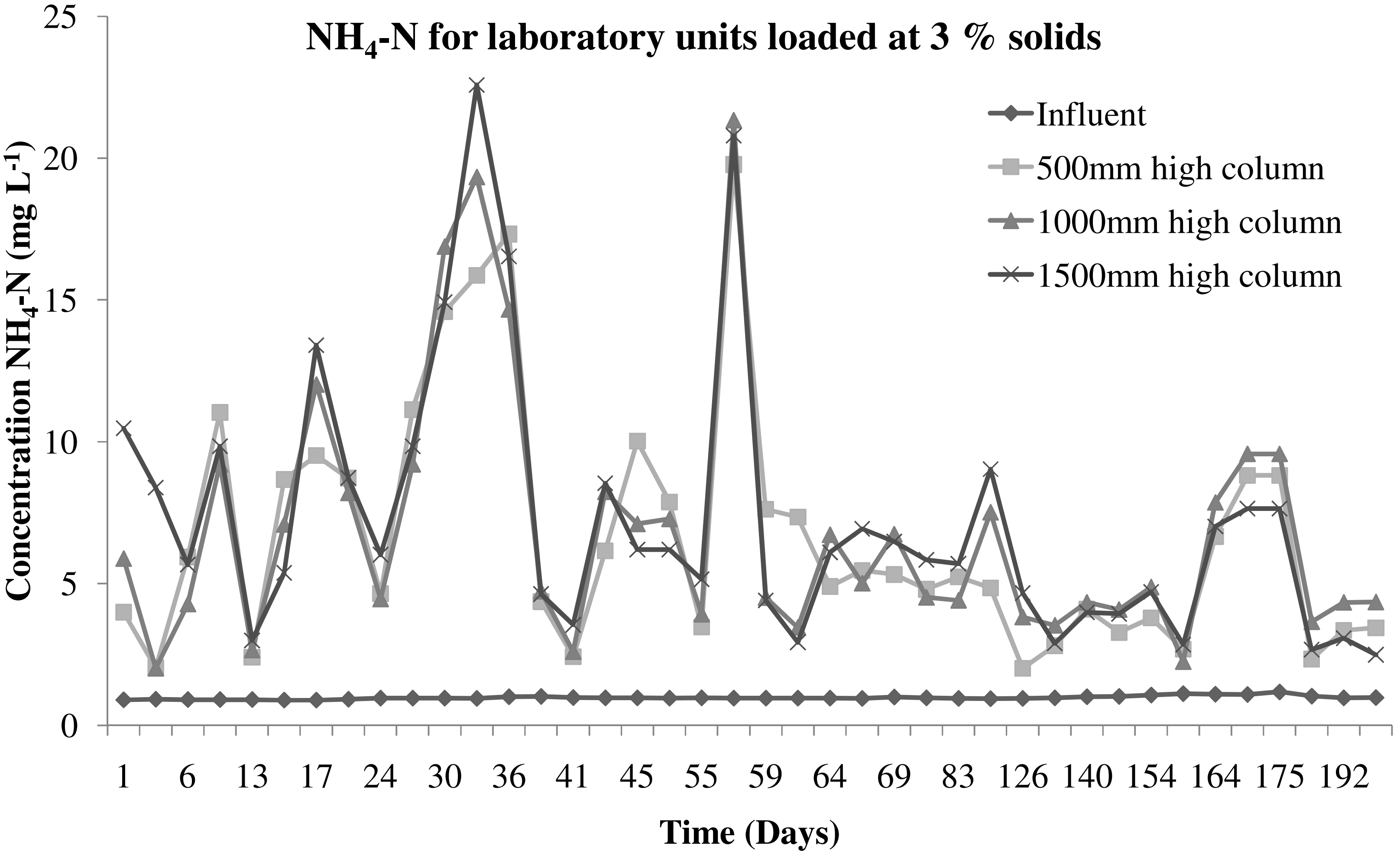
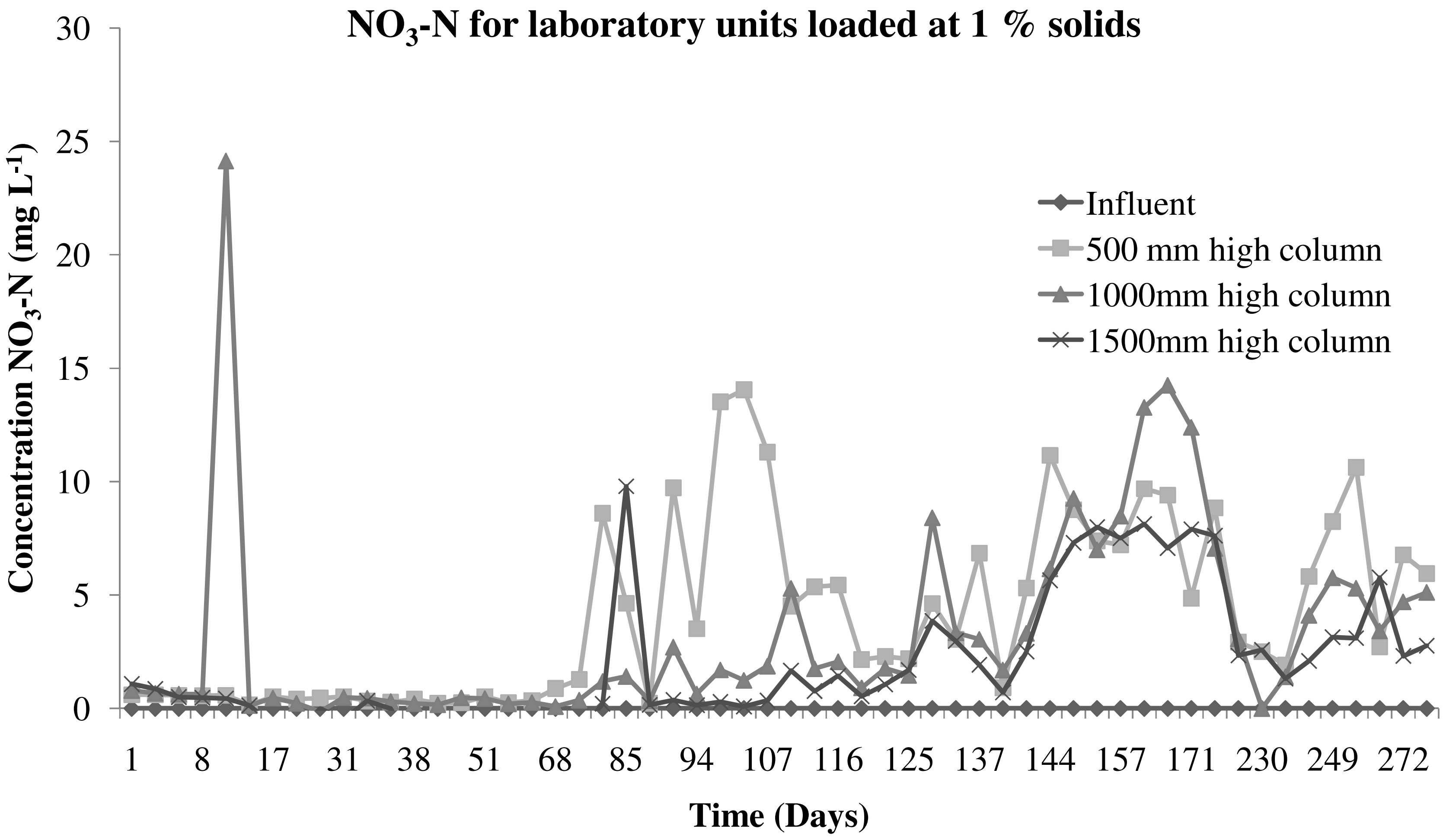

NH$_4$-N for laboratory units loaded at 3 % solids
Influent
500mm high column
1000mm high column
1500mm high column
Concentratiion NH$_4$-N (mg L^{-1})
25
20
15
10
5
0
1
6
13
17
24
30
36
41
45
55
59
64
69
83
126
140
154
164
175
192
Time (Days)

Table A.17 Results for NO_3-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008	0	0.6	0.6		0.60	0.88	0.79	0.72	0.80	1.77	0.8	0.66	1.08
3	18/06/2008	0	0.58	0.63	0.6	0.60	0.72	0.64	0.66	0.67	1.09	0.63		0.86
5	20/06/2008	0		0.57	0.59	0.58	0.64	0.64	0.63	0.64	0.55	0.5	0.46	0.50
8	23/06/2008	0	0.61	0.57	0.5	0.56	0.6	0.65	0.66	0.64	0.53	0.44	0.45	0.47
10	25/06/2008	0	0.6	0.56	0.57	0.58	0.67	0.71	71.04	24.14	0.46	0.39	0.46	0.44
15	30/06/2008	0	0.17	0.16	0.15	0.16	0.14	0.13	0.13	0.13	0.13	0.13		0.13
17	02/07/2008	0	0.6	0.5	0.47	0.52	0.46	0.43	0.49	0.46	0.45	-1.59	-1.02	-0.72
19	04/07/2008	0	0.42	0.42	0.4	0.41	0.38	-0.08	0.39	0.23	0.37	-2	-1.61	-1.08
24	09/07/2008	0	0.46	0.45	0.46	0.46	0.41	-1.25	0.41	-0.14	0.43	0.39	-0.835	0.00
31	16/07/2008	0	0.52	0.5	0.54	0.52	0.48	0.5	0.49	0.49	-0.52	-1.74	0.78	-0.49
33	18/07/2008	0	0.34	0.32	0.34	0.33	0.34	0.31	0.72	0.46	0.38	0.32	0.3	0.33
36	21/07/2008	0	0.31	0.28	0.24	0.28	0.37	0.28	0.27	0.31	0.26	0.27	-0.56	-0.01
38	23/07/2008	0	0.39	0.45	0.39	0.41	0.36	-0.06	0.36	0.22	-1.19	-2.74	-1.39	-1.77
40	25/07/2008	0	0.24	0.28	0.19	0.24	0.17	0.17	0.16	0.17	0.17	0.16	-2.48	-0.72
43	28/07/2008	0	0.27	0.24	0.24	0.25	0.2	0.31	0.91	0.47	0.2	-1.92	0.19	-0.51
51	05/08/2008	0	0.61	0.48	0.47	0.52	0.49	0.41	0.43	0.44	-1.86	0.41	0.43	-0.34
57	11/08/2008	0	0.25	0.28	0.23	0.25	0.21	0.2	0.2	0.20	0.2	0.2	-1.71	-0.44
64	18/08/2008	0	0.34	0.36	0.34	0.35	0.27	0.27	0.25	0.26	0.23	-2.93	-2.26	-1.65
68	22/08/2008	0	0.55	1.56	0.53	0.88	-0.22	0.25	0.23	0.09	0.24	0.22	-2.26	-0.60
74	28/08/2008	0	0.85	2.18	0.81	1.28	0.39	0.37	0.34	0.37	-1.62	0.34	-2.01	-1.10
80	03/09/2008	0	3.51	13.7		8.61	2.67	0.53	0.39	1.20	0.21	0.18	0.23	0.21
85	08/09/2008	0	0.18	6.56	7.16	4.63	1.8	0.47	1.97	1.41	0.44	0.12	28.81	9.79
88	11/09/2008	0	0.25	0.36	0.07	0.23	0.71	0.18	0.12	0.34	0.09	0.22	0.16	0.16
92	15/09/2008	0	23.67	-0.81	6.33	9.73	2.49	0.56	5.07	2.71	1.2	0.21	-0.28	0.38
94	17/09/2008	0	-0.85	5.95	5.44	3.51	1.1	0.4	0.41	0.64	0.32	0.34	-0.23	0.14
96	19/09/2008	0	8.63	20.12	11.82	13.52	3.09	1.44	0.57	1.70	-0.22	0.77	0.32	0.29
99	22/09/2008	0	8.93	25.64	7.58	14.05		2.07	0.41	1.24	-0.17	0.29	0.15	0.09
107	29/09/2008	0	18.46	6.91	8.53	11.30	2.35	0.59	2.67	1.87	0.64	0.22	0.17	0.34

Table A.18 Results for NO_3-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
111	03/10/2008	0	3.88	4.42	5.24	4.51	0.88	0.62	14.38	5.29	4.16	0.66	0.19	1.67
114	06/10/2008	0	6.62	3.78	5.69	5.36	1.98	1.59	1.69	1.75	0.93	0.87	0.5	0.77
116	08/10/2008	0	7.4	5.1	3.81	5.44	1.52	2.44	2.23	2.06	1.8	1.63	0.87	1.43
121	13/10/2008	0	2.13	2.42	1.91	2.15	0.5	0.96	1.27	0.91	0.77		0.3	0.54
123	15/10/2008	0	2.09	2.59	2.19	2.29	0.91	2.7	1.71	1.77	0.84	1.92	0.42	1.06
125	17/10/2008	0	2.58	2.02	1.96	2.19	1.23	1.66	1.5	1.46	2.02	2.44	0.61	1.69
128	20/10/2008	0	4.01	6.74	3.13	4.63	2.64	15.09	7.49	8.41	4.84	4.24	2.5	3.86
136	28/10/2008	0	2.09	4.37	2.68	3.05	1.73	2.74	5.55	3.34	3.86	4.07	0.98	2.97
137	29/10/2008	0	8.04	7.66	4.84	6.85	3.27	3.16	2.73	3.05	2.18	2.52	1.07	1.92
139	31/10/2008	0		0.93	0.9	0.92	2.29		1.1	1.70	0.82	0.83	0.47	0.71
142	03/11/2008	0	4	5.6	6.34	5.31	3.47	2.63	3.83	3.31	2.64	2.64	2.23	2.50
144	05/11/2008	0	5.42	14.25	13.79	11.15	6.44	4.7	7.34	6.16	5.24	4.27	7.44	5.65
149	10/11/2008	0	4.87	10.95	10.45	8.76	9.28	8.01	10.49	9.26	6.81	6.46	8.63	7.30
153	14/11/2008	0	4.6	5.69	11.87	7.39	8.54	6.22	6.23	7.00	8.46	6.72	8.79	7.99
157	18/11/2008	0	5.35	6.87	9.41	7.21	10.41	6.92	8.13	8.49	8.73	8.36	5.43	7.51
160	21/11/2008	0	6.91	8.11	14.04	9.69	14.91	11.67	13.23	13.27	9.83	5.89	8.66	8.13
163	24/11/2008	0	6.07	8.81	13.33	9.40	17.03	13.81	11.9	14.25	6.92	5.66	8.63	7.07
171	02/12/2008	0	7.11	0.74	6.73	4.86	11.06	12.54	13.58	12.39	8.32	8.48	6.91	7.90
206	06/01/2009	0	7.84	11.14	7.55	8.84	7.07	7.08	7.03	7.06	8.9	7.24	6.7	7.61
220	20/01/2009	0	3.41	2.39	2.96	2.92	3.35	3.09	2.78	3.07	2.12	2.2	2.68	2.33
230	30/01/2009	0	1.79	2.38	3.34	2.50	-12.44	1.95	1.53	-2.99	2.3	2.77	2.67	2.58
240	09/02/2009	0	2	2.34	1.42	1.92	1.18	1.33	1.71	1.41	1.53	0.91	1.51	1.32
244	13/02/2009	0	4.78	7.95	4.71	5.81	4.32	3.94	4.05	4.10	3.05	1.95	1.29	2.10
249	18/02/2009	0	8.02	9.3	7.4	8.24	6.29	5.95	5.06	5.77	4.11	2.86	2.47	3.15
254	24/02/2009	0	8.27	14.5	9.13	10.63	5.36	4.95	5.61	5.31	3.59	3.17	2.53	3.10
261	02/03/2009	0	2.55	2.021	3.575	2.72	3.768	3.521	2.968	3.42	5.024	6.292	6.008	5.77
272	13/03/2009	0	5.47	7.04	7.79	6.77	5.12	3.63	5.35	4.70	2.81	2.17	1.96	2.31
277	18/03/2009	0	5.66	6.05	6.13	5.95	5.98	4	5.38	5.12	3.05	2.98	2.26	2.76



NO_3-N for laboratory units loaded at 1 % solids
Concentration NO_3-N (mg L^{-1})
30
25
20
15
10
5
0
Influent
500 mm high column
1000mm high column
1500mm high column
1
8
17
31
38
51
68
85
94
107
116
125
137
144
157
171
230
249
272
Time (Days)

Table A.19 Results for NO_3-N for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	0.5	0.04	0.05	0.12	0.07	0.05	0.02	0.02	0.03	0.02	0.01	0.01	0.01
3	05/09/2008	0.48	0.18	0.08	0.29	0.18	0.08	0.02	0.02	0.04	0.04	0.01	0.01	0.02
6	08/09/2008	0.48	0.1	0.04		0.07	0.02	0	0.02	0.01	0.04	0.03	0.03	0.03
9	11/09/2008	0.47	0.12	0.03	0.01	0.05	0.02	0.02	0.02	0.02	0.03	0.01	0.02	0.02
13	15/08/2008	0.53	0.23	0.12	0.07	0.14	0.05	0.04	0.05	0.05	0.02	0.02	0.01	0.02
15	17/08/2008	0.47	0.12	0.03	0	0.05	0.02	0	0.03	0.02	0.01	0.02	0.02	0.02
17	19/08/2008	0.46	0.26	0.1	0.15	0.17	0.1	0.07	0.08	0.08	0.09	0.06	0.06	0.07
20	22/08/2008	0.61	0.16	0.07	0.17	0.13	0.03	0	0	0.01	0	0	0	0.00
24	26/08/2008	0.41	2	0.23	0.41	0.88	0.24	0.16	0.2	0.20	0.15	0.1	0.04	0.10
27	29/08/2008	0.63	0.12	0.03	2.4	0.85	0.02	0.02	0.01	0.02	0.03	0	0.02	0.02
30	02/10/2008	0.41	4.39	0.72	0.29	1.80	0.07	0.03	0.03	0.04	0.41	0.01	0	0.14
34	06/10/2008	0.43	0.535	0.221	0.38	0.38	0.05	-0.02	0.03	0.02	0.02	0.05	0.03	0.03
36	08/10/2008	0.44	9.56	2.78	1.22	4.52	0.16	0.06	0.05	0.09	0.03	0.05	0.13	0.07
38	10/10/2008	0.42	0.17		0.19	0.18		0.03	0.03	0.03	0.05	0.02	0.03	0.03
41	13/10/2008	0.46	0.23	0.16	0.17	0.19	0.07	0.12	0.07	0.09	0.06	0.05	0.13	0.08
43	15/10/2008	0.42	0.24	0.18	0.28	0.23	0.14	0.1	0.16	0.13	0.12	0.16	0.15	0.14
45	17/10/2008	0.41	0.59	0.58	0.53	0.57	0.35	0.37	0.42	0.38	0.39	0.47	0.43	0.43
48	20/10/2008	0.41	1.08	0.85	0.99	0.97	0.61	0.78	0.7	0.70	0.76	0.88	0.97	0.87
55	28/10/2008	0.41	1.36	1.39	1.4	1.38	0.49	0.68	0.56	0.58	0.43	0.43	0.79	0.55
56	29/10/2008	0.41	2.05	1.2	1.84	1.70	0.79	0.84	0.88	0.84	0.89	1.03	1.27	1.06
59	31/10/2008	0.78	0.76	0.22	0.19	0.39	0.17	0.23	0.18	0.19	0.21	0.19	0.19	0.20
62	03/11/2008	0.68	4.03	2.21	1.58	2.61	1.33	1.14	1.18	1.22	1.04	1.23	1.26	1.18
64	05/11/2008	0.89	1.93	1.59	1.58	1.70	1.21	1.2	1.25	1.22	1.3	1.45	1.57	1.44
66	07/11/2008	0.46	2.94	1.44	1.96	2.11	0.8	0.99	0.74	0.84	1.31	1.7	1.44	1.48

Table A.20 Results for NO_3-N for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
69	10/11/2008	0.39	2.82	1.69	2.41	2.31	0.96	1.76	0.6	1.11	1.24	1.69	1.53	1.49
73	14/11/2008	0.44	2.65	1.56	1.71	1.97	1.23	1.2	1.22	1.22	1.28	1.58	1.34	1.40
83	24/11/2008	0.76	3.18	3.2	2.02	2.80	1.56	1.11	1.44	1.37	1.32	1.56	1.72	1.53
119	29/12/2008	0.61	8.67	3.88	4.54	5.70	6.94	6.33	5.86	6.38	4.14	3.25	4.68	4.02
126	06/01/2009	0.42	8.4	6.27	6.06	6.91	9.04	10.34	8.58	9.32	7.65	6.42	7.36	7.14
128	08/01/2009	0.44	8.1	6.29	6.11	6.83	6.99	7.39	7.3	7.23	6.4	6.39	6.45	6.41
140	20/01/2009	0.45	8.64	10.12	7.1	8.62	8.31	9.98	6.95	8.41	8	7.81	6.68	7.50
150	30/01/2009	0.89	4.2	3.8	3.9	3.97	4.43	5.33	4.55	4.77	4.72	4.65	3.51	4.29
154	03/02/2009	0.7	3.62	0.41	0.79	1.61	4.43	2.45	3	3.29	1.45	1.83	2.3	1.86
160	09/02/2009	0.55	3.45	1.08	0.98	1.84	6.57	3.62	3.77	4.65	1.75	1.65	2.7	2.03
164	13/02/2009	0.54	5.89	4.5	2.54	4.31	7.09	6.84	7.41	7.11	3.7	4.9	3.52	4.04
167	16/02/2009	0.55	8.74	2.7	4.1	5.18	9.23	8.93	8.65	8.94	4.63	6.03	4.45	5.04
175	24/02/2009	0.8	8.74	2.7	4.1	5.18	9.23	8.93	-0.13	6.01	4.63	6.03	4.45	5.04
182	02/03/2009	0.46	5.387	2.147	2.394	3.31	14.82	6.438	8.14	9.80	4.73	5.31	3.658	4.57
192	13/03/2009	0.83	4.31	2.07	3.29	3.22	5.44	5.51	6.72	5.89	3.25	3.21	1.39	2.62
197	18/03/2009	0.61	5.41	3.25	3.33	4.00	4.89	5.53	5.82	5.41	3.96	2.65	3.11	3.24

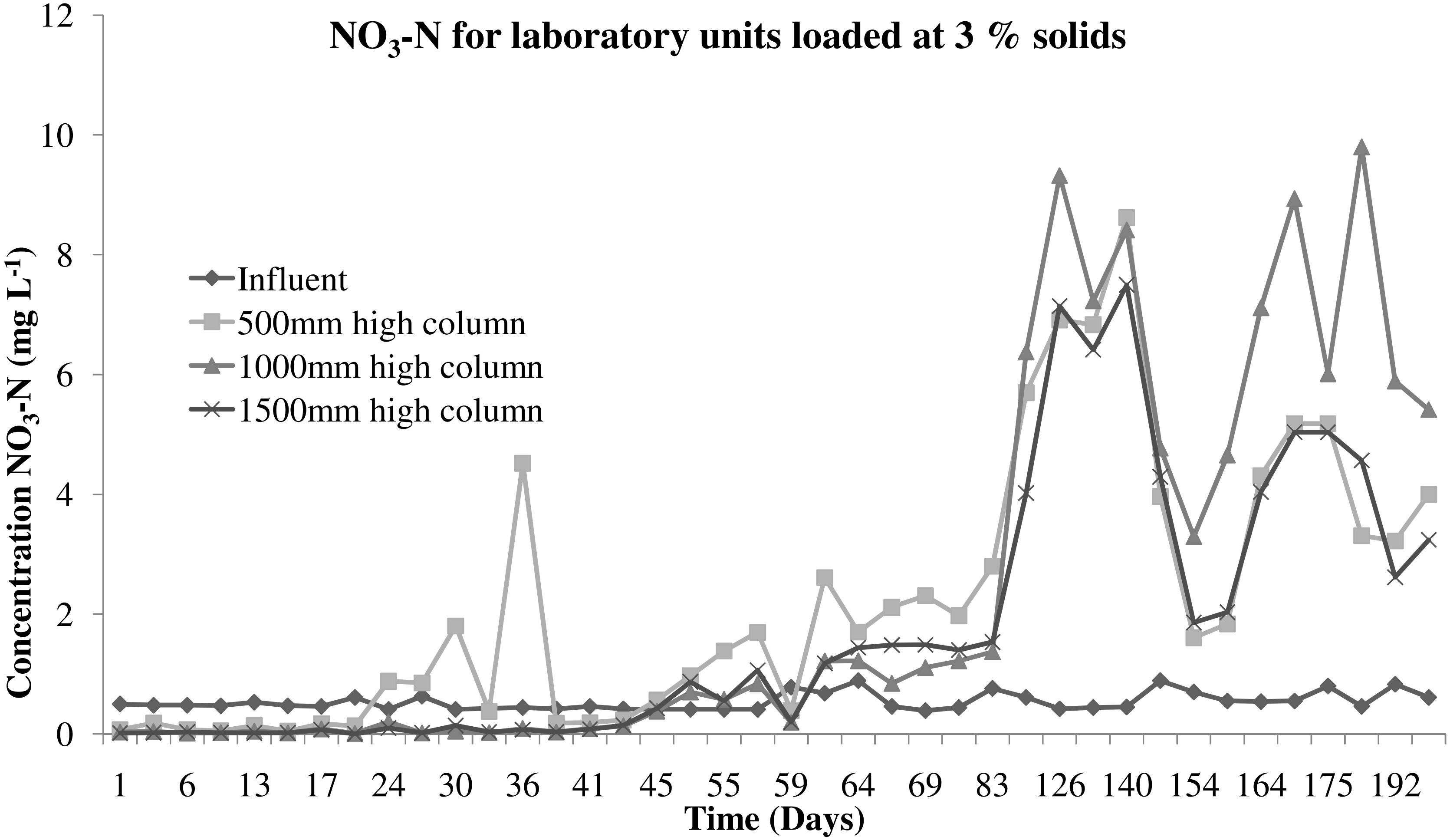

NO3-N for laboratory units loaded at 3 % solids
Concentration NO3-N (mg L-1)
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column
0
2
4
6
8
10
12
1
6
13
17
24
30
36
41
45
55
59
64
69
83
126
140
154
164
175
192

Table A.21 Results for NO_2-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008		-0.01	-0.01		-0.01	0	0	0	0.00	0.02	-0.01	0.05	0.02
3	18/06/2008		-0.02	-0.01	-0.02	-0.02	-0.01	-0.01	-0.01	-0.01	0.04	0		0.02
5	20/06/2008			-0.02	-0.03	-0.03	-0.01	-0.02	0	-0.01	0	-0.02	-0.01	-0.01
8	23/06/2008	0	-0.02	-0.03	0	-0.02	-0.02	-0.02	-0.01	-0.02	0	0.01	0.01	0.01
10	25/06/2008	0	-0.01	-0.03	-0.03	-0.02	-0.02	-0.02	-0.04	-0.03	0.01	0.03	-0.01	0.01
15	30/06/2008	0	0	0	0	0.00	0	0	0	0.00	0	0		0.00
17	02/07/2008	0	-0.05	-0.09	-0.09	-0.08	-0.09	-0.08	-0.09	-0.09	-0.09	-0.08	-0.9	-0.36
19	04/07/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
24	09/07/2008	0	-0.06	-0.07	-0.07	-0.07	-0.08	-0.06	-0.07	-0.07	-0.08	-0.08	-1.29	-0.48
31	16/07/2008	0	-0.06	-0.09	-0.1	-0.08	-0.09	-0.09	-0.08	-0.09	-0.07	-0.08	-1.37	-0.51
33	18/07/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
36	21/07/2008	0	-0.06	-0.07	-0.01	-0.05	-0.16	-0.08	-0.07	-0.10	-0.06	-0.07	-1.15	-0.43
38	23/07/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
40	25/07/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
43	28/07/2008	0	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
51	05/08/2008	0	0.19	0	0	0.06	0	0	0	0.00	0	0	0	0.00
57	11/08/2008	0	0	-0.07	0	-0.02	0	0	0	0.00	0	0	0	0.00
64	18/08/2008	0	0.47	0.3	0.1	0.29	-0.01	-0.04	0	-0.02	0.02	0.81	-0.04	0.26
68	22/08/2008	0	0.26	0.62	0.29	0.39	0.55	0	0.07	0.21	0	0	0	0.00
74	28/08/2008	0	0.8	1.05	0.5	0.78	0.03	-0.01	0.08	0.03	0	0	0	0.00
80	03/09/2008	0	1.89	4.67		3.28	1.31	0.52	0.98	0.94	0.94	0.53	0.29	0.59
85	08/09/2008	0	4.73	1.65	0.75	2.38	0.99	0.6	3.38	1.66	0.91	0.64	0.19	0.58
88	11/09/2008	0	0.76	0.02	0	0.26	0.3	0.51	0.28	0.36	0.15	0.55	0.57	0.42
92	15/09/2008	0	0.79	9.02	1.58	3.80	0.3	0.51	0.28	0.36	0.15	0.55	0.57	0.42
94	17/09/2008	0	3.69	1.95	0.51	2.05	2.05	0.73	0.38	1.05	0.23	0.38	0.78	0.46
96	19/09/2008	0	1.8	4.61	1.78	2.73	1.41	1.47	0.71	1.20	0.71	0.28	0.73	0.57
99	22/09/2008	0	1.65	6.04	1.36	3.02		1.55	0.7	1.13	0.67	0	0.14	0.27

Table A.22 Results for NO_2-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
107	29/09/2008	0	6	2.15	0.95	3.03	1.24	0.73	4.13	2.03	1.14	0.81	0.27	0.74
111	03/10/2008	0	0.97	0.74	0.37	0.69	0.94	0.64	10.96	4.18	3.53	0.99	0.29	1.60
114	06/10/2008	0	0.78	0.33	0.28	0.46	0.38	0.67	0.79	0.61	1.19	0.67	0.17	0.68
116	08/10/2008	0	0.49	0.19	0.04	0.24	0.82	0.85	0.83	0.83	0.48	1.19	0.22	0.63
121	13/10/2008	0	0.06	0.01	0	0.02	0.29	0.32	0.44	0.35	0.24		0.18	0.21
123	15/10/2008	0	0.09	0.05	0.01	0.05	0.7	0.73	0.47	0.63	0.22	1.98	0.3	0.83
125	17/10/2008	0	0.54	0	0	0.18	0.73	0.36	0.44	0.51	0.5	1.76	0.19	0.82
128	20/10/2008	0	0.12	0.23	0.05	0.13	2.1	2.64	2.5	2.41	0.98	2.18	1.32	1.49
136	28/10/2008	0	0.06	0.25	0.04	0.12	1.17	0.26	1.12	0.85	0.55	1.34	0.39	0.76
137	29/10/2008	0	0.15	0.82	0.83	0.60	2.72	0.71	0.3	1.24	0.07	0.35	0.5	0.31
139	31/10/2008	0		0.24	0.2	0.22	4.01		1.02	2.52	0.23	0.43	0.17	0.28
142	03/11/2008	0	0.14	0.39	0.18	0.24	1.43	0.21	0.38	0.67	0.15	0.1	0.26	0.17
144	05/11/2008	0	0.08	0.82	0.55	0.48	2.86	0.55	0.76	1.39	0.35	0.57	0.46	0.46
149	10/11/2008	0	0.1	0.32	0.52	0.31	0.14	0.97	0.72	0.61	0.42	0.51	0.51	0.48
153	14/11/2008	0	0.52	0.45	0.1	0.36	0.87	1.01	0.74	0.87	0.55	0.42	0.19	0.39
157	18/11/2008	0	0.79	0.52	0.71	0.67	0.82	0.91	1.01	0.91	0.39	0.42	0.72	0.51
160	21/11/2008	0	0.21	0.12	0.08	0.14	0.32	0.45	0.18	0.32	0.29	0.34	0.49	0.37
163	24/11/2008	0	0.1	0.42	0.81	0.44	0.16	0.42	0.24	0.27	0.31	0.48	0.51	0.43
171	02/12/2008	0	0.12	0.47	0.61	0.40	0.23	0.43	0.65	0.44	0.82	0.14	0.23	0.40
198	29/12/2008	0	0.63	0.68	0.61	0.64	0.44	0.44	0.47	0.45	0.4	0.13	0.21	0.25
206	06/01/2009	0	1.19	0.83	0.54	0.85	0.33	0.31	0.12	0.25	0.35	0.08	0.04	0.16
220	20/01/2009	0	0.01	0.09	0.14	0.08	0.61	0.14	0.19	0.31	0.11	0.21	0.23	0.18
230	30/01/2009	0	0.13	0.04	0.07	0.08	14	0.29	0.61	4.97	0.71	0.15	0.11	0.32
240	09/02/2009	0	0.31	0.11	0.02	0.15	0.01	0.02	0.05	0.03	0.05	0	0.06	0.04
244	13/02/2009	0	0.01	0.21	0.14	0.12	0.15	0.18	0.19	0.17	0.21	0.13	0.08	0.14
249	18/02/2009	0	0.07	0.23	0.13	0.14	0.1	0.26	0.07	0.14	0.23	0.08	0.06	0.12
254	24/02/2009	0	0.13	0.42	0.38	0.31	0.13	0.23	0.25	0.20	0.05	0.1	0.06	0.07

Table A.22 Results for NO_2-N for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
261	02/03/2009	0	0.03	0.019	0.135	0.06	0.132	0.339	0.102	0.19	0.156	0.288	0.092	0.18
272	13/03/2009	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
277	18/03/2009	0	0.01	0.09	0.1	0.07	0.01	0.23	0.04	0.09	0.09	0.01	0.05	0.05

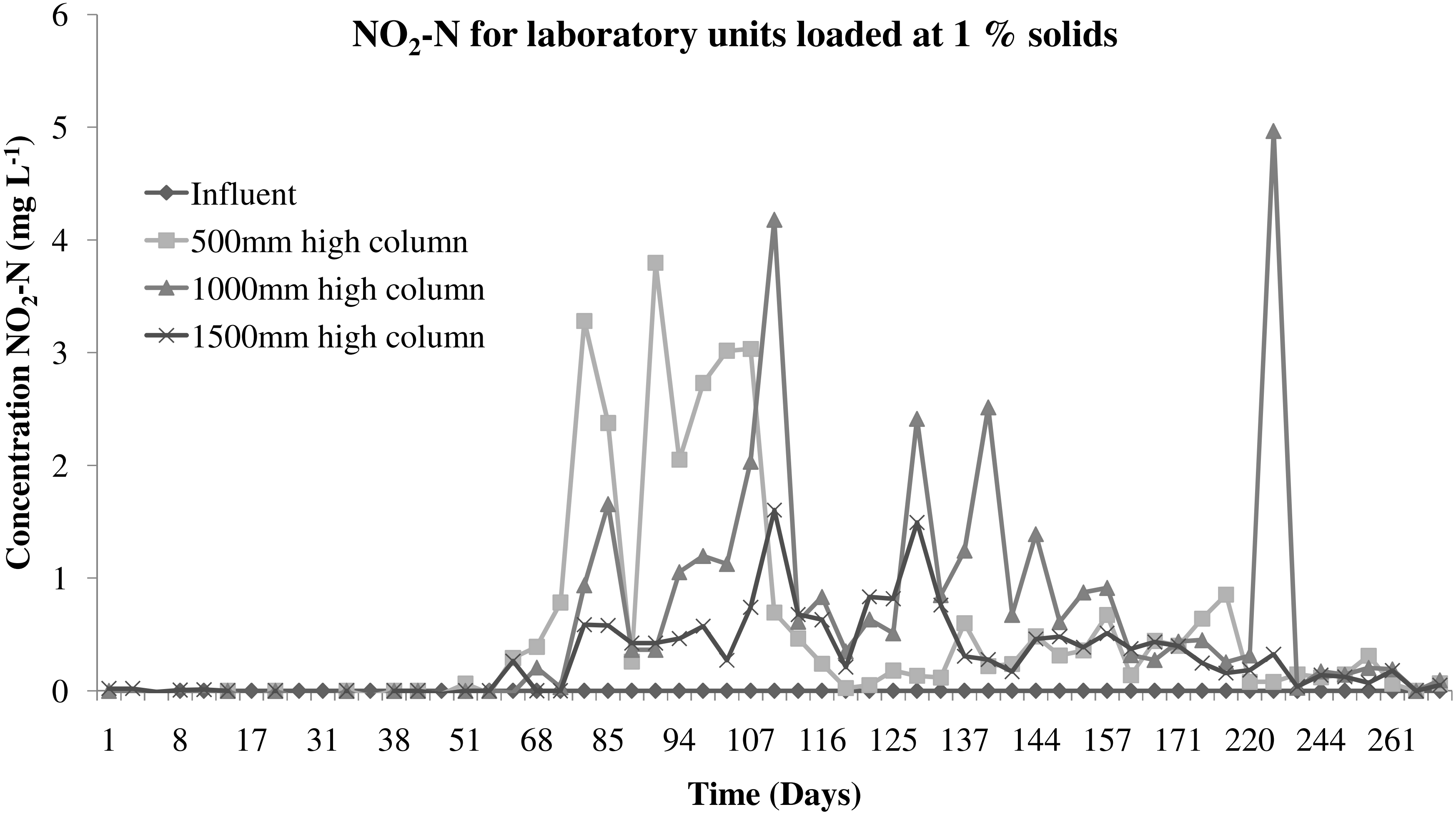
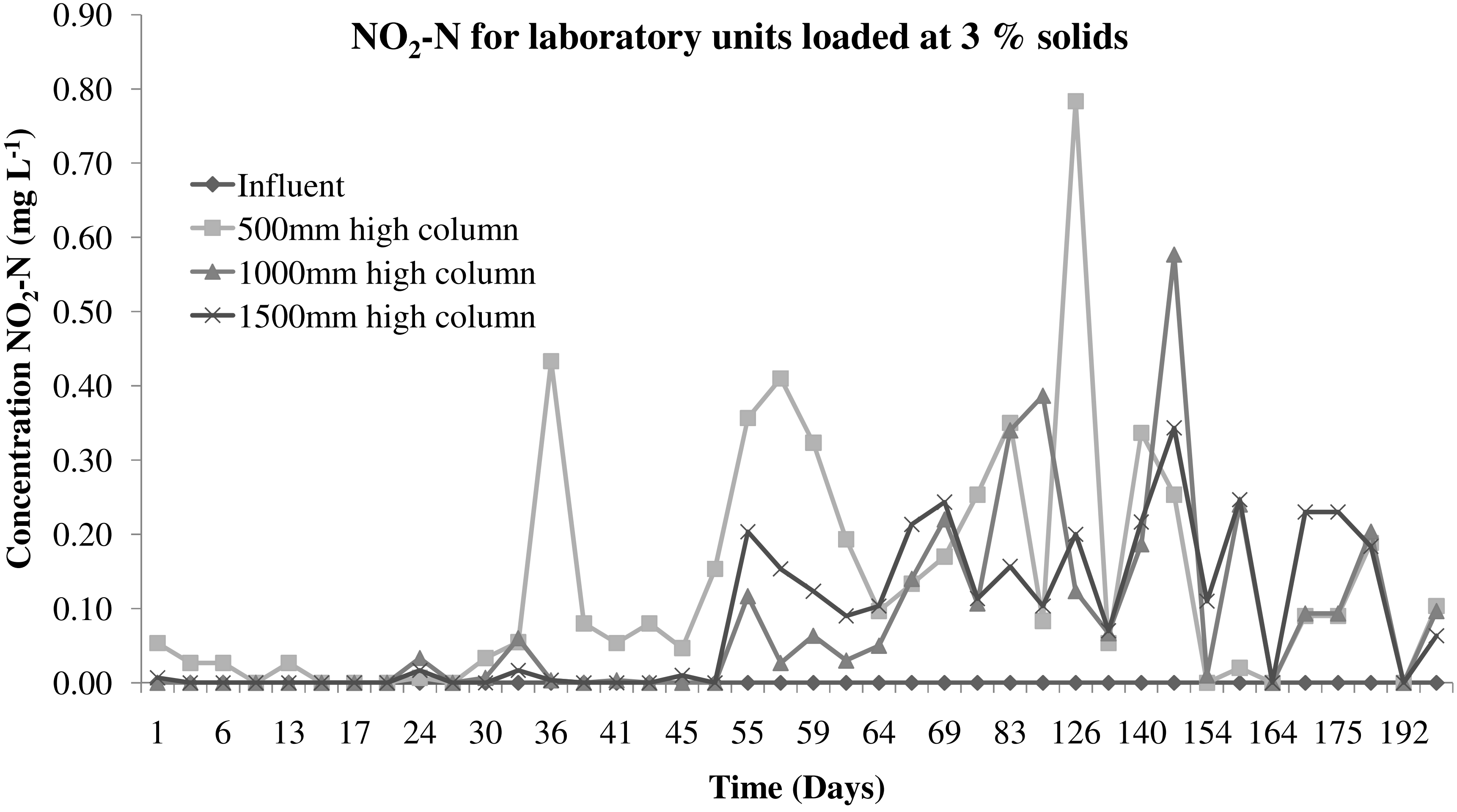

NO₂-N for laboratory units loaded at 1 % solids
Concentration NO₂-N (mg L⁻¹)
0
1
2
3
4
5
6
Influent
500mm high column
1000mm high column
1500mm high column
1
8
17
31
38
51
68
85
94
107
116
125
137
144
157
171
220
244
261
Time (Days)

Table A.23 Results for NO_2-N for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	0	0.08	0.01	0.07	0.05	0	0	0	0.00	0.02	0	0	0.01
3	05/09/2008	0	0	0	0.08	0.03	0	0	0	0.00	0	0	0	0.00
6	08/09/2008	0	0.01	0	0.07	0.03	0	0	0	0.00	0	0	0	0.00
9	11/09/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
13	15/08/2008	0	0.01	0	0.07	0.03	0	0	0	0.00	0	0	0	0.00
15	17/08/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
17	19/08/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
20	22/08/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
24	26/08/2008	0	0	0.02	0	0.01	0.1	0	0	0.03	0	0.05	0	0.02
27	29/08/2008	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
30	02/10/2008	0	0.09	0.01	0	0.03	0.02	0	0	0.01	0	0	0	0.00
34	06/10/2008	0	0.045	0.019	0.1	0.05	0.08	0.07	0.03	0.06	0.01	0	0.04	0.02
36	08/10/2008	0	0.9	0.28	0.12	0.43	0.01	0	0	0.00	0	0.01	0	0.00
38	10/10/2008	0	0.16		0	0.08		0	0	0.00	0	0	0	0.00
41	13/10/2008	0	0.15	0.01	0	0.05	0	0	0.01	0.00	0	0	0	0.00
43	15/10/2008	0	0.21	0.03	0	0.08	0	0	0	0.00	0	0	0	0.00
45	17/10/2008	0	0.14	0	0	0.05	0	0	0	0.00	0.03	0	0	0.01
48	20/10/2008	0	0.4	0.06	0	0.15	0	0	0	0.00	0	0	0	0.00
55	28/10/2008	0	0.77	0.22	0.08	0.36	0.1	0.18	0.07	0.12	0.38	0.16	0.07	0.20
56	29/10/2008	0	0.92	0.24	0.07	0.41	0.06	0.02	0	0.03	0.29	0.09	0.08	0.15
59	31/10/2008	0	0.81	0.15	0.01	0.32	0.02	0.12	0.05	0.06	0.28	0.05	0.04	0.12
62	03/11/2008	0	0.46	0.09	0.03	0.19	0.01	0.06	0.02	0.03	0.24	0.02	0.01	0.09
64	05/11/2008	0	0.26	0.03	0	0.10	0.04	0.08	0.03	0.05	0.27	0.02	0.02	0.10
66	07/11/2008	0	0.18	0.01	0.21	0.13	0.17	0.12	0.13	0.14	0.32	0.19	0.13	0.21

Table A.24 Results for NO_2-N for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
69	10/11/2008	0	0.09	0.1	0.32	0.17	0.18	0.21	0.27	0.22	0.39	0.2	0.14	0.24
73	14/11/2008	0	0.32	0.18	0.26	0.25	0.14	0.08	0.1	0.11	0.19	0.01	0.14	0.11
83	24/11/2008	0	0.03	0.92	0.1	0.35	0.42	0.31	0.29	0.34	0.17	0.11	0.19	0.16
119	29/12/2008	0	0.09	0.05	0.11	0.08	0.52	0.16	0.48	0.39	0.09	0.15	0.07	0.10
126	06/01/2009	0	2.35	0	0	0.78	0.15	0.12	0.1	0.12	0.05	0.44	0.11	0.20
128	08/01/2009	0	0.11	0.04	0.01	0.05	0.08	0.04	0.08	0.07	0.03	0.13	0.05	0.07
140	20/01/2009	0	0.81	0.09	0.11	0.34	0.14	0.23	0.19	0.19	0.23	0.11	0.31	0.22
150	30/01/2009	0	0.01	0.14	0.61	0.25	0.69	0.81	0.23	0.58	0.49	0.13	0.41	0.34
154	03/02/2009	0	0	0	0	0.00	0	0	0.03	0.01	0	0.28	0.05	0.11
160	09/02/2009	0	0.03	0.02	0.01	0.02	0.32	0.17	0.23	0.24	0.16	0.37	0.21	0.25
164	13/02/2009	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
167	16/02/2009	0	0.1	0.09	0.08	0.09	0.15	0	0.13	0.09	0.08	0.44	0.17	0.23
175	24/02/2009	0	0.1	0.09	0.08	0.09	0.15	0	0.13	0.09	0.08	0.44	0.17	0.23
182	02/03/2009	0	0.04	0.015	0.51	0.19	0.29	0.174	0.147	0.20	0.001	0.353	0.197	0.18
192	13/03/2009	0	0	0	0	0.00	0	0	0	0.00	0	0	0	0.00
197	18/03/2009	0	0.21	0.01	0.09	0.10	0.1	0.09	0.1	0.10	0.14	0.02	0.03	0.06



NO$_2$-N for laboratory units loaded at 3 % solids
Concentration NO$_2$-N (mg L^{-1})
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Influent
500mm high column
1000mm high column
1500mm high column
1
6
13
17
24
30
36
41
45
55
59
64
69
83
126
140
154
164
175
192
Time (Days)

Table A.25 Results for PO_4-P for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008	5.112	11.53	12.82		12.18	6.55	11.72	9.91	9.39	6.51	6.49	6.3	6.43
3	18/06/2008	5.578	8.88	9.28	8.6	8.92	9.08	11.46	9.44	9.99	6.71	6.49		6.60
5	20/06/2008	4.993	8.88	9.28	8.6	8.92	9.08	11.46	9.44	9.99	6.71	6.49		6.60
8	23/06/2008	4.581	9.15	10.41	8.97	9.51	13.07	10.02	7.74	10.28	8.08	7.06	6.52	7.22
10	25/06/2008	4.394	9.01	8.61	11.07	9.56	12.55	9.06	10.14	10.58	7.61	5.58	6.22	6.47
15	30/06/2008	4.301	7.15	7.78	7.92	7.62	9.47	9.33	8.54	9.11	7.89	7.93		7.91
17	02/07/2008	4.439	3.96	6.54	6.98	5.83	8.55	8.52	6.02	7.70	7.03	7.51	6.76	7.10
19	04/07/2008	4.517	3.84	3.72	4.79	4.12	8.28	8.02	6.2	7.50	7.21	6.03	7.68	6.97
24	09/07/2008	4.763	4.61	7.2	5.12	5.64	5.69	7.23	4.44	5.79	5.96	5.52	5.97	5.82
31	16/07/2008	4.696	4.5	5	2.3	3.93	7.05	5.48	5.37	5.97	4.42	5.31	5.43	5.05
33	18/07/2008	4.82	3.69	4.51	5.63	4.61	6.53	5.6	4.77	5.63	5.31	4.11	7.28	5.57
36	21/07/2008	4.691	2.74	4.51	3.87	3.71	5.35	4.76	4.57	4.89	4.77	4.81	5.13	4.90
38	23/07/2008	2.226	4.82	3.61	4.38	4.27	5.78	5.01	3.78	4.86	5.98	5.87	5.13	5.66
40	25/07/2008	2.237	7.39	6.72	7.74	7.28	8.9	7.94	6.86	7.90	7.11	7.9	3.87	6.29
43	28/07/2008	2.256	6.8	7.48	6.72	7.00	7.78	6.24	5.48	6.50	4.55	5.24	5.19	4.99
51	05/08/2008	2.23	4.21	8.16	7.1	6.49	5.04	5.13	4.53	4.90	4.35	7.19	4.9	5.48
57	11/08/2008	2.275	2.74	4.51	3.87	3.71	5.35	4.76	4.57	4.89	4.77	4.81	5.13	4.90
64	18/08/2008	2.26	4.37	5.33	5.6	5.10	5.41	5.27	4.64	5.11	3.62	2.29	4.97	3.63
68	22/08/2008	2.265	5.4	4.88	5.38	5.22	5.25	5.81	4.99	5.35	4.6	5.85	4.78	5.08
74	28/08/2008	2.271	5.43	5.92	6.93	6.09	7.71	7.44	5.71	6.95	4.48	6.91	4.23	5.21
80	03/09/2008	2.289	1.89	4.67		3.28	1.31	0.52	0.98	0.94	0.94	0.53	0.29	0.59
85	08/09/2008	2.292	4.51	3.48	4.92	4.30	5.12	4.21	2.43	3.92	5.14	3.96	3.01	4.04
88	11/09/2008	4.509	4.46	3.45	5.71	4.54	5.53	3.71	0.53	3.26	5.22	3.42	2.14	3.59
92	15/09/2008	4.526	1.78	5.71	4.31	3.93	2.97	4.15	1.9	3.01	5.14	5.23	4.69	5.02
94	17/09/2008	2.294	2.13	4.48	5.36	3.99	4.88	3.49	3.85	4.07	5.2	4.69	1.96	3.95
96	19/09/2008	2.283	2.8	3.31	2.64	2.92	4	3.2	3.85	3.68	3.93	5.49	2.02	3.81
99	22/09/2008	2.28	2.97	2.51	5.7	3.73		3.95	5.27	4.61	4.77	5.91	4.03	4.90

Table A.26 Results for PO_4-P for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
107	29/09/2008	2.286	1.78	5.71	4.31	3.93	2.97	4.15	1.9	3.01	5.14	5.23	4.69	5.02
111	03/10/2008	4.852	2.79	4.67	5.78	4.41	4.73	4.85	1.84	3.81	3.28	5.35	3.42	4.02
114	06/10/2008	5.374	3.78	6.71	6.29	5.59	5.35	5.66	4.14	5.05	4.16	6.61	4.97	5.25
116	08/10/2008	5.302	5.37	6.8	7.3	6.49	5.66	2.73	4.52	4.30	5.71	5.8	5.33	5.61
121	13/10/2008	5.274	4.13	7.63	7.59	6.45	8.01	7.52	5.29	6.94	4.99		3.75	4.37
123	15/10/2008	5.213	5.59	8.11	9	7.57	6.98	6.74	4.87	6.20	5.94	4.64	5.95	5.51
125	17/10/2008	4.303	9.98	27.46	22.14	19.86	26.04	26.22	9.66	20.64	9.04	8.19	9.37	8.87
128	20/10/2008	4.98	22.81	23.87	26.26	24.31	22.9	9.28	7.17	13.12	8.54	8.03	6.35	7.64
136	28/10/2008	5.326	28.79	28.67	31.53	29.66	27.2	27.02	8.25	20.82	8.52	7.71	8.56	8.26
137	29/10/2008	5.389	8.52	10.46	9.4	9.46	6.5	9.17	6.88	7.52	7.04	6.3	6.1	6.48
139	31/10/2008	5.28		8.36	6.99	7.68	7.07		8.63	7.85	7.01	5.48	5.83	6.11
142	03/11/2008	5.204	13.56	17.004	9.99	13.52	7.71	13.66	6.78	9.38	8.15	7.865	7.92	7.98
144	05/11/2008	5.246	9.28	9.78	8	9.02	6.57	15.94	5.44	9.32	6.71	5.43	14.89	9.01
149	10/11/2008	3.348	8.97	7.32	9.14	8.48	6.23	6.97	7.14	6.78	6.97	7.5	10.21	8.23
153	14/11/2008	4.182	14.14	11.23	9.01	11.46	10.42	11.92	9.48	10.61	11.21	9.48	10.21	10.30
157	18/11/2008	4.384	9.63	8.27	9.41	9.10	10.14	9.07	9.82	9.68	7.42	8.14	9.23	8.26
160	21/11/2008	5.109	8.14	9.21	11.14	9.50	8.14	9.34	7.14	8.21	11.23	9.14	9.71	10.03
163	24/11/2008	3.984	9.38	9.17	10.92	9.82	7.23	8.42	9.19	8.28	11.23	6.42	7.14	8.26
171	02/12/2008	3.842	10.41	11.23	9.41	10.35	7.23	9.14	8.67	8.35	10.14	11.34	9.23	10.24
206	06/01/2009	3.481	6.84	9.35	8.33	8.17	8.32	10.37	9.21	9.30	6.37	6.68	6.1	6.38
220	20/01/2009	4.021	8.6	7.23	7.72	7.85	8.99	9.23	8.72	8.98	9.19	9.23	8.23	8.88
230	30/01/2009	4.523	9.21	7.36	8.41	8.33	7.99	8.24	8.99	8.41	8.14	7.36	7.77	7.76
240	09/02/2009	5.932	7.85	9.28	7.62	8.25	10.43	11.97	9.25	10.55	6.73	5.67	9.07	7.16
244	13/02/2009	5.104	10.84	11.24	11.94	11.34	10.45	14.67	14.12	13.08	6.21	7.18	9.53	7.64
254	24/02/2009	5.201	9.31	9.38	9.61	9.43	8.56	10.1	10.1	9.59	9.67	6.18	2.83	6.23
261	02/03/2009	4.832	3.133	6.67	4.901	4.90	11.393	12.265	10.293	11.32	10.39	12.135	12.114	11.55
272	13/03/2009	4.531	9.5	10.14	9.12	9.59	9.02	11.22	10.48	10.24	4.53	5.69	2.06	4.09
277	18/03/2009	4.341	10.01	9.4	8.34	9.25	9.21	8.41	9.01	8.88	6.52	7.23	6.23	6.66

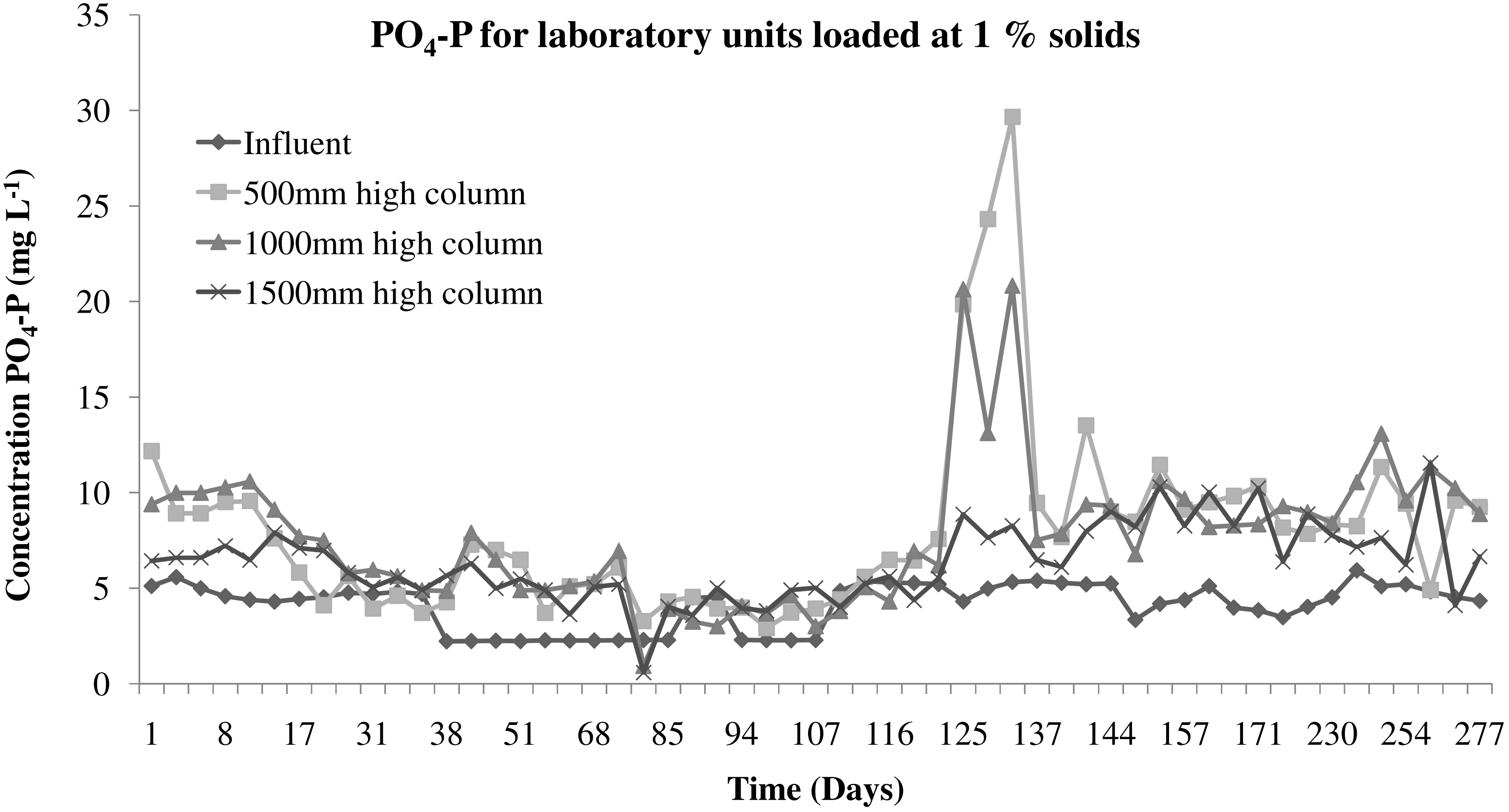
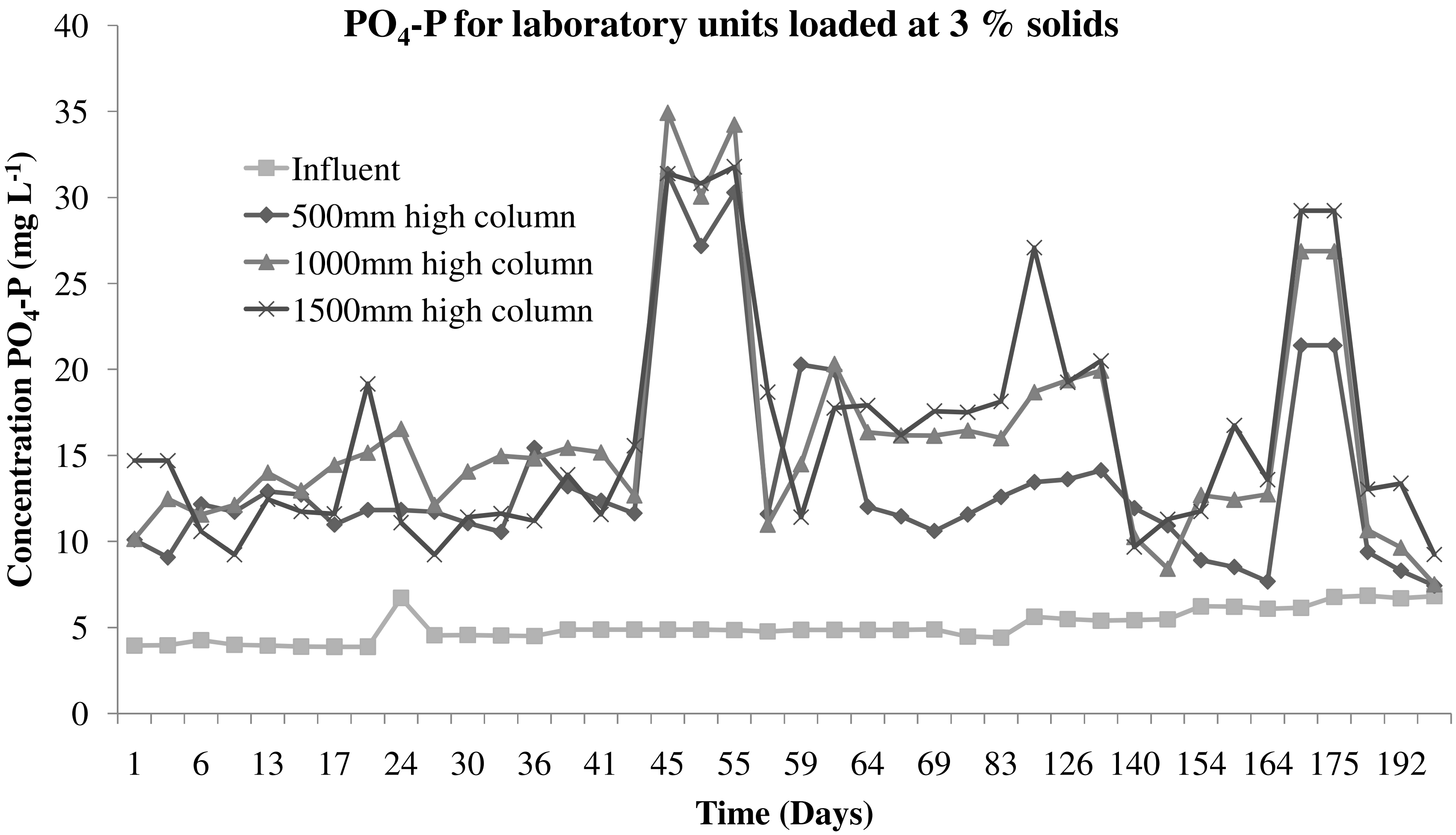

PO4-P for laboratory units loaded at 1 % solids
Influent
500mm high column
1000mm high column
1500mm high column
Concentration PO4-P (mg L-1)
0
5
10
15
20
25
30
35
1
8
17
31
38
51
68
85
94
107
116
125
137
144
157
171
230
254
277
Time (Days)

Table A.27 Results for PO_4-P for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	3.95	8.94	10.24	11.12	10.10	12.42	5.75	12.29	10.15	20.88	11.96	11.27	14.70
3	05/09/2008	3.96	8.73	10.24	8.25	9.07	12.42	12.71	12.29	12.47	20.88	11.96	11.27	14.70
6	08/09/2008	4.26	10.54	13.11	12.84	12.16	11.33	12.02	11.32	11.56	12.39	9.61	9.77	10.59
9	11/09/2008	3.99	9.76	12.89	12.52	11.72	11.36	12.18	12.82	12.12	12.83	9.99	4.86	9.23
13	15/08/2008	3.95	11.24	14.03	13.43	12.90	13.69	13.68	14.64	14.00	14.58	11.71	11.09	12.46
15	17/08/2008	3.89	10.63	13.92	13.64	12.73	12.19	13.05	13.65	12.96	13.83	10.8	10.57	11.73
17	19/08/2008	3.88	9.75	11.48	11.69	10.97	11.96	14.41	16.99	14.45	14.23	10.66	9.93	11.61
20	22/08/2008	3.88	9.45	12.92	13.12	11.83	12.92	15.18	17.37	15.16	13.99	10.81	32.69	19.16
24	26/08/2008	6.72	9.45	12.81	13.21	11.82	14.53	16.71	18.4	16.55	11.21	11.72	10.37	11.10
27	29/08/2008	4.55	9.76	12.89	12.52	11.72	11.36	12.18	12.82	12.12	12.83	9.99	4.86	9.23
30	02/10/2008	4.56	11.19	10.89	11.1	11.06	12.13	14.6	15.48	14.07	14.45	11.43	8.35	11.41
34	06/10/2008	4.53	7.76	11.49	12.42	10.56	12.81	15.62	16.5	14.98	15.55	11.36	7.94	11.62
36	08/10/2008	4.5	19.96	13.13	13.22	15.44	13.44	15.01	16.05	14.83	14.43	11	8.17	11.20
38	10/10/2008	4.88	10.63		15.78	13.21		14.8	16.09	15.45	16.61	14.11	10.89	13.87
41	13/10/2008	4.88	8.33	13.27	15.49	12.36	15.28	15.16	15.08	15.17	14.13	11.45	9.13	11.57
43	15/10/2008	4.88	8.73	12.82	13.36	11.64	11.92	13.45	12.65	12.67	14.15	15.42	17.14	15.57
45	17/10/2008	4.88	29.13	31.77	33.2	31.37	33.96	34.66	36.17	34.93	33.83	31.91	28.4	31.38
48	20/10/2008	4.88	23.57	29.78	28.18	27.18	29.1	29.64	31.44	30.06	30.54	30.66	31.24	30.81
55	28/10/2008	4.85	29.56	29.4	31.89	30.28	33.18	35.61	33.93	34.24	30.03	32.82	32.49	31.78
56	29/10/2008	4.77	7.47	13.13	14.17	11.59	6.99	10.12	15.82	10.98	17.34	15.08	23.63	18.68
59	31/10/2008	4.86	25.91	11.69	23.24	20.28	9.96	9.42	24.1	14.49	10.94	15.96	7.35	11.42
62	03/11/2008	4.86	22.02	20.45	17.43	19.97	19.78	20.85	20.32	20.32	18.44	17.54	17.31	17.76
64	05/11/2008	4.86	9.38	12.67	13.99	12.01	15.03	15.31	18.71	16.35	18.44	21.37	13.94	17.92
66	07/11/2008	4.86	10.21	11.97	12.21	11.46	14.98	16.21	17.29	16.16	19.21	17.21	12.12	16.18

Table A.28 Results for PO_4-P for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
69	10/11/2008	4.89	11.21	11.37	9.24	10.61	17.03	15.29	16.14	16.15	18.21	19.31	15.21	17.58
73	14/11/2008	4.47	11.32	9.38	13.99	11.56	16.14	15.97	17.23	16.45	19.1	18.978	14.45	17.51
83	24/11/2008	4.41	13.23	11.71	12.83	12.59	15.94	14.97	17.12	16.01	16.14	19.32	18.97	18.14
119	29/12/2008	5.62	12.21	13.91	14.23	13.45	19.41	17.32	19.32	18.68	13.72	18.12	49.41	27.08
126	06/01/2009	5.49	11.85	14.38	14.61	13.61	19.04	18.03	21.05	19.37	21.21	18.38	18.17	19.25
128	08/01/2009	5.4	11.62	14.04	16.72	14.13	19.49	18.71	21.6	19.93	21.63	20.23	19.62	20.49
140	20/01/2009	5.43	11.68	12.21	11.92	11.94	10.41	11.23	9.14	10.26	9.11	9.79	10.14	9.68
150	30/01/2009	5.47	9.14	11.23	12.41	10.93	8.97	7.14	9.13	8.41	11.23	10.51	12.14	11.29
154	03/02/2009	6.23	7.77	8.8	10.15	8.91	13.07	13.01	12.01	12.70	13.93	11.99	9.32	11.75
160	09/02/2009	6.21	7.38	8.29	9.86	8.51	12.04	12.35	12.9	12.43	18.53	16.91	14.81	16.75
164	13/02/2009	6.09	6.49	7.51	9.02	7.67	13.11	12.89	12.21	12.74	15.48	13.28	12.03	13.60
167	16/02/2009	6.15	20.91	20.85	22.42	21.39	27.92	26.53	26.16	26.87	30.32	29.86	27.52	29.23
175	24/02/2009	6.77	20.91	20.85	22.42	21.39	27.92	26.53	26.16	26.87	30.32	29.86	27.52	29.23
182	02/03/2009	6.85	8.651	10.07	9.454	9.39	10.718	11.029	10.221	10.66	12.953	13.954	12.208	13.04
192	13/03/2009	6.7	9.34	7.46	8.09	8.30	9.91	9.76	9.26	9.64	12.93	13.37	13.82	13.37
197	18/03/2009	6.82	7.92	8.14	6.23	7.43	9.14	7.23	6.14	7.50	8.46	9.14	10.12	9.24



PO$_4$-P for laboratory units loaded at 3 % solids
Concentration PO$_4$-P (mg L^{-1})
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column
0
5
10
15
20
25
30
35
40
1
6
13
17
24
30
36
41
45
55
59
64
69
83
126
140
154
164
175
192

Table A.29 Results for SS for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	16/06/2008	10000	9	18		13.50	8	6	9	7.67	4	7		5.50
3	18/06/2008	10000	3	20	13	12.00	3	4	5	4.00	7	5		6.00
5	20/06/2008	10000		11	9	10.00	8	4	3	5.00	9	8	7	8.00
8	23/06/2008	10000	8	26	21	18.33	4	9	3	5.33	0	14	2	5.33
10	25/06/2008	10000	4	26	16	15.33	4	2	2	2.67	5	8	3	5.33
15	30/06/2008	10000	5	14	5	8.00	10	5	4	6.33	0	5		2.50
17	02/07/2008	10000	0	7	6	4.33	3	5	1	3.00	6	6	4	5.33
19	04/07/2008	10000	4	5	0	3.00	3	1	5	3.00	1	0	0	0.33
24	09/07/2008	10000	12	12	14	12.67	8	9	7	8.00	9	9	3	7.00
31	16/07/2008	10000	12	14	29	18.33	8	11	10	9.67	12	12	10	11.33
33	18/07/2008	10000	13	17	20	16.67	6	7	23	12.00	16	0	8	8.00
36	21/07/2008	10000	13	14	12	13.00	116	7	6	43.00	8	11	4	7.67
38	23/07/2008	10000	7	11	9	9.00	8	6	8	7.33	4	5	4	4.33
40	25/07/2008	10000	1	16	4	7.00	0	7	6	4.33	13	7	6	8.67
43	28/07/2008	10000	5	10	4	6.33	5	8	8	7.00	7	17	10	11.33
51	05/08/2008	10000	1	0	2	1.00	1	1	2	1.33	3	5	4	4.00
57	11/08/2008	10000	7	8	1	5.33	1	0	6	2.33	7	8	5	6.67
64	18/08/2008	10000	3	9	6	6.00	9	2	3	4.67	5	2	5	4.00
68	22/08/2008	10000	9	8	4	7.00	4	5	0	3.00	1	4	0	1.67
74	28/08/2008	10000	4	5	8	5.67	1	2	6	3.00	2	1	1	1.33
80	03/09/2008	10000	1	3		2.00	7	8	7	7.33	1	0	3	1.33
85	08/09/2008	10000	1	3	4	2.67	0	8	7	5.00	1	0	3	1.33
88	11/09/2008	10000	5	4	12	7.00	6	3	5	4.67	6	6	7	6.33
92	15/09/2008	10000	4	9	12	8.33	28	35	7	23.33	5	1	6	4.00
94	17/09/2008	10000	7	3	6	5.33	6	19	12	12.33	3	1	2	2.00
96	19/09/2008	10000	2	6	1	3.00	6	9	7	7.33	17	20	12	16.33
99	22/09/2008	10000	2	6	1	3.00	0	39	7	15.33	17	20	12	16.33
107	29/09/2008	10000	5	5	1	3.67	14	2	3	6.33	6	0	1	2.33

Table A.30 Results for SS for the laboratory scale woodchip filter study for three different heights loaded at 1 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
111	03/10/2008	10000	20	5	22	15.67	8	11	8	9.00	9	9	9	9.00
114	06/10/2008	10000	0	7	9	5.33	2	0	0	0.67	5	4	7	5.33
116	08/10/2008	10000	6	3	3	4.00	3	1	2	2.00	6	1	1	2.67
121	13/10/2008	10000	1	0	6	2.33	5	10	1	5.33	10		0	5.00
123	15/10/2008	10000	8	0	0	2.67	-5	0	13	2.67	0	1	1	0.67
125	17/10/2008	10000	8	0	0	2.67	32	0	13	15.00	0	1	1	0.67
128	20/10/2008	10000	19	40	7	22.00	1	0	0	0.33	0	3	2	1.67
136	28/10/2008	10000	12	8	4	8.00	0	0	0	0.00	7	-2	0	1.67
137	29/10/2008	10000	0	1	4	1.67	1	4	7	4.00	5	0	7	4.00
139	31/10/2008	10000		39	6	22.50	13		13	13.00	0	11	7	6.00
142	03/11/2008	10000	5	4	3	4.00	2	5	3	3.33	6	7	4	5.67
144	05/11/2008	10000	9	5	5	6.33	19	11	8	12.67	9	20	8	12.33
149	10/11/2008	10000	2	2	0	1.33	3	0	2	1.67	5	2	6	4.33
153	14/11/2008	10000	1	1	2	1.33	1	1	0	0.67	1	0	1	0.67
157	18/11/2008	10000	4	3	5	4.00	4	6	3	4.33	0	2	1	1.00
160	21/11/2008	10000	9	13	6	9.33	6	9	13	9.33	8	7	8	7.67
163	24/11/2008	10000	4	3	9	5.33	15	9	12	12.00	11	2	13	8.67
171	02/12/2008	10000	3	11	4	6.00	8	13	6	9.00	6	8	2	5.33
206	06/01/2009	10000	4	16	0	6.67	0	11	13	8.00	11	5	9	8.33
220	20/01/2009	10000	2	9	9	6.67	13	6	7	8.67	5	4	4	4.33
230	30/01/2009	10000	11	4	2	5.67	3	8	6	5.67	9	6	2	5.67
240	09/02/2009	10000	3	5	4	4.00	0	0	7	2.33	0	0	3	1.00
244	13/02/2009	10000	2	3	2	2.33	3	1	1	1.67	0	2	0	0.67
249	18/02/2009	10000	3	6	9	6.00	0	1	3	1.33	0	2	0	0.67
254	24/02/2009	10000	6	2	1	3.00	2	1	1	1.33	1	1	3	1.67
261	02/03/2009	10000	2	1	1	1.33	0	1	2	1.00	1	0	3	1.33
272	13/03/2009	10000	1	3	3	2.33	2	3	1	2.00	0	1	2	1.00
277	18/03/2009	10000	0	5	3	2.67	5	3	3	3.67	4	2	3	3.00

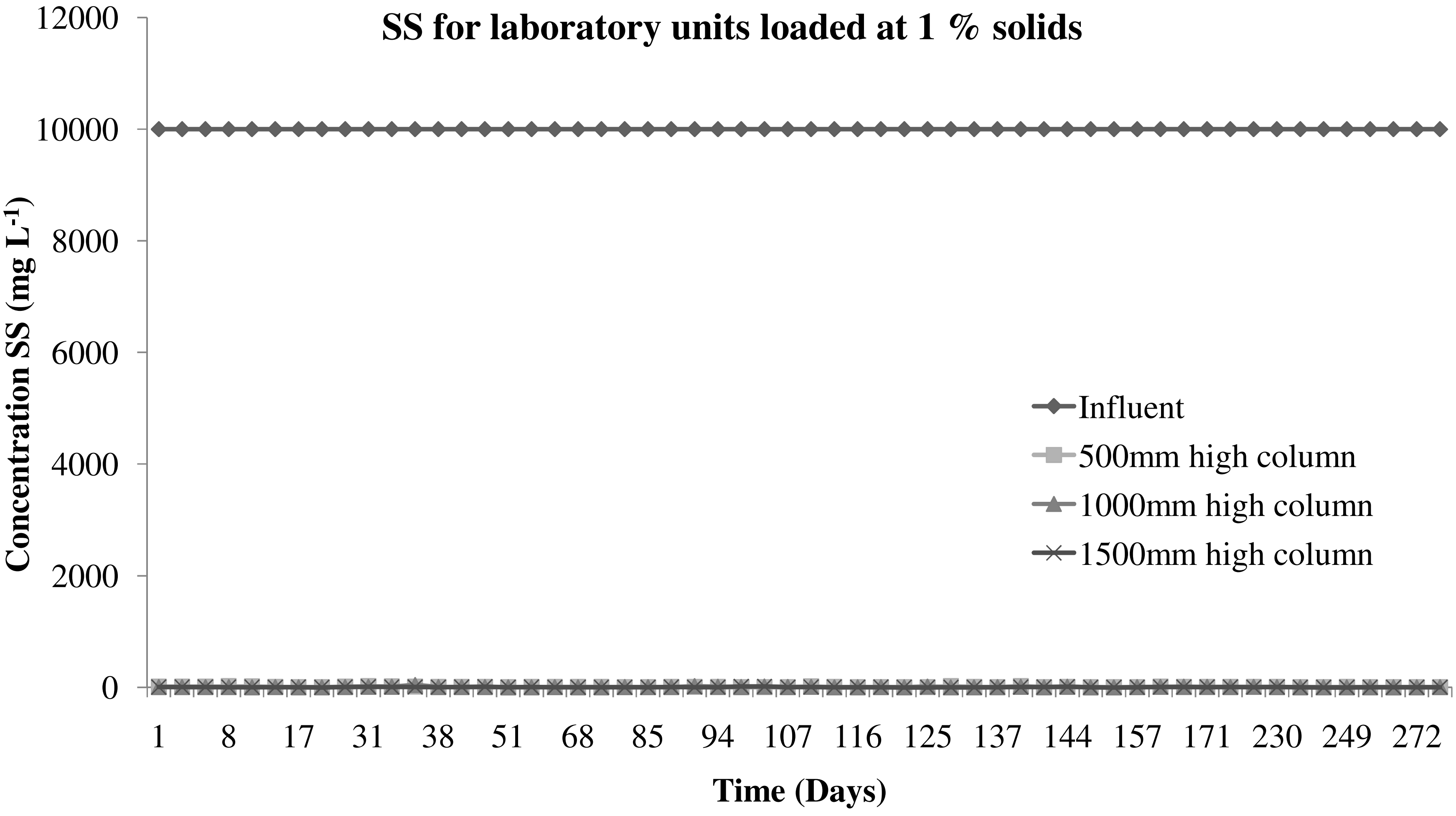
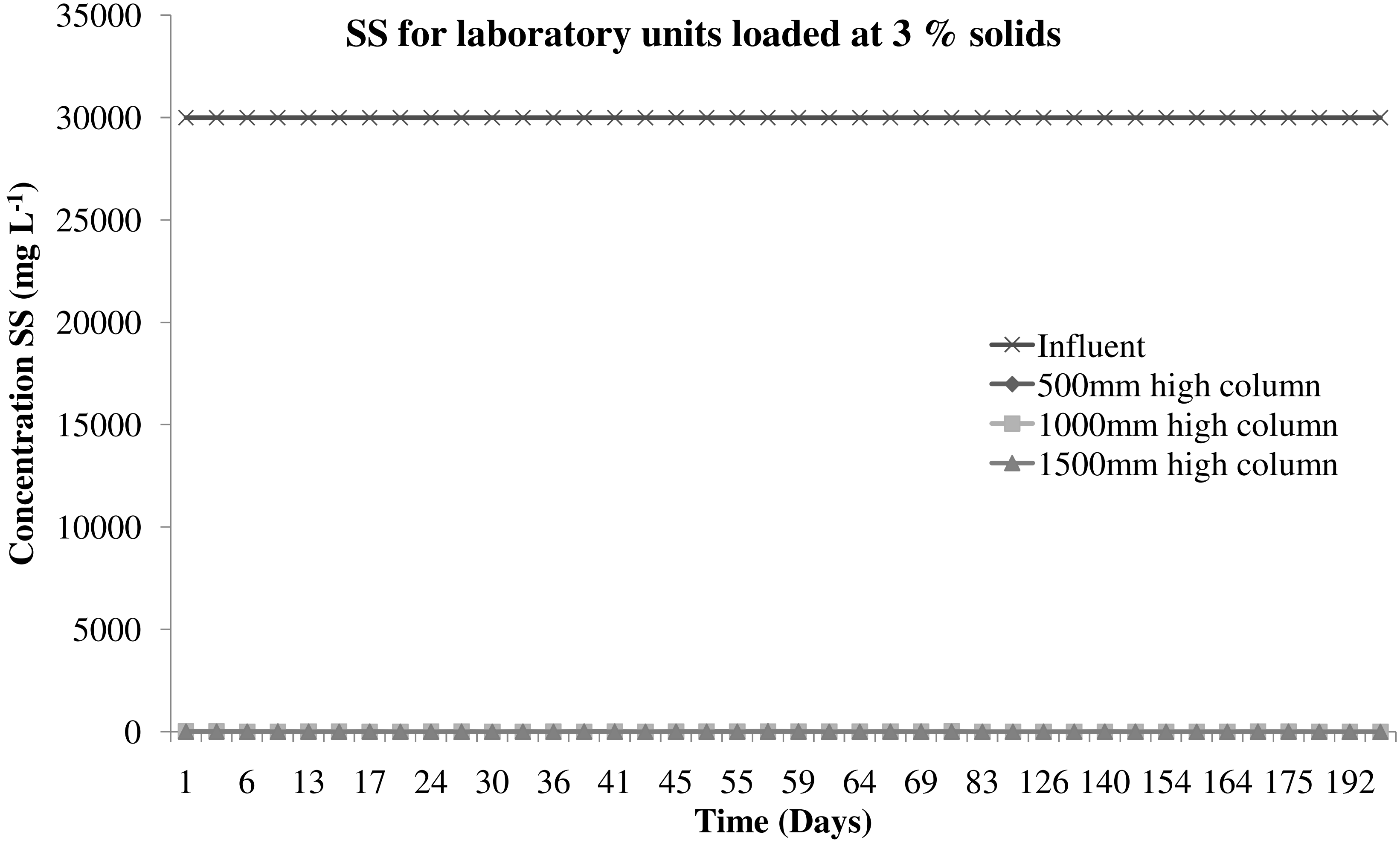

SS for laboratory units loaded at 1 % solids
Concentration SS (mg L-1)
12000
10000
8000
6000
4000
2000
0
1
8
17
31
38
51
68
85
94
107
116
125
137
144
157
171
230
249
272
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Table A.31 Results for SS for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
1	03/09/2008	30000	19	17	17	18	49	16	19	28	13	9	11	11
3	05/09/2008	30000	23	16	21	20	19	30	10	20	19	10	8	12
6	08/09/2008	30000	10	4	6	7	8	2	2	4	8	10	12	10
9	11/09/2008	30000	13	22	21	19	2	2	10	5	0	0	8	3
13	15/08/2008	30000	24	9	9	14	18	24	3	15	14	0	0	5
15	17/08/2008	30000	1	5	10	5	15	11	9	12	2	6	11	6
17	19/08/2008	30000	1	6	10	6	4	6	9	6	18	7	10	12
20	22/08/2008	30000	9	6	10	8	1	6	12	6	4	5	11	7
24	26/08/2008	30000	9	11	4	8	6	19	11	12	2	10	5	6
27	29/08/2008	30000	11	8	12	10	14	6	3	8	3	1	5	3
30	02/10/2008	30000	11	11	3	8	11	8	1	7	10	10	5	8
34	06/10/2008	30000	10	3	12	8	0	11	7	6	5	10	14	10
36	08/10/2008	30000	5	10	7	7	13	11	2	9	6	4	8	6
38	10/10/2008	30000	16		14	15	7	6	4	6	4	15	24	14
41	13/10/2008	30000	16	5	16	12	10	8	4	7	4	10	1	5
43	15/10/2008	30000	8	0	0	3	5	0	13	6	0	1	1	1
45	17/10/2008	30000	12	3	9	8	9	11	5	8	16	6	7	10
48	20/10/2008	30000	9	6	14	10	7	10	4	7	6	3	4	4
55	28/10/2008	30000	10	5	12	9	8	1	12	7	4	8	2	5
56	29/10/2008	30000	30	21	20	24	20	17	17	18	20	13	8	14
59	31/10/2008	30000	17	27	12	19	9	8	19	12	14	9	10	11
62	03/11/2008	30000	10	13	6	10	4	17	8	10	1	9	8	6
64	05/11/2008	30000	10	13	6	10	4	17	8	10	1	9	8	6
66	07/11/2008	30000	5	4	8	6	12	21	16	16	11	9	10	10

Table A.32 Results for SS for the laboratory scale woodchip filter study for three different heights loaded at 3 % solids concentration

Day No.	Date	Influent	Effluent											
			500mm high				1000mm high				1500mm high			
			1	2	3	Average	4	5	6	Average	7	8	9	Average
69	10/11/2008	30000	21	13	15	16	10	13	9	11	5	10	2	6
73	14/11/2008	30000	13	3	6	7	17	40	15	24	15	9	10	11
83	24/11/2008	30000	5	7	5	6	3	5	6	5	5	7	6	6
119	29/12/2008	30000	5	4	7	5	5	9	6	7	10	4	4	6
126	06/01/2009	30000	7	7	4	6	7	2	3	4	5	2	2	3
128	08/01/2009	30000	7	6	6	6	4	2	2	3	5	2	2	3
140	20/01/2009	30000	6	5	4	5	2	3	6	4	12	5	14	10
150	30/01/2009	30000	3	3	0	2	1	2	1	1	5	4	3	4
154	03/02/2009	30000	4	2	3	3	4	6	2	4	4	2	1	2
160	09/02/2009	30000	4	4	3	4	1	1	0	1	1	1	0	1
164	13/02/2009	30000	4	2	19	8	2	0	12	5	2	6	6	5
167	16/02/2009	30000	13	14	18	15	9	20	8	12	0	7	4	4
175	24/02/2009	30000	13	14	18	15	9	20	8	12	0	7	4	4
182	02/03/2009	30000	1	3	1	2	2	1	0	1	2	2	2	2
192	13/03/2009	30000	4	2	6	4	4	6	4	5	2	2	3	2
197	18/03/2009	30000	1	1	3	2	1	0	3	1	2	1	0	1


SS for laboratory units loaded at 3 % solids
Concentration SS (mg L-1)
35000
30000
25000
20000
15000
10000
5000
0
1
6
13
17
24
30
36
41
45
55
59
64
69
83
126
140
154
164
175
192
Time (Days)
Influent
500mm high column
1000mm high column
1500mm high column

Appendix 2 – Pictures of the construction of the farm-scale filter

Liner to collect effluent at the base of the filter

Effluent collection pipes exiting the liner at the base of the filter

Stone layer creating a level base for the woodchip

Overview of the three-replicate farm filters with the distribution system on top

Appendix 3 – Results from the farm-scale woodchip filter experiment

Table B.1 Results for COD_T for the farm scale filter

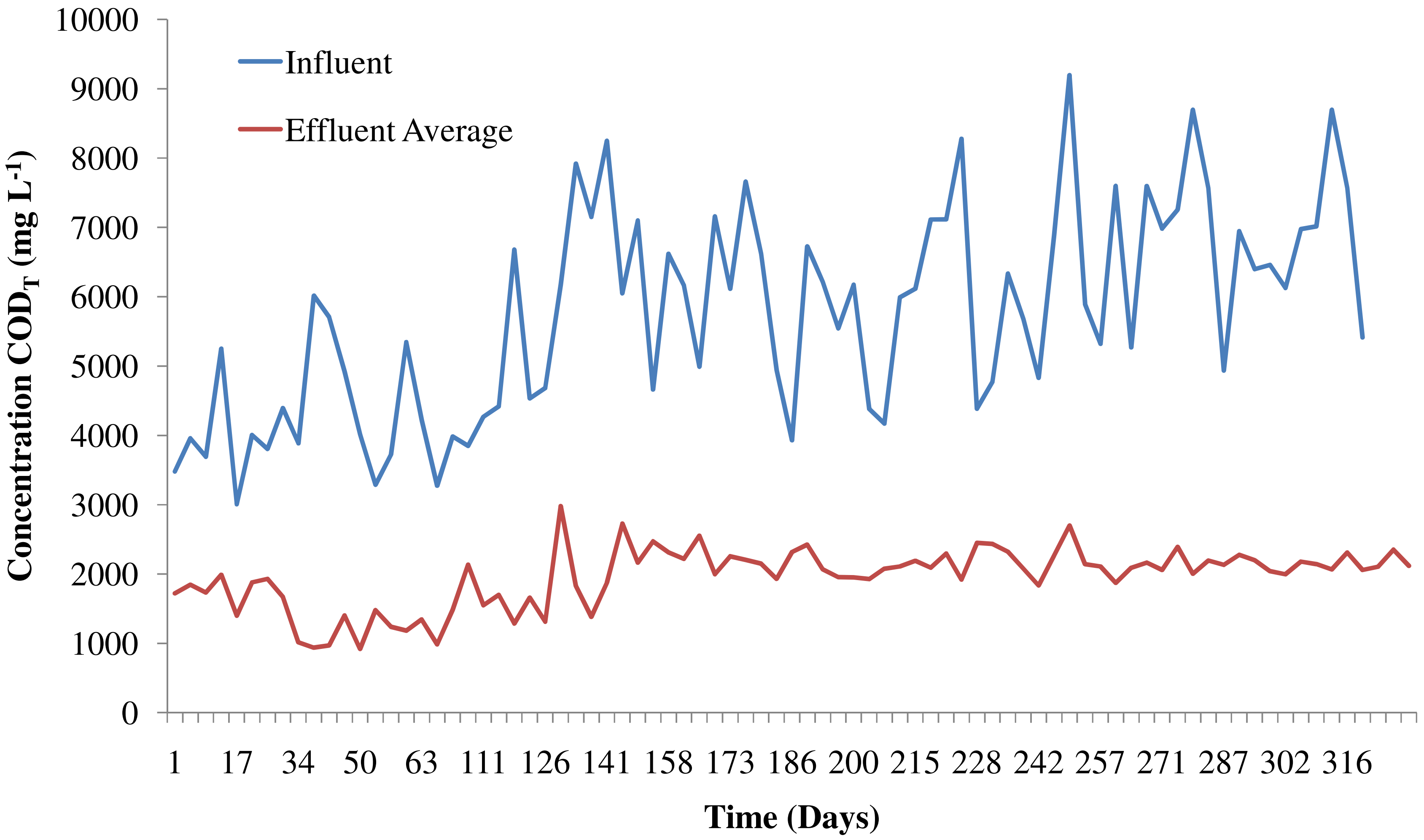
Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	3480	1870	1790	2310	1990	280	43
5	20/10/2009	3960	1420	1340	1440	1400	53	65
7	22/10/2009	3690	1850	1750	2040	1880	147	49
12	27/10/2009	5250	2320	1180	2296	1932	651	63
17	01/11/2009	3005	1800	1504	1694	1666	150	45
20	04/11/2009	4005	1358	830	856	1015	298	75
26	10/11/2009	3805	1014	904	900	939	65	75
28	12/11/2009	4395	924	940	1052	972	70	78
34	18/11/2009	3885	1642	1202	1362	1402	223	64
41	25/11/2009	6015	1090	842	826	919	148	85
43	27/11/2009	5710	1686	1306	1446	1479	192	74
47	01/12/2009	4923	1239	1341	1134	1238	104	75
50	04/12/2009	4012	1124	1098	1324	1182	124	71
54	08/12/2009	3290	1494	1222	1322	1346	138	59
57	11/12/2009	3723	938	1024	992	985	43	74
60	14/12/2009	5345	1584	1414	1452	1483	89	72
63	17/12/2009	4220	2232	1990	2188	2137	129	49
100	23/01/2010	3275	1640	1220	1784	1548	293	53
105	28/01/2010	3985	1746	1582	1772	1700	103	57
109	01/02/2010	3850	1392	758	1708	1286	484	67
111	03/02/2010	4265	1574	1520	1888	1661	199	61
117	09/02/2010	4420	1548	780	1604	1311	460	70
120	12/02/2010	6680	2930	3080	2930	2980	87	55
123	15/02/2010	4535	1416	1986	2076	1826	358	60
126	18/02/2010	4685	1514	1020	1612	1382	317	71
131	23/02/2010	6175	3178	996	1452	1875	1151	70
134	26/02/2010	7920	2754	2734	2692	2727	32	66
137	01/03/2010	7150	2236	2378	1876	2163	259	70
141	05/03/2010	8250	2852	2032	2532	2472	413	70

Table B.2 Results for COD_T for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	6050	2322	2382	2224	2309	80	62
148	12/03/2010	7100	2312	2132	2218	2221	90	69
153	17/03/2010	4660	2258	3082	2316	2552	460	45
158	22/03/2010	6620	2240	1996	1752	1996	244	70
161	25/03/2010	6160	2246	2264	2262	2257	10	63
165	29/03/2010	4990	1978	2196	2436	2203	229	56
169	02/04/2010	7160	1774	2112	2568	2151	398	70
173	06/04/2010	6115	1334	1970	2490	1931	579	68
176	09/04/2010	7660	2596	2374	1990	2320	307	70
179	12/04/2010	6620	2646	2476	2152	2425	251	63
182	15/04/2010	4940	1576	1974	2658	2069	547	58
186	19/04/2010	3930	1996	1984	1884	1955	61	50
190	23/04/2010	6725	1758	2174	1922	1951	210	71
194	27/04/2010	6215	1774	2214	1790	1926	250	69
197	30/04/2010	5545	1928	2174	2128	2077	131	63
200	03/05/2010	6175	1690	2152	2482	2108	398	66
203	06/05/2010	4385	2396	1992	2186	2191	202	50
207	10/05/2010	4170	2130	1796	2352	2093	280	50
211	14/05/2010	5990	2198	2396	2290	2295	99	62
215	18/05/2010	6115	1992	1774	1988	1918	125	69
218	21/05/2010	7115	2434	2552	2370	2452	92	66
222	25/05/2010	7120	2648	2348	2312	2436	184	66
229	27/05/2010	8280	1810	2578	2574	2321	442	72
228	31/05/2010	4385	2334	1988	1904	2075	228	53
231	03/06/2010	4770	2130	1596	1782	1836	271	62
236	08/06/2010	6335	2378	2108	2318	2268	142	64
239	11/06/2010	5675	3758	2128	2214	2700	917	52
242	14/06/2010	4830	2075	1885	2465	2142	296	56
245	17/06/2010	6880	2100	2400	1824	2108	288	69

Table B.3 Results for COD_T for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	9200	1629	1755	2235	1873	320	80
252	24/06/2010	5896	1625	2965	1680	2090	758	65
257	29/06/2010	5320	2236	2378	1876	2163	259	59
260	02/07/2010	7598	2143	1987	2045	2058	79	73
263	05/07/2010	5270	2510	2351	2314	2392	104	55
266	08/07/2010	7598	1989	2045	1978	2004	36	74
271	13/07/2010	6984	2460	1975	2152	2196	245	69
274	16/07/2010	7256	1989	2063	2341	2131	186	71
280	22/07/2010	8698	2013	2314	2512	2280	251	74
284	26/07/2010	7568	2078	2546	1966	2197	308	71
287	29/07/2010	4935	1987	1996	2142	2042	87	59
291	02/08/2010	6945	1546	2085	2356	1996	412	71
294	05/08/2010	6398	1996	2451	2089	2179	240	66
299	10/08/2010	6458	2075	2315	2033	2141	152	67
302	13/08/2010	6125	2130	2087	1978	2065	78	66
306	17/08/2010	6975	1985	2986	1966	2312	583	67
308	19/08/2010	7015	1789	2345	2043	2059	278	71
312	23/08/2010	8695	2045	2163	2105	2104	59	76
316	27/08/2010	7569	2335	2423	2301	2353	63	69
320	31/08/2010	5412	1962	1987	2401	2117	247	61



Influent
Effluent Average
Concentration COD_T (mg L^{-1})
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1
17
34
50
63
111
126
141
158
173
186
200
215
228
242
257
271
287
302
316
Time (Days)

Table B.4 Results for COD_F for the farm scale filter

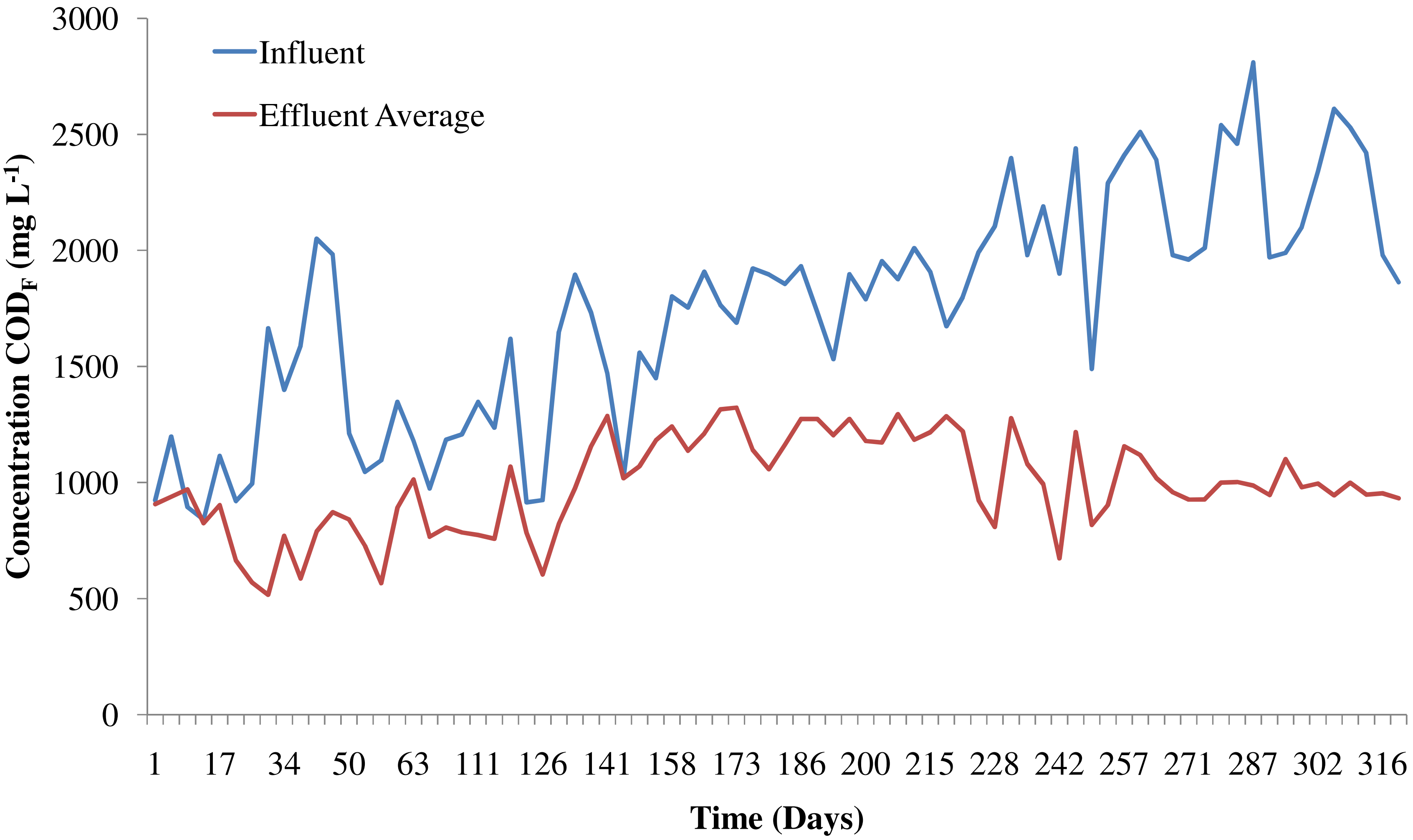
Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	923	877	948	898	908	36	2
5	20/10/2009	1198	903	968	944	938	33	22
7	22/10/2009	894	964	950	998	971	25	-9
12	27/10/2009	840	961	655	859	825	156	2
17	01/11/2009	1115	968	838	901	902	65	19
20	04/11/2009	920	942	543	506	664	242	28
26	10/11/2009	995	635	533	539	569	57	43
28	12/11/2009	1665	539	478	533	517	34	69
34	18/11/2009	1400	964	676	671	770	168	45
41	25/11/2009	1590	681	570	510	587	87	63
43	27/11/2009	2050	930	620	819	790	157	61
47	01/12/2009	1983	822	901	893	872	43	56
50	04/12/2009	1214	892	798	834	841	47	31
54	08/12/2009	1046	820	710	653	728	85	30
57	11/12/2009	1095	492	610	598	567	65	48
60	14/12/2009	1348	842	1076	758	892	165	34
63	17/12/2009	1180	991	1073	976	1013	52	14
100	23/01/2010	974	755	802	742	766	32	21
105	28/01/2010	1184	813	845	762	807	42	32
109	01/02/2010	1208	867	776	713	785	77	35
111	03/02/2010	1348	744	829	750	774	47	43
117	09/02/2010	1236	802	692	780	758	58	39
120	12/02/2010	1620	1459	943	802	1068	346	34
123	15/02/2010	915	852	562	936	783	196	14
126	18/02/2010	925	685	540	588	604	74	35
131	23/02/2010	1650	1361	572	540	824	465	50
134	26/02/2010	1895	1326	1061	540	976	400	49
137	01/03/2010	1732	1062	1325	1081	1156	147	33
141	05/03/2010	1470	1468	1116	1277	1287	176	12

Table B.5 Results for COD_F for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	1020	1060	984	1013	1019	38	0
148	12/03/2010	1560	1085	1080	1048	1071	20	31
153	17/03/2010	1450	999	1501	1048	1183	277	18
158	22/03/2010	1802	1280	1456	989	1242	236	31
161	25/03/2010	1754	1190	1354	867	1137	248	35
165	29/03/2010	1908	1170	1267	1198	1212	50	36
169	02/04/2010	1765	1210	1438	1298	1315	115	25
173	06/04/2010	1689	1324	1535	1109	1323	213	22
176	09/04/2010	1923	1256	1289	876	1140	230	41
179	12/04/2010	1897	1087	1187	899	1058	146	44
182	15/04/2010	1856	1267	1245	978	1163	161	37
186	19/04/2010	1932	1287	1315	1219	1274	49	34
190	23/04/2010	1734	1198	1298	1326	1274	67	27
194	27/04/2010	1532	1156	1345	1109	1203	125	21
197	30/04/2010	1898	1320	1287	1216	1274	53	33
200	03/05/2010	1789	1298	1245	995	1179	162	34
203	06/05/2010	1954	1287	1287	943	1172	199	40
207	10/05/2010	1876	1328	1318	1239	1295	49	31
211	14/05/2010	2010	1109	1567	877	1184	351	41
215	18/05/2010	1907	1187	1498	965	1217	268	36
218	21/05/2010	1674	1215	1321	1322	1286	61	23
222	25/05/2010	1799	989	1210	1465	1221	238	32
229	27/05/2010	1994	878	989	899	922	59	54
228	31/05/2010	2104	985	598	843	809	196	62
231	03/06/2010	2398	1290	1109	1432	1277	162	47
236	08/06/2010	1980	912	997	1332	1080	222	45
239	11/06/2010	2190	876	878	1223	992	200	55
242	14/06/2010	1900	670	434	916	673	241	65
245	17/06/2010	2440	1545	1245	862	1217	342	50

Table B.6 Results for COD_F for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	1490	589	928	936	818	198	45
252	24/06/2010	2290	948	936	824	903	68	61
257	29/06/2010	2410	1062	1325	1081	1156	147	52
260	02/07/2010	2510	985	1285	1085	1118	153	55
263	05/07/2010	2390	976	1096	986	1019	67	57
266	08/07/2010	1980	938	964	973	958	18	52
271	13/07/2010	1960	876	976	928	927	50	53
274	16/07/2010	2010	928	1086	769	928	159	54
280	22/07/2010	2540	893	1280	829	1001	244	61
284	26/07/2010	2460	1005	946	1056	1002	55	59
287	29/07/2010	2810	928	938	1097	988	95	65
291	02/08/2010	1970	1069	829	939	946	120	52
294	05/08/2010	1990	1150	1204	948	1101	135	45
299	10/08/2010	2100	983	1087	869	980	109	53
302	13/08/2010	2340	928	973	1086	996	81	57
306	17/08/2010	2610	970	908	957	945	33	64
308	19/08/2010	2530	1096	964	937	999	85	61
312	23/08/2010	2420	976	973	897	949	45	61
316	27/08/2010	1980	928	975	958	954	24	52
320	31/08/2010	1863	873	869	1053	932	105	50



Influent
Effluent Average
Concentration COD_F (mg L^{-1})
3000
2500
2000
1500
1000
500
0
1
17
34
50
63
111
126
141
158
173
186
200
215
228
242
257
271
287
302
316
Time (Days)

Table B.7 Results for SS for the farm scale filter

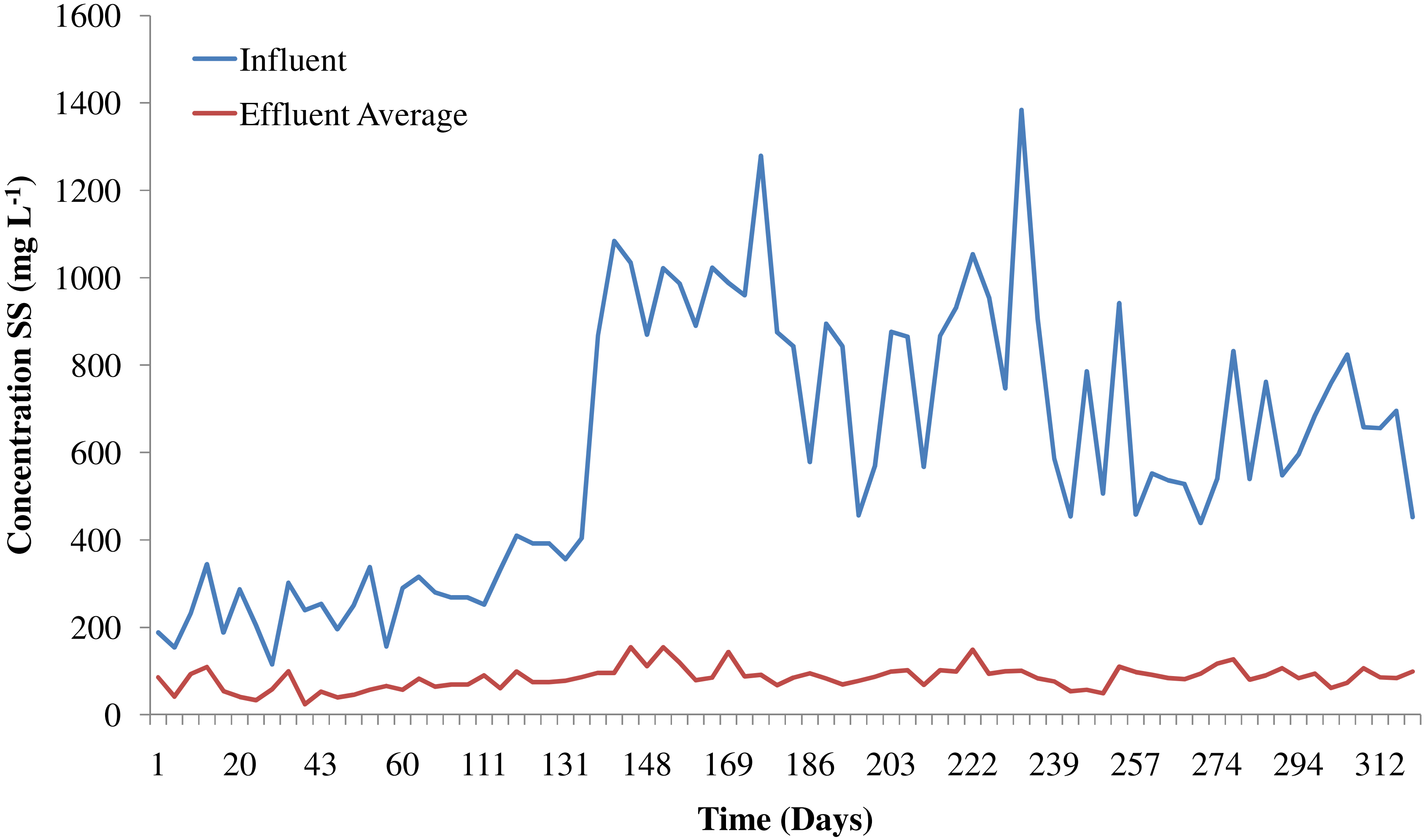
Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	188	81	74	102	86	15	54
5	20/10/2009	154	46	35	44	42	6	73
7	22/10/2009	232	49	69	161	93	60	60
12	27/10/2009	344	114	78	136	109	29	68
17	01/11/2009	188	59	45	58	54	8	71
20	04/11/2009	287	43	12	68	41	28	86
26	10/11/2009	205	36	35	28	33	4	84
28	12/11/2009	115	50	46	78	58	17	50
34	18/11/2009	302	92	64	143	100	40	67
41	25/11/2009	239	28	20	24	24	4	90
43	27/11/2009	254	52	54	53	53	1	79
47	01/12/2009	196	30	48	41	40	9	80
50	04/12/2009	250	54	36	47	46	9	82
54	08/12/2009	338	50	57	65	57	8	83
57	11/12/2009	156	47	62	88	66	21	58
60	14/12/2009	290	50	57	65	57	8	80
63	17/12/2009	316	92	88	67	82	13	74
100	23/01/2010	280	80	41	71	64	20	77
105	28/01/2010	268	77	59	72	69	9	74
109	01/02/2010	268	77	59	72	69	9	74
111	03/02/2010	252	88	68	115	90	24	64
117	09/02/2010	332	86	8	87	60	45	82
120	12/02/2010	410	87	119	91	99	17	76
123	15/02/2010	392	70	70	84	75	8	81
126	18/02/2010	392	70	70	84	75	8	81
131	23/02/2010	356	98	47	88	78	27	78
134	26/02/2010	404	75	95	88	86	10	79
137	01/03/2010	868	84	109	94	96	13	89
141	05/03/2010	1084	98	84	105	96	11	91

Table B.8 Results for SS for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	1034	140	175	148	154	18	85
148	12/03/2010	870	99	104	130	111	17	87
153	17/03/2010	1022	122	235	107	155	70	85
158	22/03/2010	987	87	178	94	120	51	88
161	25/03/2010	890	86	85	67	79	11	91
165	29/03/2010	1023	97	83	74	85	12	92
169	02/04/2010	988	196	136	98	143	49	85
173	06/04/2010	960	56	103	105	88	28	91
176	09/04/2010	1279	76	78	120	91	25	93
179	12/04/2010	875	87	57	59	68	17	92
182	15/04/2010	843	57	109	88	85	26	90
186	19/04/2010	578	97	99	89	95	5	84
190	23/04/2010	895	106	84	59	83	24	91
194	27/04/2010	843	65	57	86	69	15	92
197	30/04/2010	456	75	79	78	77	2	83
200	03/05/2010	568	97	76	87	87	11	85
203	06/05/2010	876	86	120	90	99	19	89
207	10/05/2010	865	106	96	104	102	5	88
211	14/05/2010	567	56	89	59	68	18	88
215	18/05/2010	867	83	103	120	102	19	88
218	21/05/2010	933	78	120	99	99	21	89
222	25/05/2010	1054	197	127	122	149	42	86
229	27/05/2010	955	87	95	98	93	6	90
228	31/05/2010	747	97	104	97	99	4	87
231	03/06/2010	1384	145	90	67	101	40	93
236	08/06/2010	906	64	97	88	83	17	91
239	11/06/2010	586	55	86	88	76	19	87
242	14/06/2010	454	8	42	110	53	52	88
245	17/06/2010	786	71	58	43	57	14	93

Table B.9 Results for SS for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	506	52	40	55	49	8	90
252	24/06/2010	942	100	131	99	110	18	88
257	29/06/2010	458	90	109	94	98	10	79
260	02/07/2010	552	99	89	86	91	7	83
263	05/07/2010	536	98	59	95	84	22	84
266	08/07/2010	528	120	48	76	81	36	85
271	13/07/2010	439	125	76	82	94	27	79
274	16/07/2010	539	130	95	125	117	19	78
280	22/07/2010	832	109	128	143	127	17	85
284	26/07/2010	539	99	46	96	80	30	85
287	29/07/2010	762	89	95	86	90	5	88
291	02/08/2010	548	81	135	104	107	27	81
294	05/08/2010	596	69	108	75	84	21	86
299	10/08/2010	684	93	92	98	94	3	86
302	13/08/2010	759	76	43	64	61	17	92
306	17/08/2010	824	59	86	75	73	14	91
308	19/08/2010	658	124	91	105	107	17	84
312	23/08/2010	656	106	75	76	86	18	87
316	27/08/2010	695	93	64	95	84	17	88
320	31/08/2010	452	76	128	93	99	27	78



Influent
Effluent Average
Concentration SS (mg L^{-1})
1600
1400
1200
1000
800
600
400
200
0
1
20
43
60
111
131
148
169
186
203
222
239
257
274
294
312
Time (Days)

Table B.10 Results for TN_T for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	280	140	110	150	133	21	52
5	20/10/2009	380	120	150	70	113	40	70
7	22/10/2009	300	70	70	70	70	0	77
12	27/10/2009	400	270	120	260	217	84	46
17	01/11/2009	185	90	78	88	85	6	54
20	04/11/2009	230	52	48	50	50	2	78
26	10/11/2009	135	60	52	62	58	5	57
28	12/11/2009	155	54	48	68	57	10	63
34	18/11/2009	165	70	62	62	65	5	61
41	25/11/2009	230	44	38	46	43	4	81
43	27/11/2009	245	78	68	88	78	10	68
47	01/12/2009	183	45	52	41	46	6	75
50	04/12/2009	242	102	110	92	101	9	58
54	08/12/2009	190	103	62	53	73	27	62
57	11/12/2009	241	78	89	91	86	7	64
60	14/12/2009	288	106	78	89	91	14	68
63	17/12/2009	292	136	104	122	121	16	59
100	23/01/2010	232	108	64	101	91	24	61
105	28/01/2010	244	107	84	102	98	12	60
109	01/02/2010	254	78	33	79	63	26	75
111	03/02/2010	248	85	78	89	84	6	66
117	09/02/2010	254	95	41	85	74	29	71
120	12/02/2010	365	176	158	148	161	14	56
123	15/02/2010	230	140	122	120	127	11	45
126	18/02/2010	190	137	88	106	110	25	42
131	23/02/2010	365	135	90	106	110	23	70
134	26/02/2010	385	111	160	106	126	30	67
137	01/03/2010	460	204	230	182	205	24	55
141	05/03/2010	450	252	234	238	241	9	46

Table B.11 Results for TN_T for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	270	196	208	214	206	9	24
148	12/03/2010	405	194	180	186	187	7	54
153	17/03/2010	510	216	276	218	237	34	54
158	22/03/2010	435	202	196	246	215	27	51
161	25/03/2010	460	198	174	196	189	13	59
165	29/03/2010	465	204	202	156	187	27	60
169	02/04/2010	500	246	190	206	214	29	57
173	06/04/2010	435	268	206	216	230	33	47
176	09/04/2010	395	198	220	194	204	14	48
179	12/04/2010	470	208	174	174	185	20	61
182	15/04/2010	380	220	184	136	180	42	53
186	19/04/2010	490	212	208	184	201	15	59
190	23/04/2010	530	268	206	258	244	33	54
194	27/04/2010	390	242	194	190	209	29	46
197	30/04/2010	280	194	148	218	187	36	33
200	03/05/2010	410	214	166	226	202	32	51
203	06/05/2010	360	238	180	196	205	30	43
207	10/05/2010	405	208	210	152	190	33	53
211	14/05/2010	345	218	226	166	203	33	41
215	18/05/2010	345	262	170	178	203	51	41
218	21/05/2010	350	156	186	186	176	17	50
222	25/05/2010	400	174	148	206	176	29	56
229	27/05/2010	395	150	216	180	182	33	54
228	31/05/2010	405	196	192	186	191	5	53
231	03/06/2010	370	170	206	228	201	29	46
236	08/06/2010	430	202	214	396	271	109	37
239	11/06/2010	360	190	196	312	233	69	35
242	14/06/2010	305	164	240	258	221	50	28
245	17/06/2010	410	165	135	114	138	26	66

Table B.12 Results for TN_T for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	355	105	126	126	119	12	66
252	24/06/2010	405	185	155	165	168	15	58
257	29/06/2010	410	210	198	202	203	6	50
260	02/07/2010	450	202	242	198	214	24	52
263	05/07/2010	395	248	222	204	225	22	43
266	08/07/2010	405	224	264	230	239	22	41
271	13/07/2010	455	198	198	240	212	24	53
274	16/07/2010	410	206	258	242	235	27	43
280	22/07/2010	355	242	196	192	210	28	41
284	26/07/2010	325	194	220	210	208	13	36
287	29/07/2010	395	174	186	242	201	36	49
291	02/08/2010	505	170	202	208	193	20	62
294	05/08/2010	480	196	220	198	205	13	57
299	10/08/2010	425	224	254	206	228	24	46
302	13/08/2010	460	218	176	208	201	22	56
306	17/08/2010	350	246	204	264	238	31	32
308	19/08/2010	360	202	216	220	213	9	41
312	23/08/2010	455	190	196	198	195	4	57
316	27/08/2010	490	196	250	224	223	27	54
320	31/08/2010	440	198	198	242	213	25	52

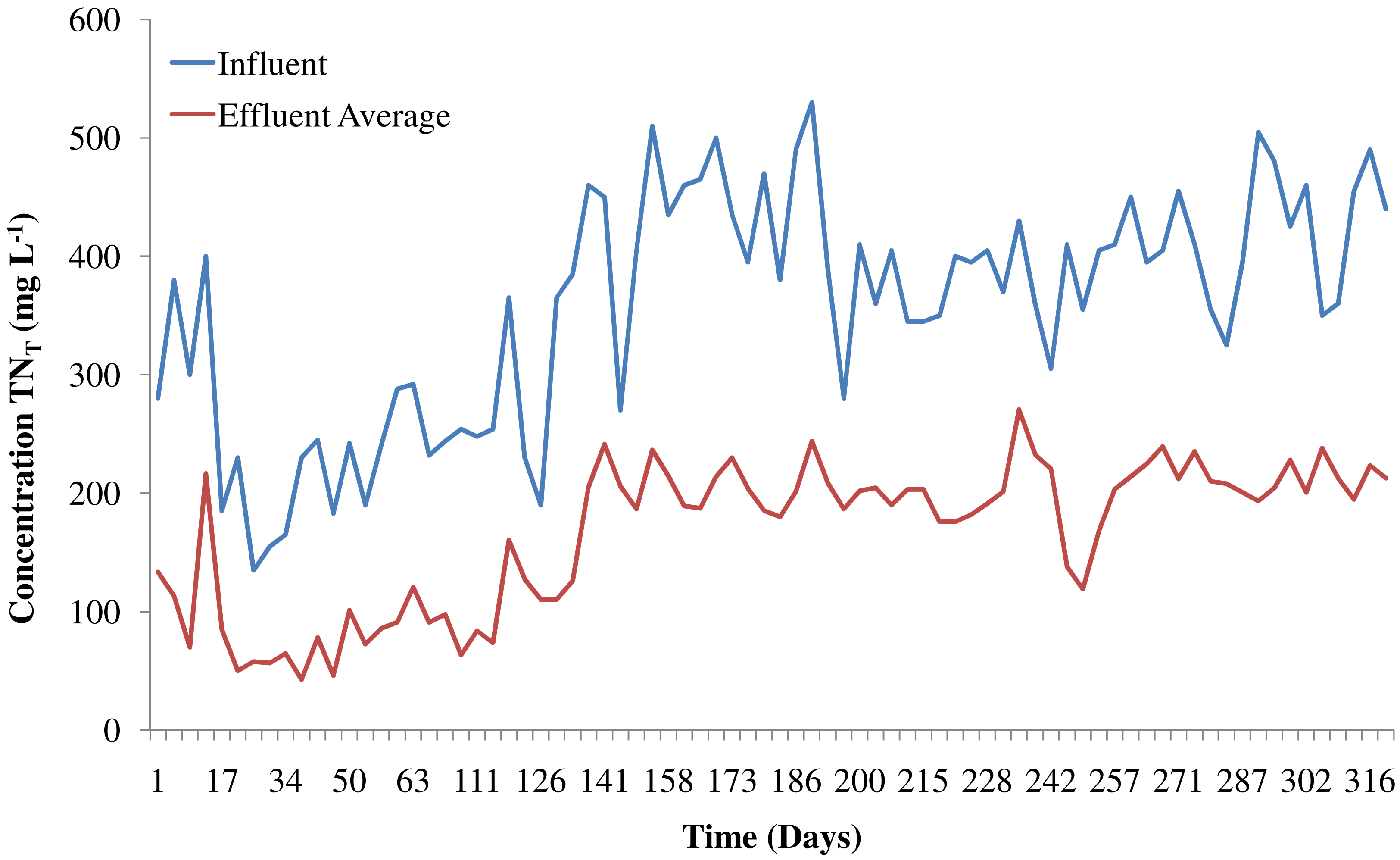

Influent
Effluent Average
Concentration TN_T (mg L^{-1})
600
500
400
300
200
100
0
1
17
34
50
63
111
126
141
158
173
186
200
215
228
242
257
271
287
302
316
Time (Days)

Table B.13 Results for TN_F for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	152	90	78	92	87	8	43
5	20/10/2009	160	93	52	67	71	21	56
7	22/10/2009	71	53	52	56	54	2	24
12	27/10/2009	231	140	120	180	147	31	37
17	01/11/2009	130	83	63	64	70	11	46
20	04/11/2009	130	60	50	44	51	8	61
26	10/11/2009	85	59	52	61	57	5	33
28	12/11/2009	90	53	47	57	52	5	42
34	18/11/2009	112	54	35	39	43	10	62
41	25/11/2009	110	48	35	44	42	7	62
43	27/11/2009	140	76	49	50	58	15	58
47	01/12/2009	183	45	52	41	46	6	75
50	04/12/2009	131	69	42	51	54	14	59
54	08/12/2009	126	67	32	41	47	18	63
57	11/12/2009	134	62	58	41	54	11	60
60	14/12/2009	156	61	47	46	51	8	67
63	17/12/2009	154	84	62	95	80	17	48
100	23/01/2010	110	90	44	50	61	25	44
105	28/01/2010	138	84	48	51	61	20	56
109	01/02/2010	130	67	27	38	44	21	66
111	03/02/2010	128	66	43	45	51	13	60
117	09/02/2010	136	68	31	38	46	20	66
120	12/02/2010	215	142	82	82	102	35	53
123	15/02/2010	135	73	45	69	62	15	54
126	18/02/2010	135	75	55	60	63	10	53
131	23/02/2010	225	90	52	62	68	20	70
134	26/02/2010	270	75	80	62	72	9	73
137	01/03/2010	260	128	97	97	107	18	59
141	05/03/2010	205	86	86	86	86	0	58

Table B.14 Results for TN_F for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	144	74	125	102	100	26	30
148	12/03/2010	262	126	98	72	99	27	62
153	17/03/2010	202	96	74	137	102	32	49
158	22/03/2010	224	95	88	97	93	5	58
161	25/03/2010	216	143	89	72	101	37	53
165	29/03/2010	334	86	110	145	114	30	66
169	02/04/2010	228	95	69	97	87	16	62
173	06/04/2010	216	75	102	89	89	14	59
176	09/04/2010	212	57	76	85	73	14	66
179	12/04/2010	236	132	99	125	119	17	50
182	15/04/2010	270	99	128	123	117	16	57
186	19/04/2010	216	86	85	98	90	7	58
190	23/04/2010	246	125	136	128	130	6	47
194	27/04/2010	256	120	153	67	113	43	56
197	30/04/2010	206	102	53	97	84	27	59
200	03/05/2010	196	85	54	163	101	56	49
203	06/05/2010	210	99	99	86	95	8	55
207	10/05/2010	234	94	64	96	85	18	64
211	14/05/2010	224	99	117	120	112	11	50
215	18/05/2010	198	110	119	99	109	10	45
218	21/05/2010	188	96	97	97	97	1	49
222	25/05/2010	286	96	102	110	103	7	64
229	27/05/2010	252	119	126	105	117	11	54
228	31/05/2010	236	87	70	187	115	63	51
231	03/06/2010	210	136	98	153	129	28	39
236	08/06/2010	210	76	84	133	98	31	53
239	11/06/2010	234	125	99	132	119	17	49
242	14/06/2010	240	84	74	74	77	6	68
245	17/06/2010	312	146	170	128	148	21	53

Table B.15 Results for TN_F for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	324	55	37	76	56	20	83
252	24/06/2010	342	80	90	62	77	14	77
257	29/06/2010	286	128	133	137	133	5	54
260	02/07/2010	302	129	121	113	121	8	60
263	05/07/2010	292	120	118	98	112	12	62
266	08/07/2010	278	99	132	115	115	17	59
271	13/07/2010	280	89	128	123	113	21	60
274	16/07/2010	308	112	110	109	110	2	64
280	22/07/2010	328	138	109	99	115	20	65
284	26/07/2010	278	128	128	123	126	3	55
287	29/07/2010	282	142	134	109	128	17	54
291	02/08/2010	258	118	128	124	123	5	52
294	05/08/2010	254	99	113	137	116	19	54
299	10/08/2010	286	134	108	125	122	13	57
302	13/08/2010	298	129	99	108	112	15	62
306	17/08/2010	304	120	128	134	127	7	58
308	19/08/2010	274	112	116	99	109	9	60
312	23/08/2010	256	118	99	128	115	15	55
316	27/08/2010	306	102	110	120	111	9	64
320	31/08/2010	286	131	130	119	127	7	56

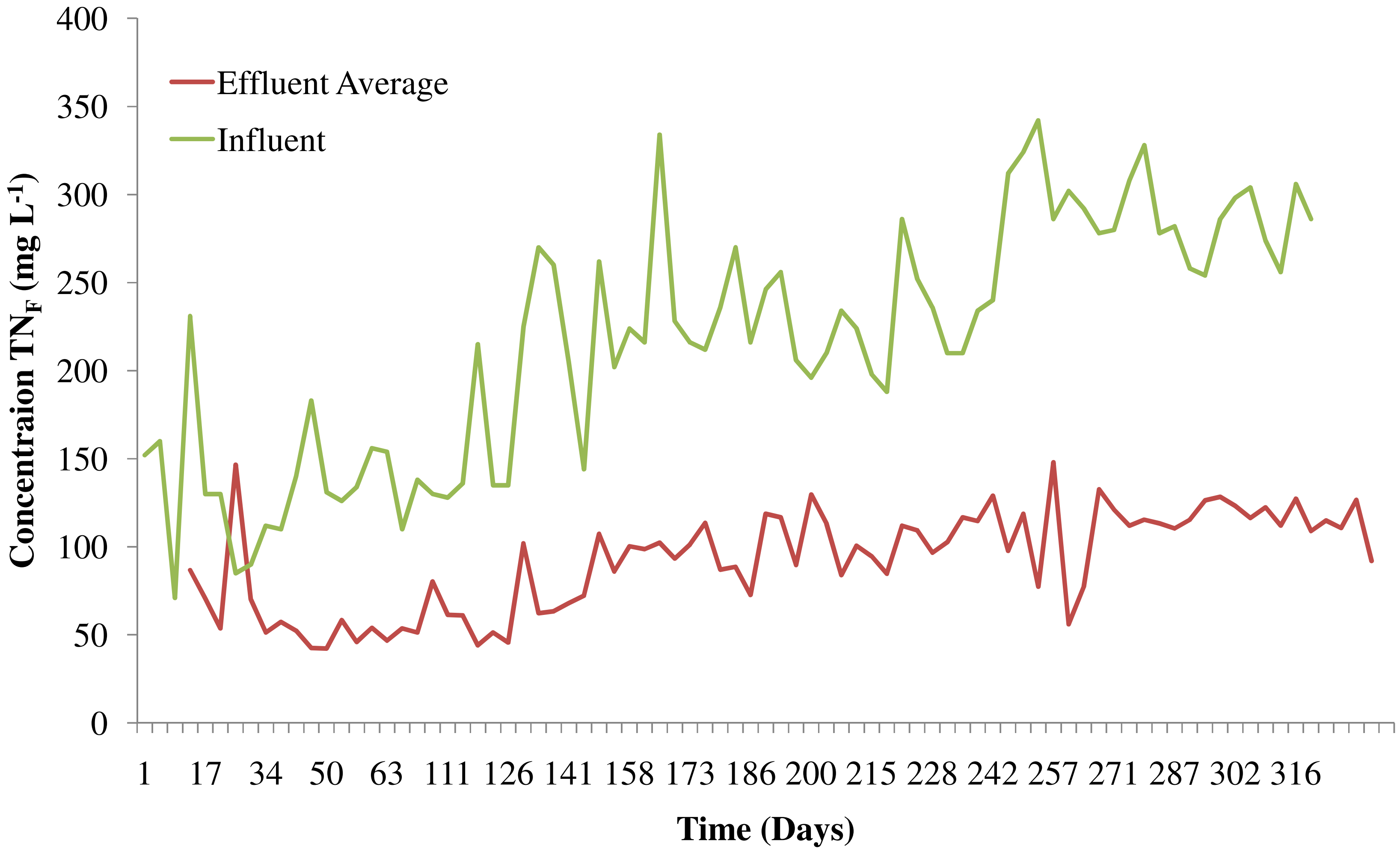

Effluent Average
Influent
Concentraion TN_F (mg L^{-1})
400
350
300
250
200
150
100
50
0
1
17
34
50
63
111
126
141
158
173
186
200
215
228
242
257
271
287
302
316
Time (Days)

Table B.16 Results for NO_2-N for the farm scale filter

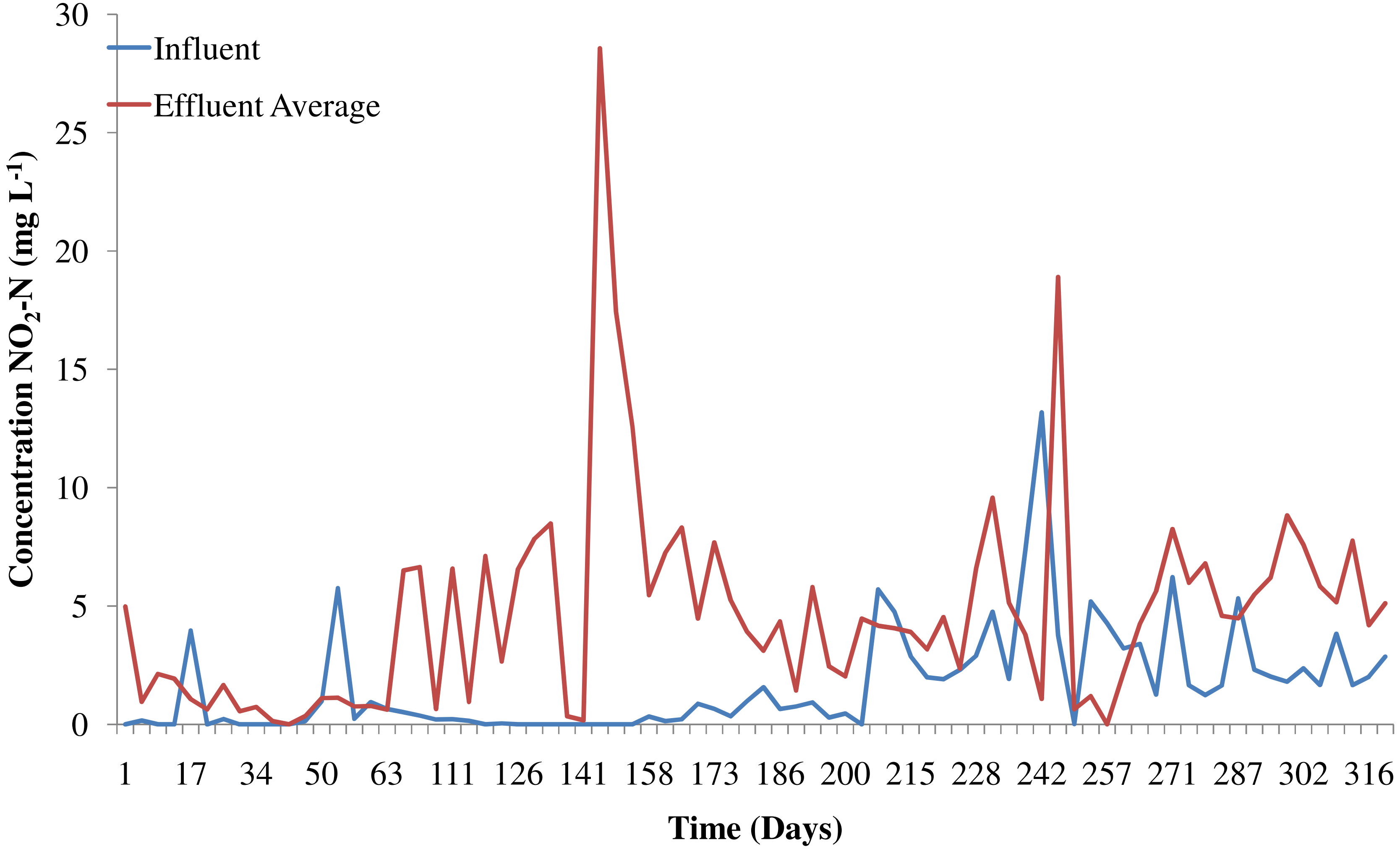
Day No.	**Date**	**Influent** (mg/L)	**Pad 1** (mg/L)	**Pad 2** (mg/L)	**Pad 3** (mg/L)	**Average**	**SD**	**%RED**
1	16/10/2009	0	5.66	4.47	4.8	4.98	1	
5	20/10/2009	0.15	0.79	0.52	1.52	0.94	1	-529
7	22/10/2009	0	2.49	2.77	1.12	2.13	1	
12	27/10/2009	0	0	5.29	0.47	1.92	3	
17	01/11/2009	3.96	3.19	0	0	1.06	2	73
20	04/11/2009	0	1.3	0.45	0.12	0.62	1	
26	10/11/2009	0.22	1.97	0.48	2.53	1.66	1	-655
28	12/11/2009	0	1.2	0.17	0.29	0.55	1	
34	18/11/2009	0	2.01	0.18	0	0.73	1	
41	25/11/2009	0	0.4	0	0	0.13	0	
43	27/11/2009	0	0	0	0	0.00	0	
47	01/12/2009	0.13	0.23	0.42	0.39	0.35	0	-167
50	04/12/2009	0.98	0.89	1.01	1.41	1.10	0	-13
54	08/12/2009	5.753	0.22	2.8	0.34	1.12	1	81
57	11/12/2009	0.23	1.04	0.98	0.23	0.75	0	-226
60	14/12/2009	0.93	0.39	0.74	1.2	0.78	0	16
63	17/12/2009	0.65	0.44	0.2	1.2	0.61	1	6
100	23/01/2010	0.51	8.26	2.91	8.34	6.50	3	-1175
105	28/01/2010	0.37	8.62	3.56	7.74	6.64	3	-1695
109	01/02/2010	0.2	0.7	0.89	0.33	0.64	0	-220
111	03/02/2010	0.21	9.23	4.2	6.31	6.58	3	-3033
117	09/02/2010	0.14	0.81	1.07	0.94	0.94	0	-571
120	12/02/2010	0	4.3	8.43	8.6	7.11	2	
123	15/02/2010	0.04	7.95	0	0	2.65	5	-6525
126	18/02/2010	0	7.92	5.23	6.5	6.55	1	
131	23/02/2010	0	4.67	8.63	10.19	7.83	3	
134	26/02/2010	0	5.07	10.2	10.19	8.49	3	
137	01/03/2010	0	0	0	1	0.33	1	
141	05/03/2010	0	0	0.46	0.03	0.16	0	

Table B.17 Results for NO_2-N for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	0	29.8	25.19	30.72	28.57	3	
148	12/03/2010	0	4.29	19.04	28.98	17.44	12	
153	17/03/2010	0	29.64	3.13	4.9	12.56	15	
158	22/03/2010	0.32	4.13	5.35	6.87	5.45	1	-1603
161	25/03/2010	0.13	5.99	12.87	2.87	7.24	5	-5472
165	29/03/2010	0.21	12.43	8.76	3.76	8.32	4	-3860
169	02/04/2010	0.87	5.87	2.65	4.87	4.46	2	-413
173	06/04/2010	0.64	13.87	6.32	2.87	7.69	6	-1101
176	09/04/2010	0.34	9.87	3.54	2.32	5.24	4	-1442
179	12/04/2010	0.98	3.2	6.54	1.98	3.91	2	-299
182	15/04/2010	1.56	4.2	2.43	2.71	3.11	1	-100
186	19/04/2010	0.65	3.87	6.82	2.34	4.34	2	-568
190	23/04/2010	0.75	1.2	1.43	1.65	1.43	0	-90
194	27/04/2010	0.92	9.43	6.09	1.87	5.80	4	-530
197	30/04/2010	0.28	3.2	1.43	2.71	2.45	1	-774
200	03/05/2010	0.45	1.3	1.45	3.32	2.02	1	-350
203	06/05/2010	0	3.76	7.12	2.5	4.46	2	
207	10/05/2010	5.7	4.65	4.97	2.87	4.16	1	27
211	14/05/2010	4.76	7.98	1.32	2.87	4.06	3	15
215	18/05/2010	2.87	2.1	6.58	3.01	3.90	2	-36
218	21/05/2010	1.98	2.87	3.76	2.87	3.17	1	-60
222	25/05/2010	1.9	8.76	1.83	2.98	4.52	4	-138
229	27/05/2010	2.3	1.43	2.43	3.18	2.35	1	-2
228	31/05/2010	2.9	6.4	9.9	3.48	6.59	3	-127
231	03/06/2010	4.75	9.88	14.3	4.55	9.58	5	-102
236	08/06/2010	1.91	4,3	7.43	2.84	5.14	3	-169
239	11/06/2010	7.34	5.2	2.54	3.65	3.80	1	48
242	14/06/2010	13.177	0	3.21	0	1.07	2	92
245	17/06/2010	3.759	24.382	15.803	16.523	18.90	5	-403

Table B.18 Results for NO$_2$-N for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	0.01	1.807	0.111	0	0.64	1	-6293
252	24/06/2010	5.19	1.02	0.73	1.83	1.19	1	77
257	29/06/2010	4.269	0	0	0	0.00	0	100
260	02/07/2010	3.21	3.56	0.98	1.97	2.17	1	32
263	05/07/2010	3.4	5.65	1.95	5.13	4.24	2	-25
266	08/07/2010	1.25	6.59	2.65	7.65	5.63	3	-350
271	13/07/2010	6.21	10.25	6.35	8.14	8.25	2	-33
274	16/07/2010	1.65	12.02	4.25	1.65	5.97	5	-262
280	22/07/2010	1.23	8.63	6.35	5.41	6.80	2	-453
284	26/07/2010	1.64	3.13	1.95	8.65	4.58	4	-179
287	29/07/2010	5.32	6.53	2.56	4.32	4.47	2	16
291	02/08/2010	2.31	5.31	9.65	1.46	5.47	4	-137
294	05/08/2010	2.01	4.69	12.32	1.58	6.20	6	-208
299	10/08/2010	1.8	13.26	10.54	2.67	8.82	5	-390
302	13/08/2010	2.364	5.362	11.624	5.749	7.58	4	-221
306	17/08/2010	1.657	6.338	7.651	3.492	5.83	2	-252
308	19/08/2010	3.825	4.658	5.647	5.163	5.16	0	-35
312	23/08/2010	1.658	9.483	5.167	8.62	7.76	2	-368
316	27/08/2010	2.015	6.712	3.897	1.964	4.19	2	-108
320	31/08/2010	2.85	4.659	8.654	2.031	5.11	3	-79



Influent
Effluent Average
Concentration NO_2-N (mg L^{-1})
30
25
20
15
10
5
0
1
17
34
50
63
111
126
141
158
173
186
200
215
228
242
257
271
287
302
316
Time (Days)

Table B.19 Results for NO_3-N for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	1.47	9.64	7.02	31.77	16.14	14	-998
5	20/10/2009	4.07	16.25	12.88	29.52	19.55	9	-380
7	22/10/2009	2.91	15.21	13.99	12.46	13.89	1	-377
12	27/10/2009	3.24	0.72	42.36	7.63	16.90	22	-422
17	01/11/2009	1.1	1.25	0.1	0.1	0.48	1	56
20	04/11/2009	0.1	7.29	5.74	2.47	5.17	2	-5067
26	10/11/2009	0.28	4.45	3.31	0	2.59	2	-824
28	12/11/2009	0.1	3.37	1.43	7.22	4.01	3	-3907
34	18/11/2009	0.1	0.1	0.24	4.83	1.72	3	-1623
41	25/11/2009	0.10	0.42	0.10	0.78	0.43	0	-333
43	27/11/2009	0.10	0.00	0.10	11.32	3.81	7	-3707
47	01/12/2009	0.10	0.75	0.62	0.62	0.67	0	-565
50	04/12/2009	2.30	0.72	0.41	0.11	0.41	0	82
54	08/12/2009	1.56	1.29	3.61	1.29	2.06	1	-33
57	11/12/2009	0.26	3.24	2.94	1.75	2.64	1	-917
60	14/12/2009	2.14	1.41	1.62	0.48	1.17	1	45
63	17/12/2009	1.57	1.41	1.26	0.48	1.05	1	33
100	23/01/2010	1.45	28.35	32.05	19.33	26.58	7	-1730
105	28/01/2010	1.38	20.31	25.06	19.02	21.46	3	-1461
109	01/02/2010	5.55	1.71	35.35	1.41	12.82	20	-131
111	03/02/2010	1.2	29.64	25.469	22.586	25.90	4	-2058
117	09/02/2010	1.171	3.04	34.258	1.712	13.00	18	-1010
120	12/02/2010	16.84	11.97	12	15.38	13.01	2	23
123	15/02/2010	19.56	40.59	9	8.51	19.24	18	2
126	18/02/2010	17.78	40.47	19	15.53	24.91	14	-40
131	23/02/2010	17.56	46.29	18	20.17	28.02	16	-60
134	26/02/2010	17.06	19.37	16	20.17	18.53	2	-9
137	01/03/2010	12.1	8.53	11.26	7.88	9.22	2	24
141	05/03/2010	12	99	30	21	49.89	43	-333

Table B.20 Results for NO_3-N for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	17.95	98.68	19.71	25.08	47.82	44	-166
148	12/03/2010	18	98.68	14.36	16.43	43.16	48	-140
153	17/03/2010	18	17.47	11.27	14.27	14.34	3	20
158	22/03/2010	24.4	10.8	9.86	17.78	12.81	4	47
161	25/03/2010	31.7	15.47	7.44	18.44	13.78	6	57
165	29/03/2010	24.4	10.8	9.86	17.78	12.81	4	47
169	02/04/2010	19.7	28.76	10.65	21.4	20.27	9	-3
173	06/04/2010	11.43	32.6	23.43	19.56	25.20	7	-120
176	09/04/2010	12.3	29.87	67.34	48.23	48.48	19	-294
179	12/04/2010	16.5	45.67	54.54	37.56	45.92	8	-178
182	15/04/2010	12.43	23.4	19.54	26.81	23.25	4	-87
186	19/04/2010	16.5	34.98	27.65	18.7	27.11	8	-64
190	23/04/2010	18.54	76.54	23.54	51.67	50.58	27	-173
194	27/04/2010	16.54	34.5	29.54	43.1	35.71	7	-116
197	30/04/2010	19.3	54.54	34.54	49.59	46.22	10	-139
200	03/05/2010	23.5	29.87	28.38	17.65	25.30	7	-8
203	06/05/2010	14.3	32.7	26.73	34.52	31.32	4	-119
207	10/05/2010	12.3	43.1	56.43	61.2	53.58	9	-336
211	14/05/2010	11.98	53.98	43.65	67.31	54.98	12	-359
215	18/05/2010	18.6	34.1	21.43	32.97	29.50	7	-59
218	21/05/2010	10.7	25.91	13.43	17.65	19.00	6	-78
222	25/05/2010	13.96	19.7	23.54	38.64	27.29	10	-96
229	27/05/2010	18.65	23.5	39.87	16.54	26.64	12	-43
228	31/05/2010	16.8	26.54	43.54	31.65	33.91	9	-102
231	03/06/2010	20.98	37.65	17.65	27.61	27.64	10	-32
236	08/06/2010	24.9	47.45	41.9	25.9	38.42	11	-54
239	11/06/2010	19.76	28.7	39.4	31.54	33.21	6	-68
242	14/06/2010	28.024	9.16	12.32	9.69	10.39	2	63
245	17/06/2010	26.074	53.942	34.401	31.451	39.93	12	-53

Table B.21 Results for NO_3-N for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	21.695	24.038	23.151	22.507	23.23	1	-7
252	24/06/2010	24.022	11.92	10.44	10.19	10.85	1	55
257	29/06/2010	37.778	8.53	11.26	8.88	9.56	1	75
260	02/07/2010	19.58	5.98	10.36	9.68	8.67	2	56
263	05/07/2010	11.25	23.36	19.65	16.56	19.86	3	-77
266	08/07/2010	9.85	29.86	23.65	21.56	25.02	4	-154
271	13/07/2010	19.65	28.23	23.68	25.64	25.85	2	-32
274	16/07/2010	9.58	31.25	31.82	27.65	30.24	2	-216
280	22/07/2010	12.58	22.65	42.56	31.65	32.29	10	-157
284	26/07/2010	12.66	25.98	38.32	34.56	32.95	6	-160
287	29/07/2010	19.75	42.85	21.56	39.65	34.69	11	-76
291	02/08/2010	17.28	25.96	24.32	19.65	23.31	3	-35
294	05/08/2010	21.56	34.65	25.14	25.65	28.48	5	-32
299	10/08/2010	19.3	39.87	35.68	29.65	35.07	5	-82
302	13/08/2010	9.65	18.9	29.65	35.24	27.93	8	-189
306	17/08/2010	11.56	18.65	29.56	31.25	26.49	7	-129
308	19/08/2010	8.69	18.46	31.85	29.85	26.72	7	-207
312	23/08/2010	10.56	19.87	18.65	24.65	21.06	3	-99
316	27/08/2010	11.26	10.35	25.32	19.65	18.44	8	-64
320	31/08/2010	13.56	18.65	15.95	18.26	17.62	1	-30

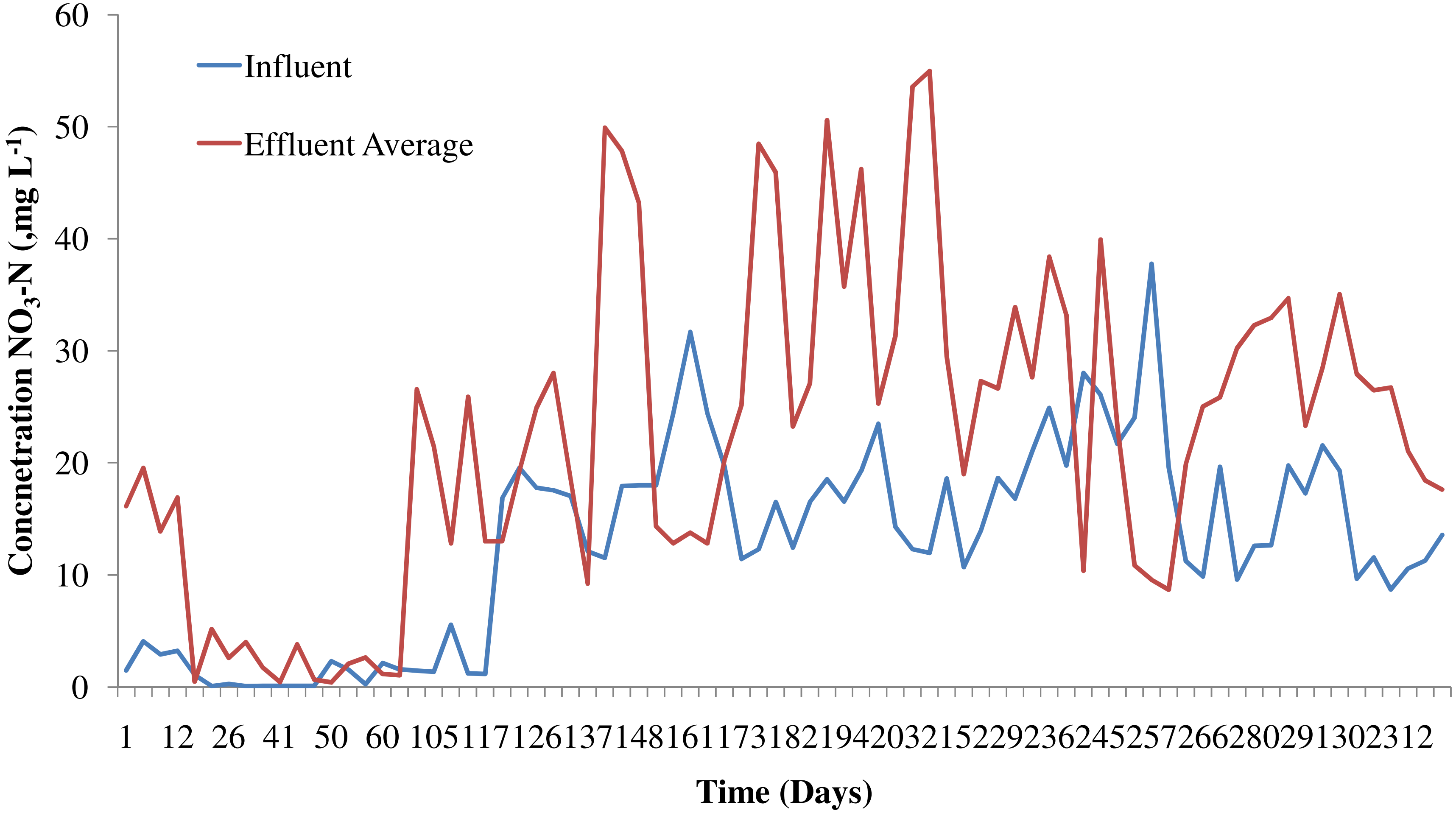

60
50
40
30
20
10
0
Influent
Effluent Average
Concnetration NO3-N (,mg L-1)
1
12
26
41
50
60
105
117
126
137
148
161
173
182
194
203
215
229
236
245
257
266
280
291
302
312
Time (Days)

Table B.22 Results for NH_4-N for the farm scale filter

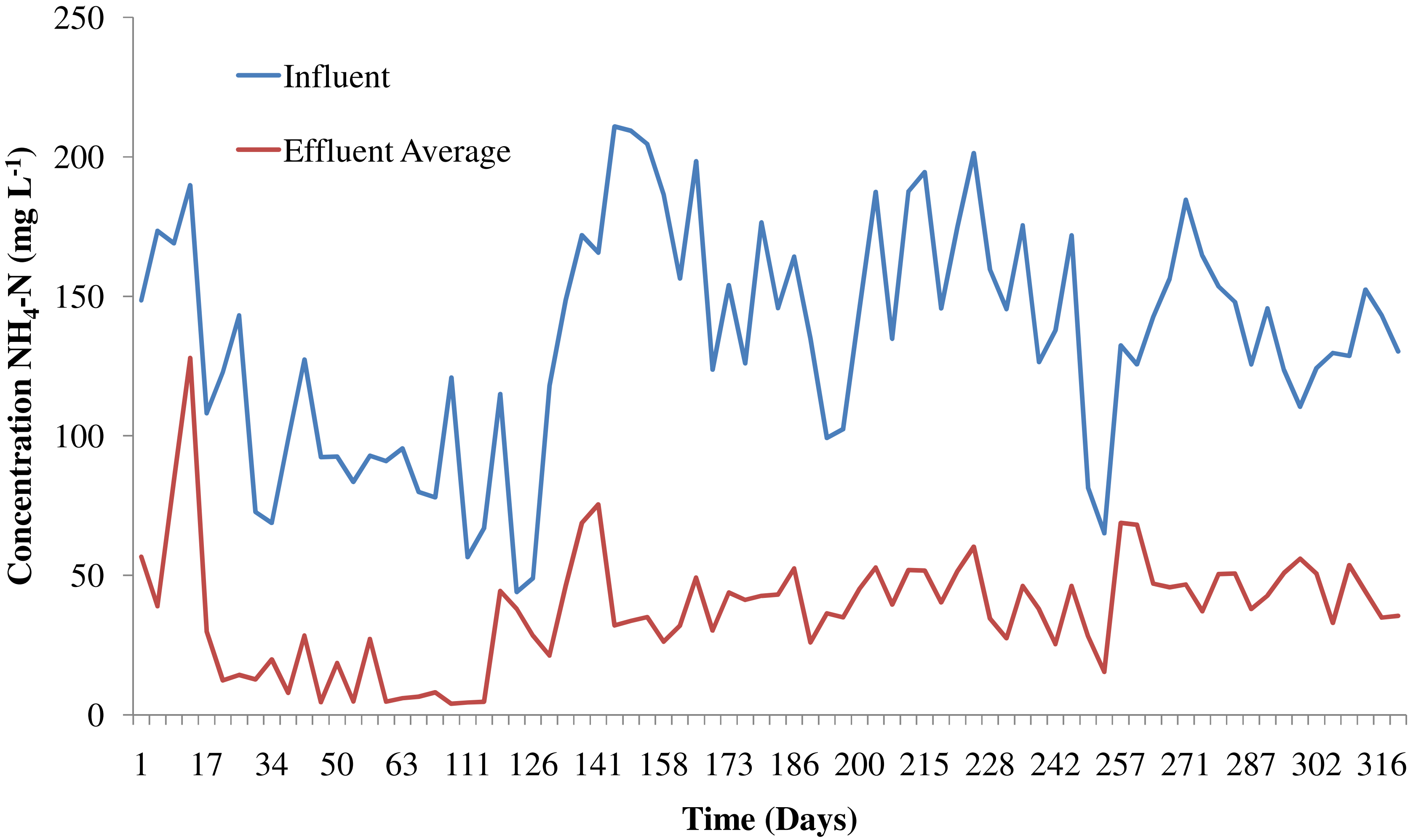
Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	148.59	61.85	55.39	52.77	57	5	62
5	20/10/2009	173.49	59.41	27.67	29.83	39	18	78
7	22/10/2009	168.99	106.69	80.14	66.4	84	20	50
12	27/10/2009	189.77	180.03	51.34	152.4	128	68	33
17	01/11/2009	108.06	32.06	26.65	31.36	30	3	72
20	04/11/2009	122.77	12.23	14.23	10.44	12	2	90
26	10/11/2009	143.15	17.97	12.82	12.074	14	3	90
28	12/11/2009	72.72	11.42	9.6	17.02	13	4	83
34	18/11/2009	68.75	30.77	11.79	17.02	20	10	71
41	25/11/2009	98.83	9.81	5.26	8.62	8	2	92
43	27/11/2009	127.33	30.02	26.65	28.58	28	2	78
47	01/12/2009	92.41	3.23	4.13	6.21	5	2	95
50	04/12/2009	92.54	14.23	21.82	19.84	19	4	80
54	08/12/2009	83.54	2.68	2.21	9.43	5	4	94
57	11/12/2009	92.85	36.14	17.82	27.82	27	9	71
60	14/12/2009	90.97	0.43	3.48	10.26	5	5	95
63	17/12/2009	95.53	0.76	1.1	15.96	6	9	94
100	23/01/2010	79.89	4.63	3.57	11.38	7	4	92
105	28/01/2010	78	5.85	6.13	12.17	8	4	90
109	01/02/2010	120.87	2.69	2.15	6.99	4	3	97
111	03/02/2010	56.51	1.8	3.67	7.9	4	3	92
117	09/02/2010	66.89	4.25	3.01	6.92	5	2	93
120	12/02/2010	115	72.47	36.21	24.37	44	25	61
123	15/02/2010	44.02	43.94	28.05	41.85	38	9	14
126	18/02/2010	49	44.44	18.3	22.14	28	14	42
131	23/02/2010	118	28.78	15.27	19.7	21	7	82
134	26/02/2010	148.72	60.04	59.15	19.7	46	23	69
137	01/03/2010	171.94	64.11	69.56	72.7	69	4	60
141	05/03/2010	165.64	98.68	51.96	75.61	75	23	54

Table B.23 Results for NH_4-N for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	210.9	36.1	28.78	31.21	32	4	85
148	12/03/2010	209.3	54.28	22.28	24.47	34	18	84
153	17/03/2010	204.6	23.35	25.05	56.65	35	19	83
158	22/03/2010	186.45	34.54	19.73	24.34	26	8	86
161	25/03/2010	156.38	24.65	37.54	33.54	32	7	80
165	29/03/2010	198.45	43.65	54.23	49.65	49	5	75
169	02/04/2010	123.75	23.65	28.66	38.42	30	8	76
173	06/04/2010	153.98	45.64	51.23	34.6	44	8	72
176	09/04/2010	125.98	34.65	42.76	46.12	41	6	67
179	12/04/2010	176.45	56.7	35.75	35.53	43	12	76
182	15/04/2010	145.76	27.43	38.76	63.23	43	18	70
186	19/04/2010	164.23	37.87	65.32	54.12	52	14	68
190	23/04/2010	134.9	32.56	19.87	25.34	26	6	81
194	27/04/2010	99.238	25.654	48.645	34.765	36	12	63
197	30/04/2010	102.34	29.88	36.54	38.32	35	4	66
200	03/05/2010	145.65	36.54	45.98	52.94	45	8	69
203	06/05/2010	187.45	26.45	87.34	44.64	53	31	72
207	10/05/2010	134.76	32.6	56.43	29.54	40	15	71
211	14/05/2010	187.65	67.5	49.76	38.39	52	15	72
215	18/05/2010	194.54	59.23	44.75	51.32	52	7	73
218	21/05/2010	145.65	37.65	29.54	53.76	40	12	72
222	25/05/2010	174.76	41.81	53.21	59.43	51	9	71
229	27/05/2010	201.34	54.9	61.43	64.37	60	5	70
228	31/05/2010	159.6	42.5	31.54	29.43	34	7	78
231	03/06/2010	145.43	23.6	27.34	31.54	27	4	81
236	08/06/2010	175.45	42.7	45.32	50.43	46	4	74
239	11/06/2010	126.4	34.4	41.54	37.81	38	4	70
242	14/06/2010	137.78	30.78	18.72	26.37	25	6	82
245	17/06/2010	171.811	59.959	41.91	36.717	46	12	73

Table B.24 Results for NH_4-N for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	81.51	28.295	21.717	34.507	28	6	65
252	24/06/2010	65.09	18.56	17.17	10.58	15	4	76
257	29/06/2010	132.41	64.11	69.56	72.7	69	4	48
260	02/07/2010	125.65	72.55	75.65	56.32	68	10	46
263	05/07/2010	142.56	42.123	59.32	39.65	47	11	67
266	08/07/2010	156.35	54.23	46.48	36.45	46	9	71
271	13/07/2010	184.65	34.26	56.32	49.65	47	11	75
274	16/07/2010	164.58	42.325	25.45	43.65	37	10	77
280	22/07/2010	153.6	39.45	39.65	72.36	50	19	67
284	26/07/2010	147.98	49.65	42.65	59.65	51	9	66
287	29/07/2010	125.65	39.412	45.654	28.654	38	9	70
291	02/08/2010	145.67	36.532	56.318	35.469	43	12	71
294	05/08/2010	123.65	28.654	69.512	54.362	51	21	59
299	10/08/2010	110.5	48.964	70.254	48.654	56	12	49
302	13/08/2010	124.36	28.654	65.485	57.562	51	19	59
306	17/08/2010	129.68	32.64	29.65	36.58	33	3	75
308	19/08/2010	128.65	64.32	51.02	45.62	54	10	58
312	23/08/2010	152.42	65.32	29.65	37.65	44	19	71
316	27/08/2010	143.12	37.65	31.02	35.91	35	3	76
320	31/08/2010	130.23	41.56	35.21	29.65	35	6	73



Concentration NH$_4$-N (mg L^{-1})
250
200
150
100
50
0
Influent
Effluent Average
1
17
34
50
63
111
126
141
158
173
186
200
215
228
242
257
271
287
302
316
Time (Days)

Table B.25 Results for PO_4-P for the farm scale filter

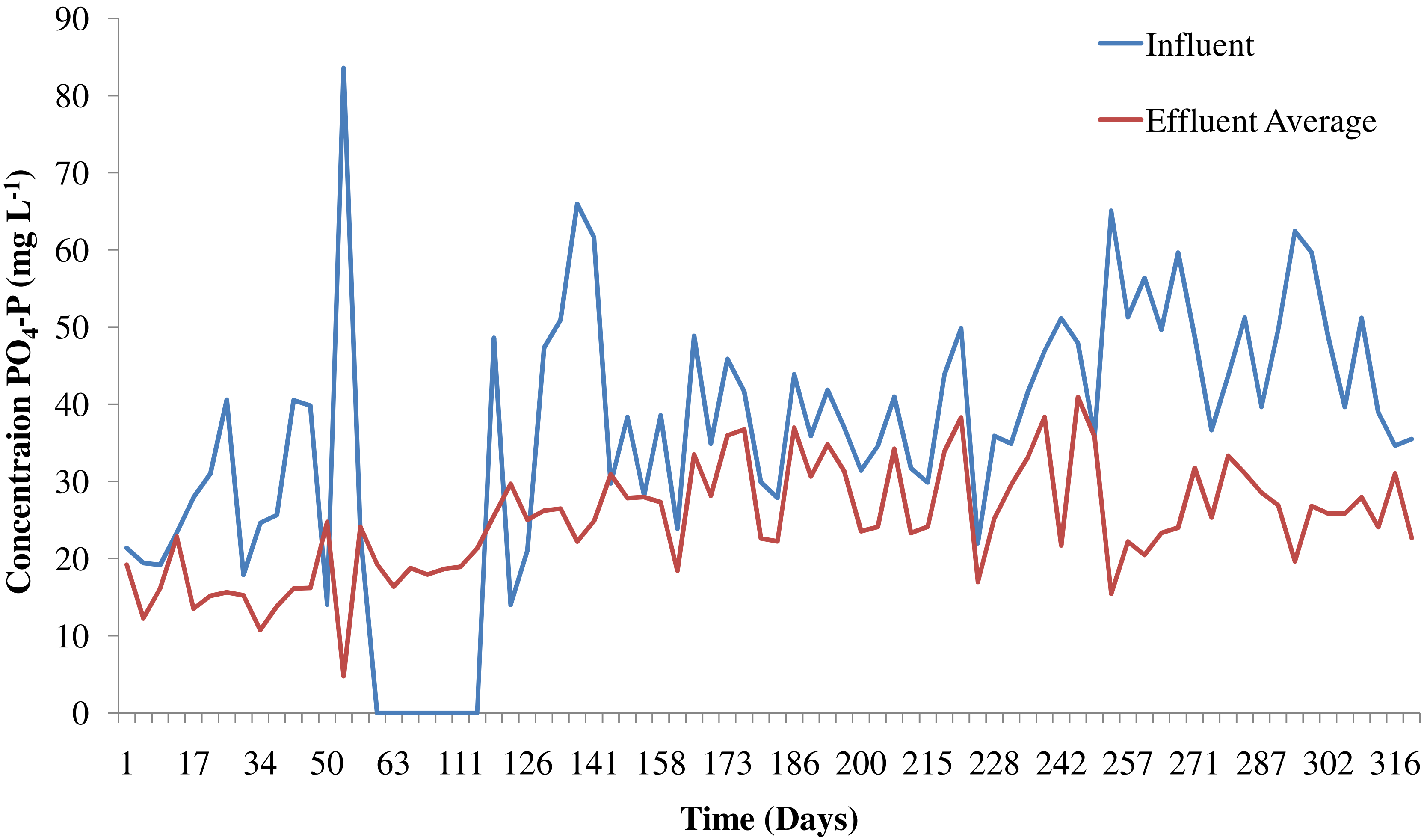
Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
1	16/10/2009	21.39	20.11	20.64	16.86	19	2	10
5	20/10/2009	19.45	11.73	12.83	12.12	12	1	37
7	22/10/2009	19.16	17.04	15.11	16.3	16	1	16
12	27/10/2009	23.42	23.96	21.12	23.46	23	2	2
17	01/11/2009	27.94	13.2	14.88	12.47	14	1	52
20	04/11/2009	30.97	16.78	13.94	14.76	15	1	51
26	10/11/2009	40.58	19.6	17.45	9.86	16	5	61
28	12/11/2009	17.89	14.19	14.87	16.69	15	1	15
34	18/11/2009	24.61	2.1	10.03	20.05	11	9	56
41	25/11/2009	25.65	16.45	14.22	10.81	14	3	46
43	27/11/2009	40.52	21.73	14.88	11.83	16	5	60
47	01/12/2009	39.83	21.28	4.13	23.24	16	11	59
50	04/12/2009	14.02	23.14	23.92	27.18	25	2	-77
54	08/12/2009	83.54	2.68	2.21	9.43	5	4	94
57	11/12/2009	23.26	24.68	27.82	19.82	24	4	-4
60	14/12/2009	0	22.22	23.93	11.68	19	7	
63	17/12/2009	0	18.2	17.47	13.44	16	3	
100	23/01/2010	0	22.28	13.37	20.69	19	5	
105	28/01/2010	0	18.65	17.37	17.77	18	1	
109	01/02/2010	0	23.28	19.28	13.34	19	5	
111	03/02/2010	0	20.38	20.58	15.89	19	3	
117	09/02/2010	0	24.83	16.84	22.28	21	4	
120	12/02/2010	48.58	23.78	26.94	25.96	26	2	47
123	15/02/2010	14	29.41	33.07	26.53	30	3	-112
126	18/02/2010	21	21.26	27.89	25.88	25	3	-19
131	23/02/2010	47.34	24.17	25.18	29.28	26	3	45
134	26/02/2010	50.92	20.45	29.66	29.28	26	5	48
137	01/03/2010	65.96	22.929	24.749	18.917	22	3	66
141	05/03/2010	61.66	25.516	25.516	23.454	25	1	60

Table B.26 Results for PO_4-P for the farm scale filter

Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
145	09/03/2010	29.75	35.174	25.334	32.25	31	5	-4
148	12/03/2010	38.37	23.948	28.594	30.99	28	4	27
153	17/03/2010	28.16	34.563	29.288	20.063	28	7	1
158	22/03/2010	38.54	29.76	27.65	24.54	27	3	29
161	25/03/2010	23.87	19.87	16.87	18.54	18	2	23
165	29/03/2010	48.87	32.4	34.65	33.45	34	1	31
169	02/04/2010	34.87	28.87	28.99	26.54	28	1	19
173	06/04/2010	45.87	37.89	34.54	35.43	36	2	22
176	09/04/2010	41.65	36.87	38.78	34.54	37	2	12
179	12/04/2010	29.87	24.5	19.87	23.43	23	2	24
182	15/04/2010	27.87	23.45	20.98	22.34	22	1	20
186	19/04/2010	43.9	36.54	38.91	35.43	37	2	16
190	23/04/2010	35.87	31.65	30.45	29.87	31	1	15
194	27/04/2010	41.87	37.6	35.43	31.45	35	3	17
197	30/04/2010	36.91	32.54	29.87	31.43	31	1	15
200	03/05/2010	31.4	26.54	24.34	19.8	24	3	25
203	06/05/2010	34.6	21.3	27.65	23.43	24	3	30
207	10/05/2010	40.98	32.45	38.76	31.43	34	4	17
211	14/05/2010	31.7	26.76	23.54	19.67	23	4	26
215	18/05/2010	29.87	23.43	25.43	23.54	24	1	19
218	21/05/2010	43.87	35.65	34.8	31.24	34	2	23
222	25/05/2010	49.87	34.78	38.76	41.34	38	3	23
229	27/05/2010	21.98	17.56	19.87	13.45	17	3	23
228	31/05/2010	35.87	27.54	24.56	23.56	25	2	30
231	03/06/2010	34.87	29.87	27.98	30.8	30	1	15
236	08/06/2010	41.6	31.43	35.43	32.45	33	2	20
239	11/06/2010	46.89	37.65	37.65	39.78	38	1	18
242	14/06/2010	51.13	23.48	19.97	21.68	22	2	58
245	17/06/2010	47.91	41.75	40.85	40.17	41	1	15

Table B.27 Results for PO_4-P for the farm scale filter

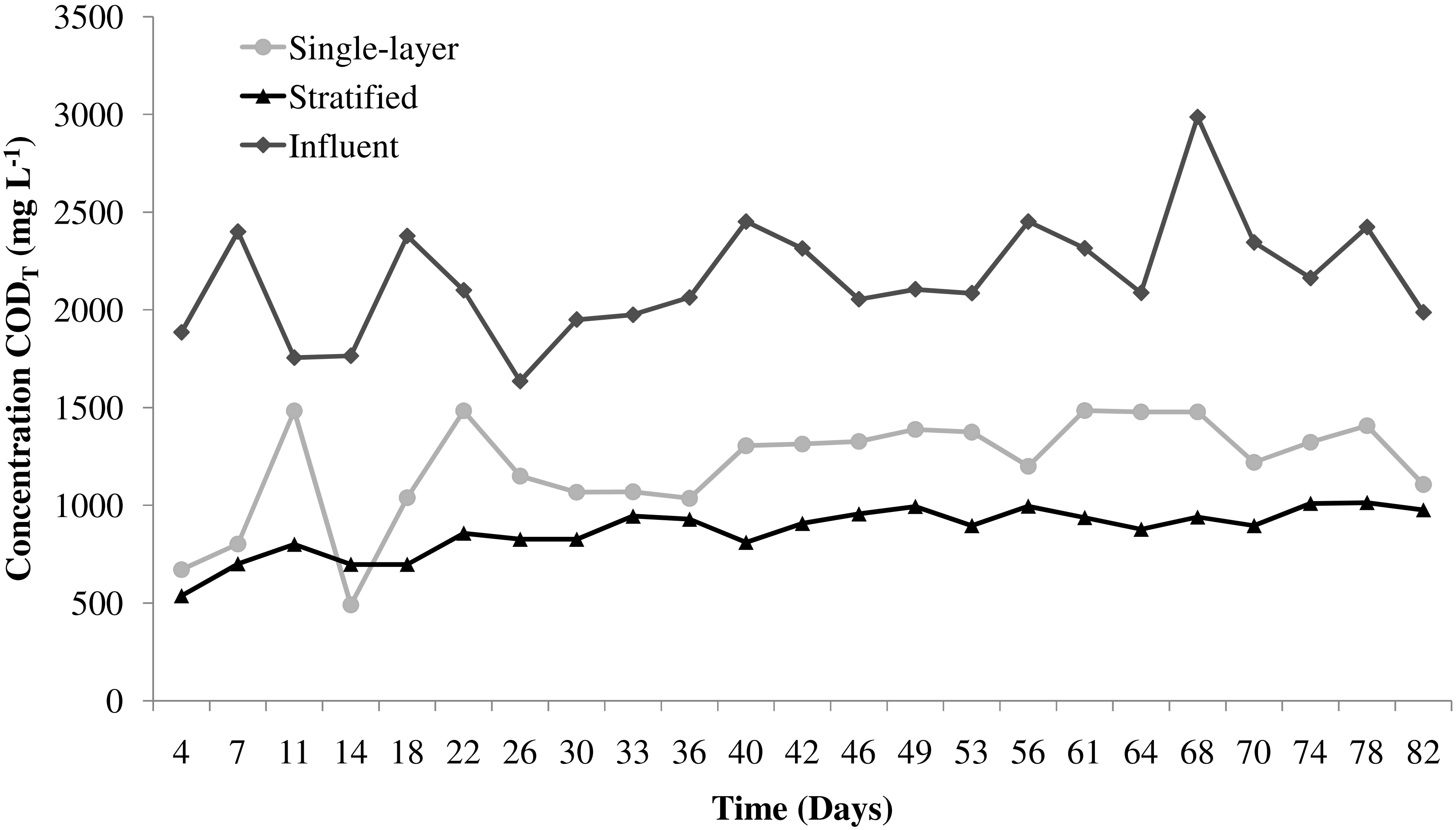
Day No.	**Date**	**Influent** (mg L^{-1})	**Pad 1** (mg L^{-1})	**Pad 2** (mg L^{-1})	**Pad 3** (mg L^{-1})	**Average**	**SD**	**%RED**
249	21/06/2010	35.89	29.51	38.82	38.97	36	5	0
252	24/06/2010	65.09	18.56	17.17	10.58	15	4	76
257	29/06/2010	51.29	22.926	24.749	18.917	22	3	57
260	02/07/2010	56.36	26.48	19.56	15.36	20	6	64
263	05/07/2010	49.65	23.65	26.65	19.65	23	4	53
266	08/07/2010	59.65	19.65	24.69	27.65	24	4	60
271	13/07/2010	48.69	29.65	34.36	31.2	32	2	35
274	16/07/2010	36.65	25.65	19.65	30.65	25	6	31
280	22/07/2010	43.65	26.46	31.02	42.5	33	8	24
284	26/07/2010	51.23	28.65	30.2	34.25	31	3	39
287	29/07/2010	39.65	26.35	29.64	29.65	29	2	28
291	02/08/2010	49.65	36.46	24.61	19.63	27	9	46
294	05/08/2010	62.45	19.65	21.58	17.65	20	2	69
299	10/08/2010	59.65	32.1	19.65	28.65	27	6	55
302	13/08/2010	48.75	29.65	26.35	21.52	26	4	47
306	17/08/2010	39.65	26.65	31.25	19.65	26	6	35
308	19/08/2010	51.2	39.65	18.65	25.65	28	11	45
312	23/08/2010	38.96	19.65	24.97	27.65	24	4	38
316	27/08/2010	34.65	27.65	35.02	30.52	31	4	10
320	31/08/2010	35.48	21.65	19.65	26.65	23	4	36


Influent
Effluent Average
Concentraion PO$_4$-P (mg L^{-1})
90
80
70
60
50
40
30
20
10
0
1
17
34
50
63
111
126
141
158
173
186
200
215
228
242
257
271
287
302
316
Time (Days)

Appendix 4 – Results from the sand filter experiment

Table C.1 Results for COD$_T$ for the sand filters

Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	1885	701	667	645	671	64	585	544	483	537	71
7	17 June 2010	2400	761	826	821	803	67	755	688	659	701	71
11	21 June 2010	1755	1658	1207	1586	1484	15	673	1062	667	801	54
14	24 June 2010	1765	454	504	515	491	72	679	776	640	698	60
18	28 June 2010	2378	1368	829	922	1040	44	679	776	640	698	29
22	02 July 2010	2100	1658	1207	1586	1484	29	673	1062	837	857	59
26	06 July 2010	1635	1099	1169	1181	1150	30	684	957	837	826	49
30	10 July 2010	1950	904	1240	1058	1067	45	684	957	837	826	58
33	13 July 2010	1975	899	1068	1241	1069	46	864	936	1035	945	52
36	16 July 2010	2063	1025	958	1125	1036	50	726	1065	996	929	55
40	20 July 2010	2451	1425	1345	1145	1305	47	637	957	839	811	67
42	22 July 2010	2314	1203	1286	1452	1314	43	829	899	996	908	61
46	26 July 2010	2054	1274	1362	1345	1327	35	976	917	974	956	53
49	29 July 2010	2105	1342	1463	1362	1389	34	765	1302	915	994	53
53	02 August 2010	2085	1068	1524	1532	1375	34	749	1105	836	897	57
56	05 August 2010	2451	1286	1036	1278	1200	51	925	996	1065	995	59
61	10 August 2010	2315	1638	1423	1395	1485	36	896	795	1120	937	60
64	13 August 2010	2087	1542	1532	1362	1479	29	936	928	769	878	58
68	17 August 2010	2986	1569	1426	1439	1478	51	1036	869	914	940	69
70	19 August 2010	2345	1347	1245	1068	1220	48	849	933	906	896	62
74	23 August 2010	2163	1362	1365	1243	1323	39	994	1103	934	1010	53
78	27 August 2010	2423	1320	1436	1465	1407	42	1034	1067	942	1014	58
82	31 August 2010	1987	976	1242	1103	1107	44	1201	934	795	977	51



Single-layer
Stratified
Influent
Concentration COD_T (mg L^{-1})
3500
3000
2500
2000
1500
1000
500
0
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)

Table C.2 Results for COD_F for the sand filters

Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	434	470	478	484	477	-10	439	451	403	431	1
7	17 June 2010	1245	436	463	471	457	63	526	491	423	480	61
11	21 June 2010	928	1086	758	1178	1007	-9	465	678	449	531	43
14	24 June 2010	899	289	323	334	315	65	540	571	483	531	41
18	28 June 2010	1325	853	643	655	717	54	540	571	483	531	40
22	02 July 2010	1240	1086	758	1178	1007	19	465	678	449	531	57
26	06 July 2010	1020	639	720	706	688	33	398	542	475	472	54
30	10 July 2010	1575	639	720	706	688	56	398	542	475	472	70
33	13 July 2010	976	702	598	462	587	40	425	465	462	451	54
36	16 July 2010	1086	732	866	625	741	32	526	521	398	482	56
40	20 July 2010	1120	563	759	562	628	44	597	397	345	446	60
42	22 July 2010	1280	896	896	758	850	34	468	621	425	505	61
46	26 July 2010	946	425	684	684	598	37	627	594	496	572	39
49	29 July 2010	938	623	563	596	594	37	631	576	501	569	39
53	02 August 2010	829	529	536	398	488	41	524	582	536	547	34
56	05 August 2010	1204	462	678	519	553	54	428	468	574	490	59
61	10 August 2010	1087	624	569	634	609	44	395	403	469	422	61
64	13 August 2010	973	425	532	567	508	48	379	364	487	410	58
68	17 August 2010	908	523	571	514	536	41	403	475	395	424	53
70	19 August 2010	964	562	684	725	657	32	421	416	426	421	56
74	23 August 2010	973	587	489	625	567	42	453	396	451	433	55
78	27 August 2010	975	496	645	693	611	37	486	346	475	436	55
82	31 August 2010	869	687	562	491	580	33	507	418	412	446	49

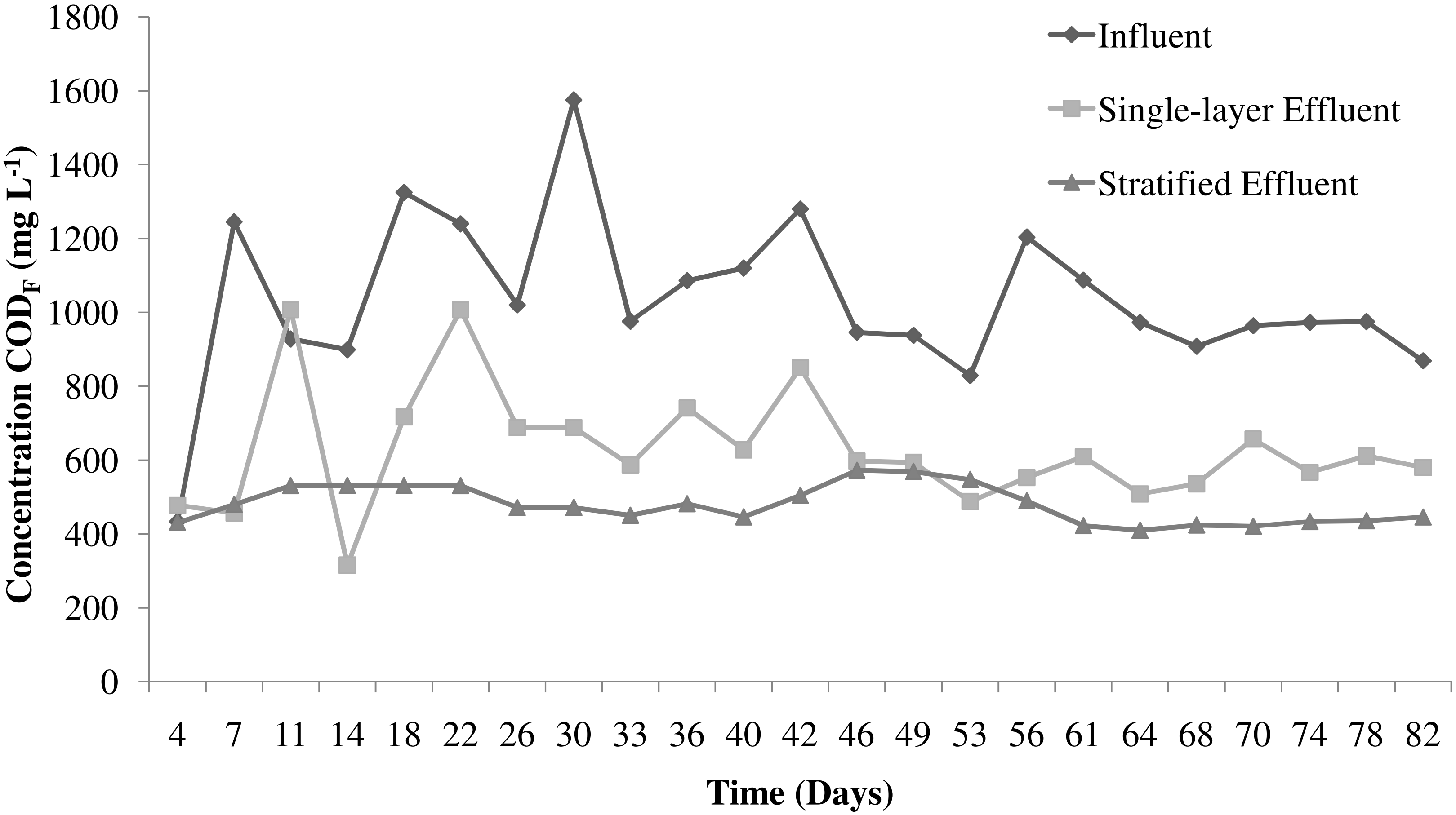

1800
1600
1400
1200
1000
800
600
400
200
0
Concentration COD_F (mg L^{-1})
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)
Influent
Single-layer Effluent
Stratified Effluent

Table C.3 Results for TN_T for the sand filters

Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	240	128	113	122	121	50	106	111	102	106	56
7	17 June 2010	135	114	121	126	120	11	102	99	109	103	23
11	21 June 2010	126	147	131	145	141	-12	108	121	109	113	11
14	24 June 2010	155	108	106	114	109	29	74	83	84	80	48
18	28 June 2010	230	84	82	89	85	37	74	83	84	80	35
22	02 July 2010	142	147	131	145	141	1	108	121	109	113	21
26	05 July 2010	124	90	88	92	90	27	66	86	83	78	37
30	08 July 2010	153	90	88	92	90	41	66	86	83	78	49
33	13 July 2010	198	88	86	99	91	54	59	72	45	59	70
36	16 July 2010	258	102	95	88	95	63	76	48	56	60	77
40	20 July 2010	195	9	75	96	60	69	49	51	85	62	68
42	22 July 2010	196	94	89	89	91	54	42	50	64	52	73
46	26 July 2010	220	106	94	93	98	56	47	51	41	46	79
49	29 July 2010	186	89	103	103	98	47	49	47	42	46	75
53	02 August 2010	202	96	120	103	106	47	45	41	51	46	77
56	05 August 2010	220	92	93	94	93	58	67	62	68	66	70
61	10 August 2010	254	79	94	124	99	61	50	49	53	51	80
64	13 August 2010	176	106	81	79	89	50	67	67	39	58	67
68	17 August 2010	204	110	115	106	110	46	41	49	50	47	77
70	19 August 2010	216	114	120	115	116	46	72	82	48	67	69
74	23 August 2010	196	93	99	89	94	52	82	79	56	72	63
78	27 August 2010	250	106	110	93	103	59	59	71	82	71	72
82	31 August 2010	198	94	98	95	96	52	69	64	56	63	68

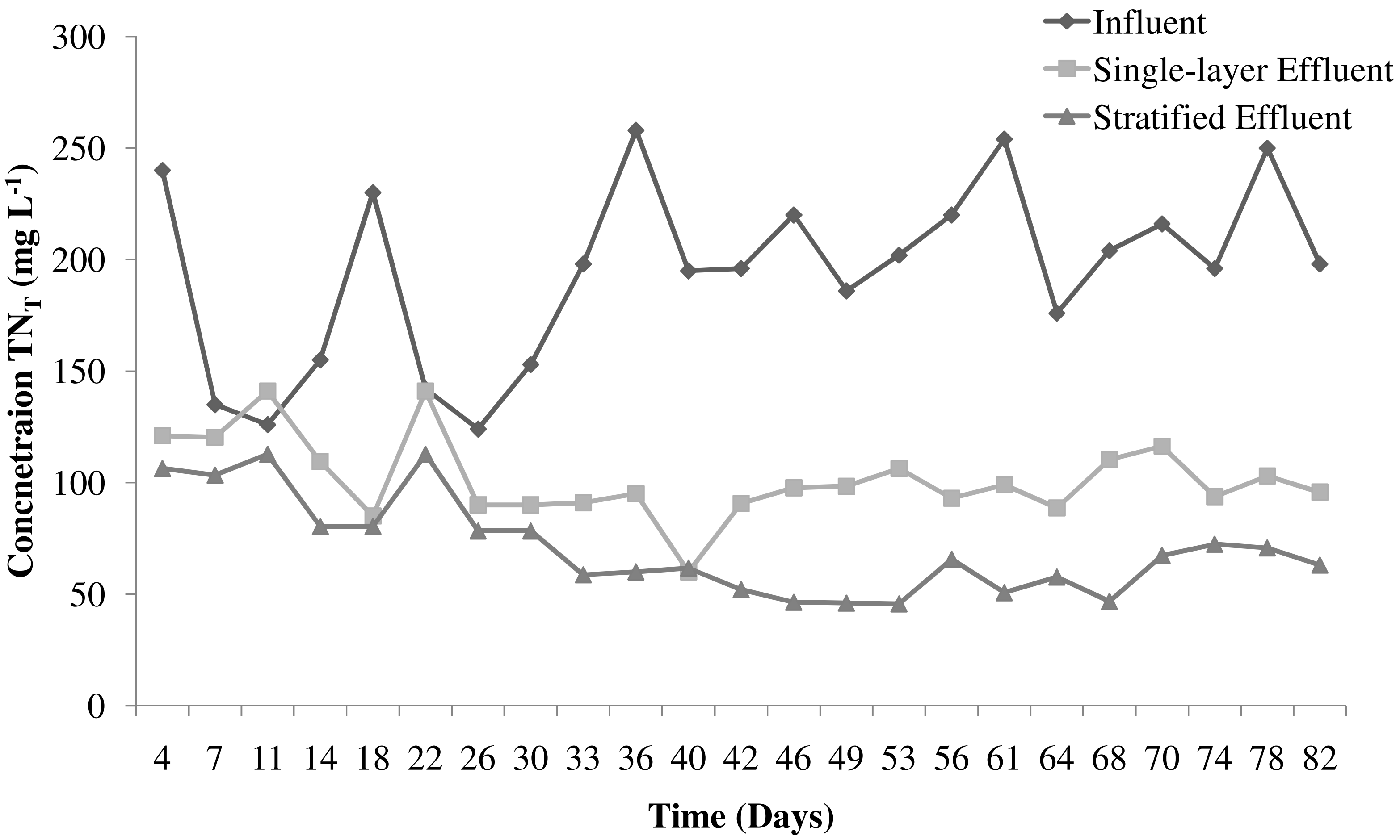
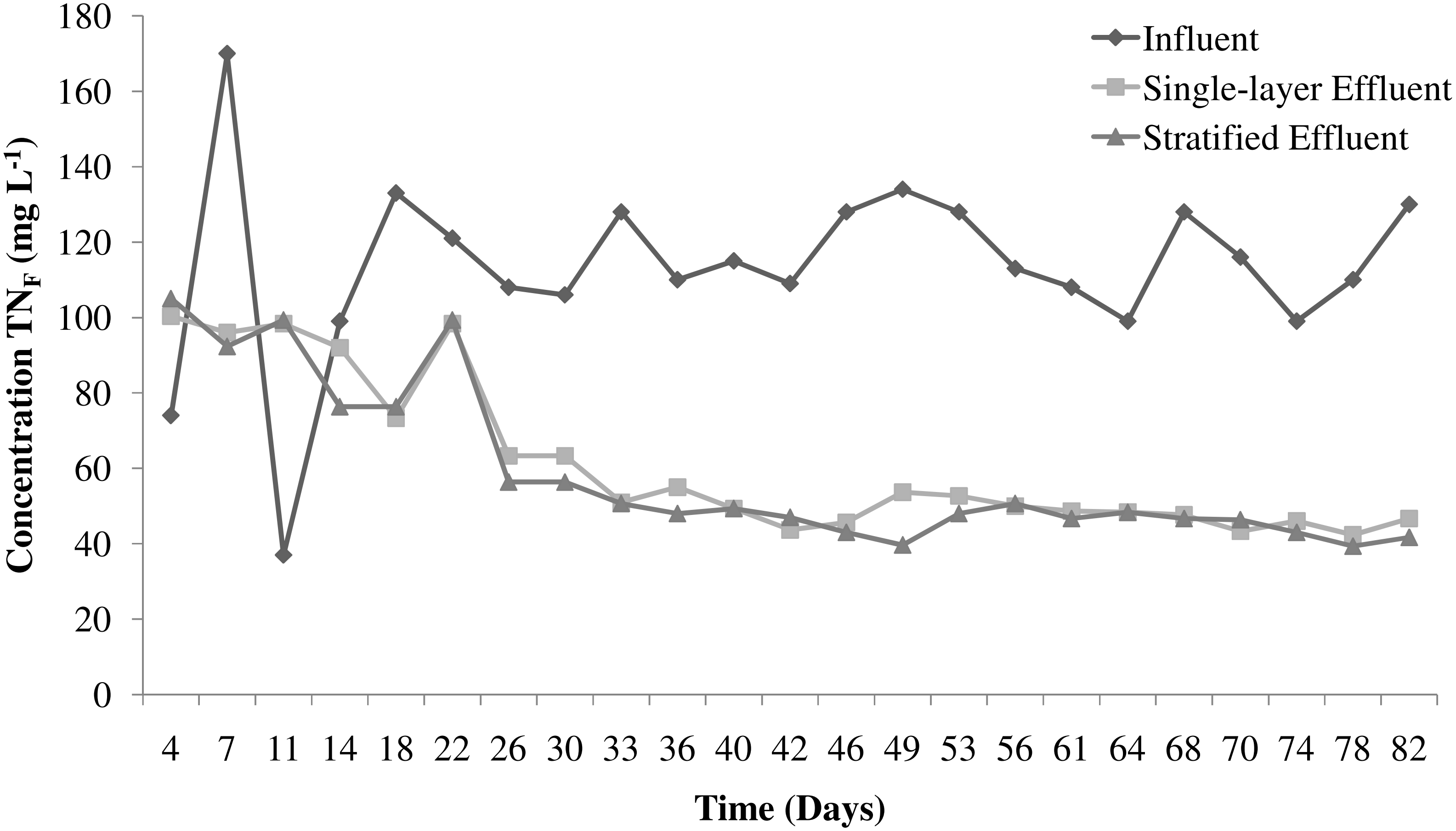

Influent
Single-layer Effluent
Stratified Effluent
Concnetraion TN$_T$ (mg L^{-1})
300
250
200
150
100
50
0
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)

Table C.4 Results for TN_F for the sand filters

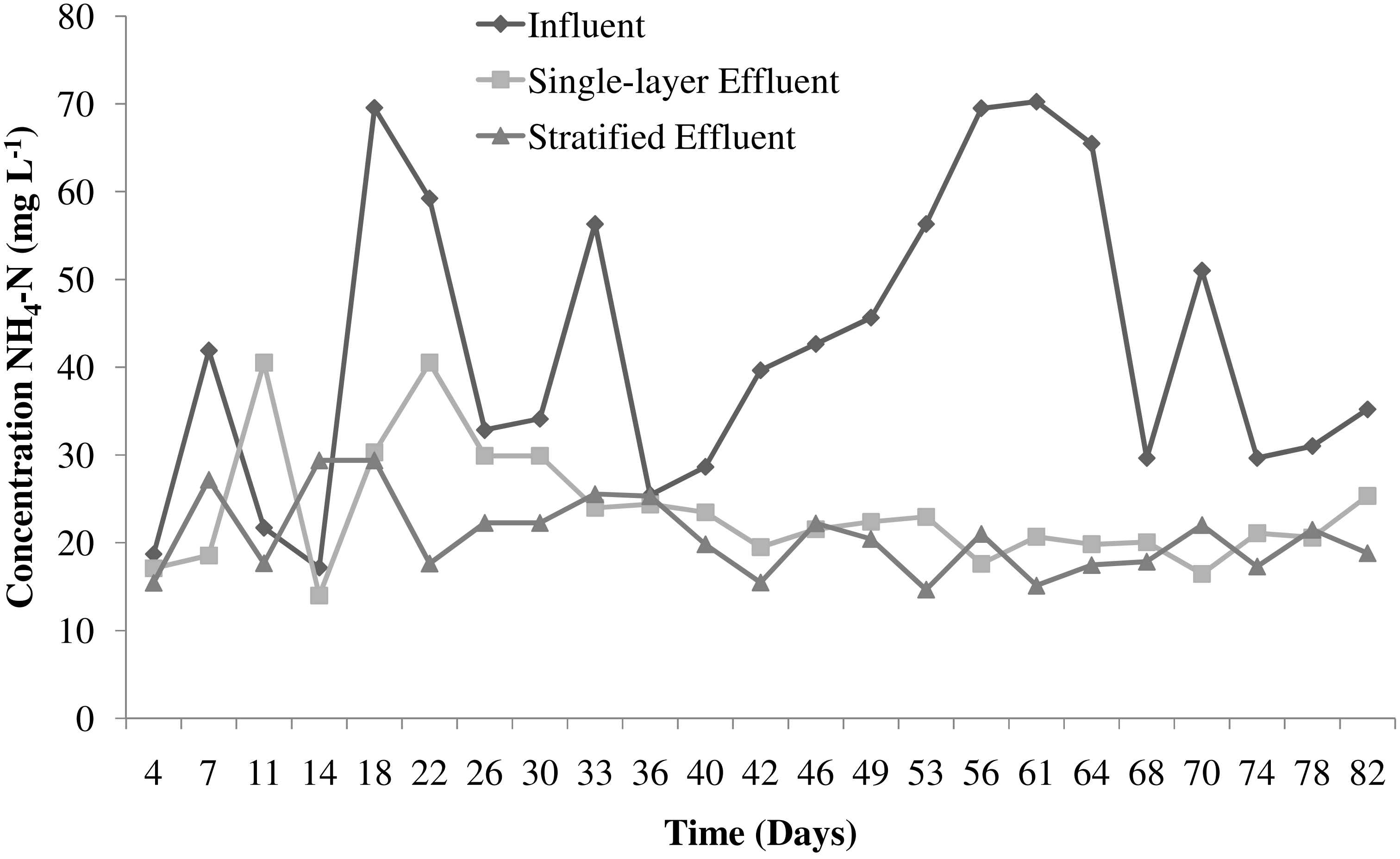
Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	74	100	94	107	100	-36	104	107	104	105	-42
7	17 June 2010	170	98	101	89	96	44	97	89	91	92	46
11	21 June 2010	37	101	95	99	98	-166	99	114	85	99	-168
14	24 June 2010	99	81	93	102	92	7	69	79	81	76	23
18	28 June 2010	133	65	74	81	73	55	69	79	81	76	57
22	02 July 2010	121	101	95	99	98	19	99	114	85	99	18
26	06 July 2010	108	56	67	67	63	41	49	60	60	56	48
30	10 July 2010	106	56	67	67	63	40	49	60	60	56	47
33	13 July 2010	128	42	52	59	51	60	42	54	56	51	60
36	16 July 2010	110	58	49	58	55	50	46	59	39	48	56
40	20 July 2010	115	39	53	56	49	57	58	48	42	49	57
42	22 July 2010	109	42	47	42	44	60	60	43	38	47	57
46	26 July 2010	128	39	49	49	46	64	49	39	41	43	66
49	29 July 2010	134	48	56	57	54	60	39	31	49	40	70
53	02 August 2010	128	52	53	53	53	59	59	35	50	48	63
56	05 August 2010	113	53	51	46	50	56	67	48	37	51	55
61	10 August 2010	108	49	57	40	49	55	52	52	36	47	57
64	13 August 2010	99	47	49	49	48	51	59	37	49	48	51
68	17 August 2010	128	56	37	50	48	63	53	46	41	47	64
70	19 August 2010	116	52	39	39	43	63	57	40	42	46	60
74	23 August 2010	99	50	40	48	46	54	41	39	49	43	57
78	27 August 2010	110	39	42	46	42	62	42	38	38	39	64
82	31 August 2010	130	40	48	52	47	64	46	42	37	42	68



180
160
140
120
100
80
60
40
20
0
Concentration TN_F (mg L^{-1})
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)
Influent
Single-layer Effluent
Stratified Effluent

Table C.5 Results for NH_4-N for the sand filters

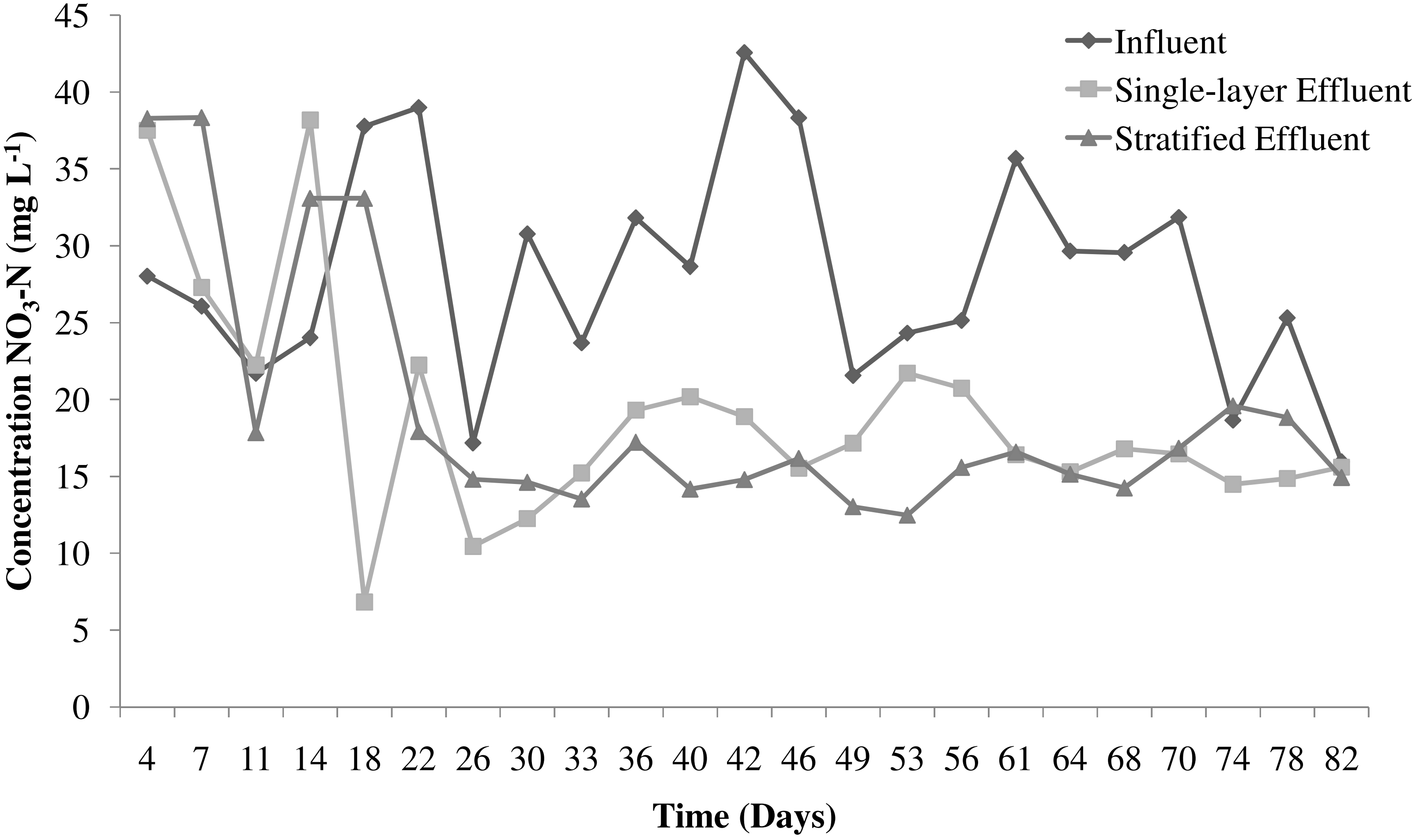
Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	18.72	16.966	16.786	17.535	17	9	15.693	15.326	15.293	15	18
7	17 June 2010	41.91	15.12	19.57	20.95	19	56	53.42	14.21	13.91	27	35
11	21 June 2010	21.717	42.93	29.51	49.11	41	-87	18.21	21.23	13.57	18	19
14	24 June 2010	17.17	14.419	13.799	13.722	14	19	31.55	31.25	25.4	29	-71
18	28 June 2010	69.56	20.14	27.34	43.42	30	44	31.55	31.25	25.4	29	42
22	02 July 2010	59.23	42.93	29.51	49.11	41	32	18.12	21.23	13.57	18	70
26	06 July 2010	32.85	24.78	25.12	39.8	30	9	18.13	27.35	21.34	22	32
30	10 July 2010	34.12	24.78	25.12	39.8	30	12	18.13	27.35	21.34	22	35
33	13 July 2010	56.32	19.65	26.65	25.65	24	57	25.35	26.67	24.62	26	55
36	16 July 2010	25.45	26.34	18.65	28.14	24	4	27.62	28.65	19.65	25	1
40	20 July 2010	28.65	24.25	24.52	21.62	23	18	24.52	16.52	18.45	20	31
42	22 July 2010	39.65	12.52	19.62	26.34	19	51	14.52	15.62	16.32	15	61
46	26 July 2010	42.65	16.32	19.62	28.65	22	50	24.52	17.62	24.52	22	48
49	29 July 2010	45.654	16.42	26.25	24.52	22	51	16.52	23.52	21.26	20	55
53	02 August 2010	56.318	20.1	24.62	24.12	23	59	12.25	16.32	15.42	15	74
56	05 August 2010	69.512	16.62	16.53	19.62	18	75	24.25	17.52	21.25	21	70
61	10 August 2010	70.254	21.25	19.56	21.25	21	71	14.52	16.35	14.52	15	78
64	13 August 2010	65.485	14.52	23.62	21.36	20	70	16.62	17.52	18.25	17	73
68	17 August 2010	29.65	21.02	13.52	25.65	20	32	12.2	20.12	21.25	18	40
70	19 August 2010	51.02	13.25	19.62	16.52	16	68	26.5	25.31	14.25	22	57
74	23 August 2010	29.65	16.25	14.52	32.54	21	29	16.32	19.32	16.25	17	42
78	27 August 2010	31.02	17.62	24.52	19.65	21	34	14.52	29.64	20.31	21	31
82	31 August 2010	35.21	16.35	34.23	25.46	25	28	17.25	19.62	19.58	19	47



Influent
Single-layer Effluent
Stratified Effluent
Concentration NH4-N (mg L-1)
80
70
60
50
40
30
20
10
0
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)

Table C.6 Results for NO_3-N for the sand filters

Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	28.024	37.74	36.598	38.196	38	-34	37.564	39.402	37.874	38	-37
7	17 June 2010	26.074	29.42	29.11	23.35	27	-5	43.69	35.97	35.37	38	-47
11	21 June 2010	21.695	42.11	12.29	12.31	22	-2	14.88	18.83	19.82	18	18
14	24 June 2010	24.022	36.086	37.504	40.942	38	-59	9	67.53	22.73	33	-38
18	28 June 2010	37.778	4.99	10.77	4.71	7	82	9	67.53	22.73	33	12
22	02 July 2010	38.99	42.11	12.29	12.31	22	43	14.88	18.83	20.02	18	54
26	06 July 2010	17.17	10.91	11.915	8.51	10	39	14.75	12.31	17.37	15	14
30	10 July 2010	30.77	12.54	14.56	9.65	12	60	12.57	15.64	15.64	15	52
33	13 July 2010	23.68	14.65	12.36	18.65	15	36	14.32	9.523	16.75	14	43
36	16 July 2010	31.82	18.65	12.85	26.45	19	39	19.45	14.56	17.65	17	46
40	20 July 2010	28.65	16.25	18.65	25.65	20	30	17.65	11.25	13.62	14	51
42	22 July 2010	42.56	17.56	19.45	19.65	19	56	12.52	12.32	19.52	15	65
46	26 July 2010	38.32	17.52	14.56	14.52	16	59	16.32	14.62	17.56	16	58
49	29 July 2010	21.56	17.56	19.65	14.25	17	20	14.25	10.23	14.62	13	40
53	02 August 2010	24.32	24.56	19.25	21.32	22	11	12.52	10.26	14.65	12	49
56	05 August 2010	25.14	14.56	22.25	25.41	21	18	15.62	14.56	16.58	16	38
61	10 August 2010	35.68	19.35	16.45	13.45	16	54	12.52	17.58	19.65	17	54
64	13 August 2010	29.65	16.85	14.52	14.52	15	48	14.25	18.65	12.52	15	49
68	17 August 2010	29.56	17.52	16.32	16.52	17	43	14.96	14.52	13.26	14	52
70	19 August 2010	31.85	16.52	13.25	19.62	16	48	19.65	16.32	14.52	17	47
74	23 August 2010	18.65	12.32	14.62	16.52	14	22	19.56	19.54	19.65	20	-5
78	27 August 2010	25.32	17.62	12.32	14.62	15	41	17.65	17.54	21.32	19	26
82	31 August 2010	15.95	18.65	14.52	13.62	16	2	18.65	12.52	13.62	15	6



45
40
35
30
25
20
15
10
5
0
Concentration NO_3-N (mg L^{-1})
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)
Influent
Single-layer Effluent
Stratified Effluent

Table C.7 Results for NO_2-N for the sand filters

Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	3.21	0.621	0.449	2.433	1	64	0	0	0	0	100
7	17 June 2010	15.803	0	0	0	0	100	0	0	0	0	100
11	21 June 2010	0.111	2.24	10.61	5.74	6	-5483	3.98	0.95	0.61	2	-1564
14	24 June 2010	2.41	0	0	0	0	100	0.77	1.27	1.06	1	57
18	28 June 2010	0	0.96	1.14	0.6	1	0	0.77	1.27	1.06	1	0
22	02 July 2010	0.51	2.24	10.61	5.74	6	-1115	3.98	0.95	0.61	2	-262
26	06 July 2010	18.72	6.2	9.77	2.18	6	68	2.56	8.2	3.26	5	75
30	10 July 2010	0.48	7.25	4.69	6.32	6	-1168	4.25	8.44	4.65	6	-1104
33	13 July 2010	6.35	4.65	2.65	5.32	4	34	2.36	4.32	1.62	3	56
36	16 July 2010	4.25	4.95	3.65	4.62	4	-4	4.32	4.21	3.15	4	8
40	20 July 2010	3.89	8.65	4.65	5.32	6	-60	6.32	2.65	4.25	4	-13
42	22 July 2010	6.35	3.65	5.62	4.32	5	29	1.65	3.45	3.14	3	57
46	26 July 2010	1.95	4.32	3.65	3.65	4	-99	5.24	5.21	4.92	5	-163
49	29 July 2010	2.56	2.65	4.69	4.69	4	-57	4.32	3.65	5.21	4	-72
53	02 August 2010	9.65	8.65	4.65	8.65	7	24	4.62	2.95	1.65	3	68
56	05 August 2010	12.32	1.25	8.65	7.65	6	53	6.95	4.21	5.62	6	55
61	10 August 2010	10.54	2.36	4.65	6.69	5	57	6.65	5.62	3.47	5	50
64	13 August 2010	11.624	1.326	2.325	1.324	2	86	2.365	3.644	2.625	3	75
68	17 August 2010	7.651	4.657	1.265	8.654	5	36	3.625	1.325	4.215	3	60
70	19 August 2010	5.647	1.544	7.654	1.362	4	38	2.35	5.246	2.365	3	41
74	23 August 2010	5.167	2.625	4.658	8.625	5	-3	4.235	1.345	2.263	3	49
78	27 August 2010	3.897	4.652	3.541	4.326	4	-7	2.654	2.642	1.654	2	41
82	31 August 2010	8.654	2.264	5.698	5.647	5	48	4.659	3.625	1.326	3	63

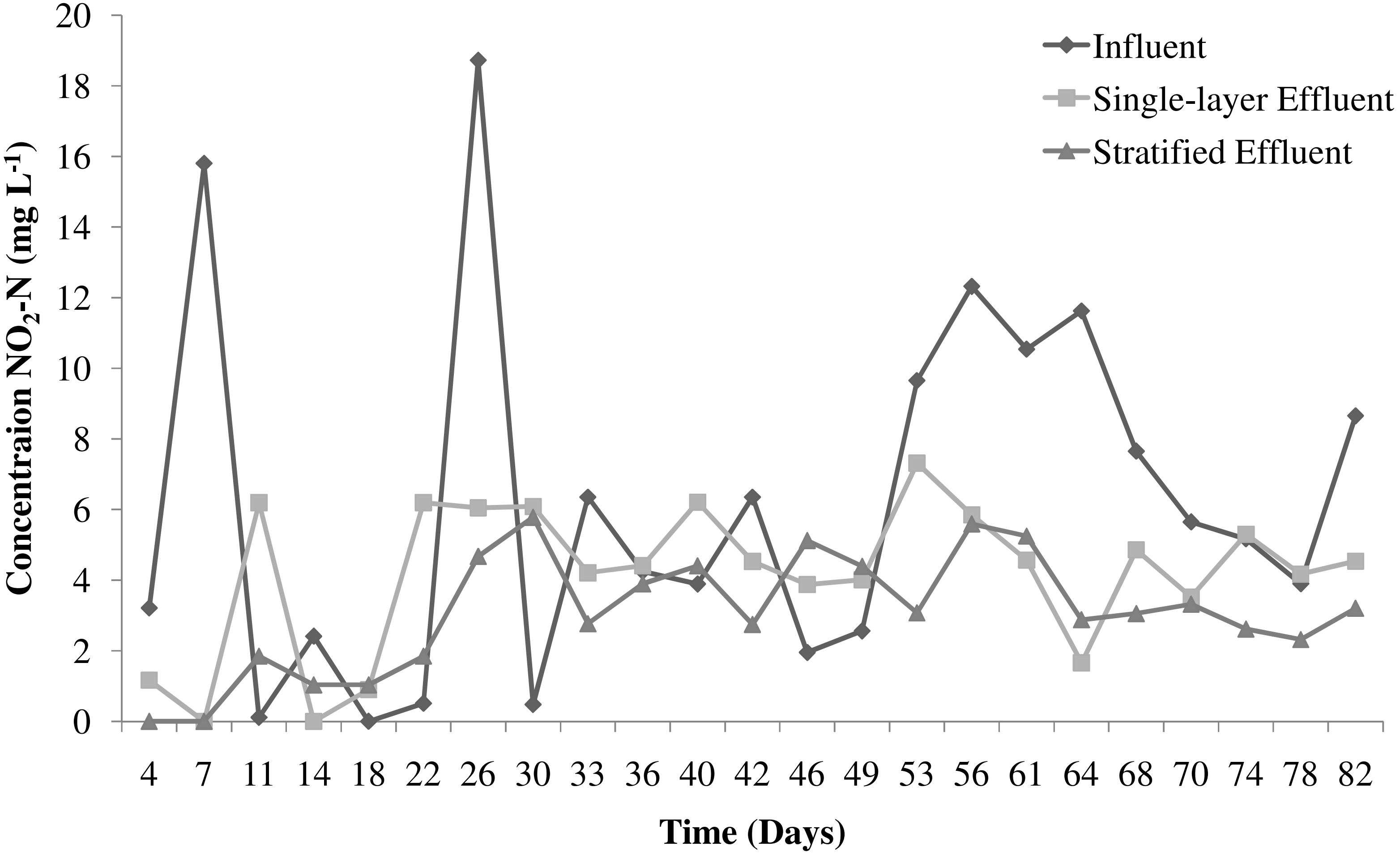

Influent
Single-layer Effluent
Stratified Effluent
Concentraion NO_2-N (mg L^{-1})
0
2
4
6
8
10
12
14
16
18
20
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)

Table C.8 Results for SS for the sand filters

Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	42	26	14	18	19	54	2	16	72	30	29
7	17 June 2010	58	28	40	92	53	8	23	38	25	29	51
11	21 June 2010	40	52	37	42	44	-9	25	28	22	25	38
14	24 June 2010	56	32	30	31	31	45	19	24	23	22	61
18	28 June 2010	109	44	26	31	34	69	19	24	23	22	80
22	02 July 2010	126	52	37	42	44	65	25	28	22	25	80
26	06 July 2010	60	55	50	51	52	13	40	48	44	44	27
30	10 July 2010	69	55	50	51	52	25	40	48	44	44	36
33	13 July 2010	76	35	28	42	35	54	28	32	28	29	61
36	16 July 2010	95	42	41	36	40	58	34	35	26	32	67
40	20 July 2010	112	56	45	25	42	63	36	42	34	37	67
42	22 July 2010	128	48	32	32	37	71	28	36	36	33	74
46	26 July 2010	46	42	38	39	40	14	43	28	25	32	30
49	29 July 2010	95	39	41	41	40	58	62	30	24	39	59
53	02 August 2010	135	64	35	46	48	64	29	44	25	33	76
56	05 August 2010	108	58	26	47	44	60	36	40	36	37	65
61	10 August 2010	92	54	34	49	46	50	37	35	30	34	63
64	13 August 2010	43	39	25	32	32	26	24	38	34	32	26
68	17 August 2010	86	54	34	39	42	51	40	29	40	36	58
70	19 August 2010	91	58	29	46	44	51	31	36	38	35	62
74	23 August 2010	75	45	34	45	41	45	35	34	29	33	56
78	27 August 2010	64	38	32	28	33	49	28	26	34	29	54
82	31 August 2010	128	54	39	29	41	68	26	36	31	31	76

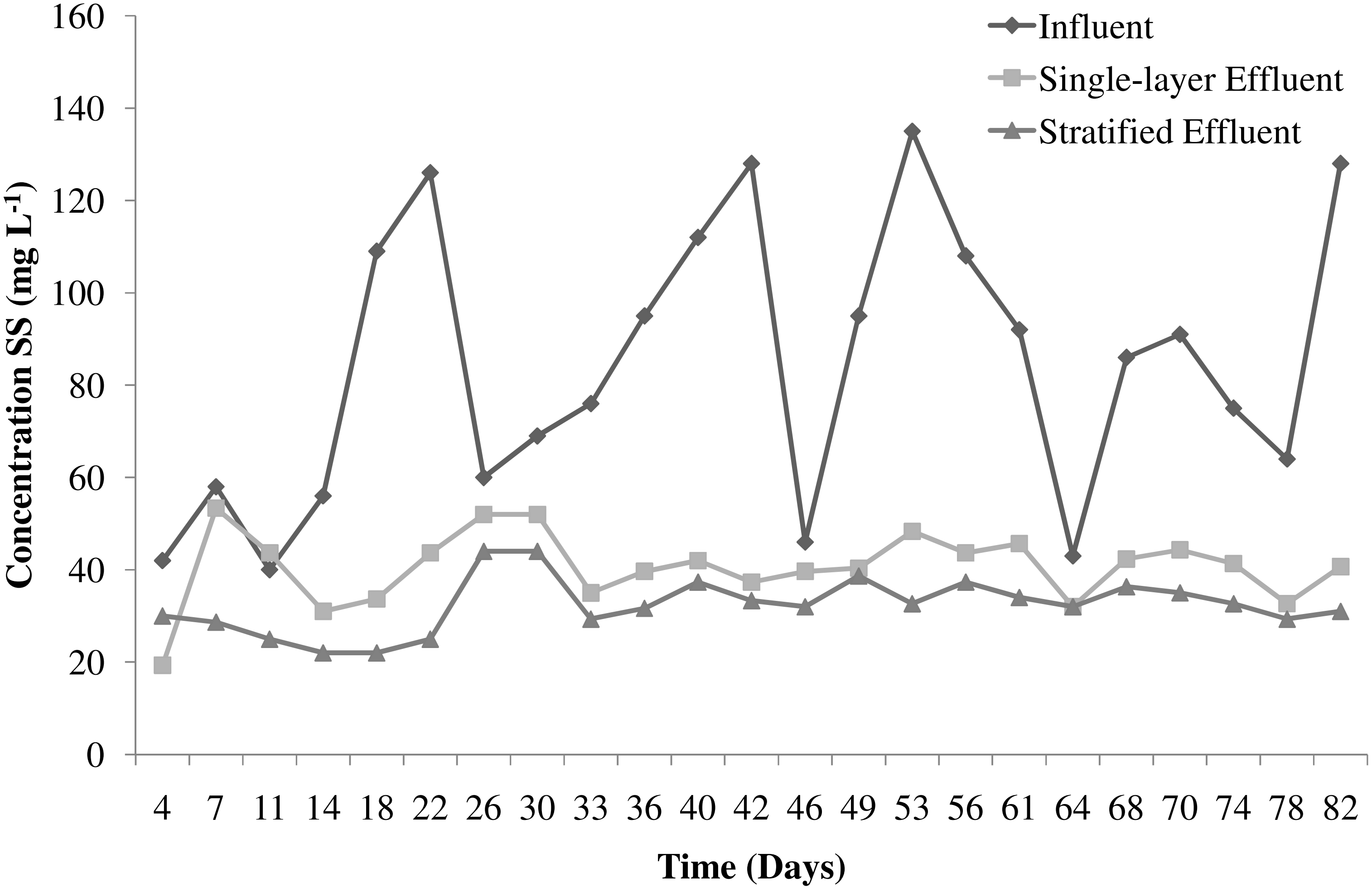
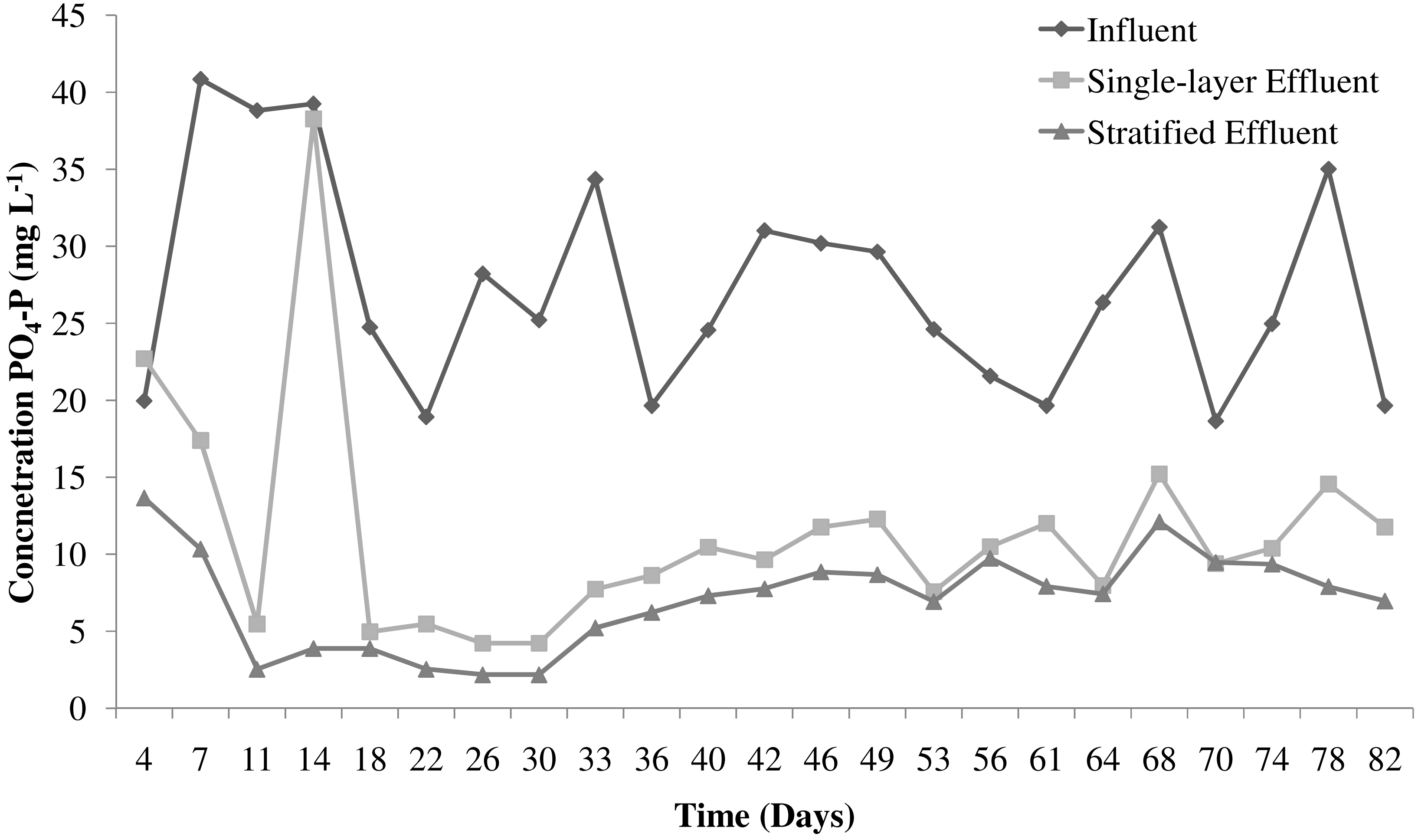

Influent
Single-layer Effluent
Stratified Effluent
Concentration SS (mg L^{-1})
160
140
120
100
80
60
40
20
0
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)

Table C.9 Results for PO_4-P for the sand filters

Day No.	Date	Influent	Single-layer					Stratified				
			1	2	3	Average	Reduction	1	2	3	Average	Reduction
			mg L^{-1}				%	mg L^{-1}				%
4	14 June 2010	19.97	25.65	22.63	19.8	23	-14	11.84	12.44	16.68	14	32
7	17 June 2010	40.85	12.54	22.72	16.89	17	57	8.39	11.55	11.07	10	75
11	21 June 2010	38.82	5.843	4.331	6.215	5	86	2.275	3.072	2.249	3	93
14	24 June 2010	39.25	49.91	34.55	30.36	38	2	3.214	4.736	3.684	4	90
18	28 June 2010	24.749	5.05	4.302	5.521	5	20	3.214	4.736	3.684	4	16
22	02 July 2010	18.92	5.843	4.331	6.215	5	71	2.275	3.072	2.249	3	87
26	06 July 2010	28.21	4.163	3.896	4.582	4	85	1.933	2.517	2.07	2	92
30	10 July 2010	25.21	4.163	3.896	4.582	4	83	1.933	2.517	2.07	2	91
33	13 July 2010	34.36	5.62	11.23	6.32	8	78	4.69	5.32	5.63	5	85
36	16 July 2010	19.65	10.26	10.23	5.36	9	56	4.65	6.35	7.65	6	68
40	20 July 2010	24.56	9.45	13.26	8.65	10	57	6.42	5.89	9.58	7	70
42	22 July 2010	31.02	6.65	9.62	12.65	10	69	5.96	9.65	7.64	8	75
46	26 July 2010	30.2	14.26	11.46	9.56	12	61	8.65	7.65	10.25	9	71
49	29 July 2010	29.64	11.25	12.32	13.25	12	59	9.35	10.25	6.41	9	71
53	02 August 2010	24.61	10.65	5.68	6.38	8	69	5.63	6.48	8.65	7	72
56	05 August 2010	21.58	9.48	7.65	14.32	10	51	7.65	9.24	12.32	10	55
61	10 August 2010	19.65	14.32	10.36	11.32	12	39	4.65	7.65	11.45	8	60
64	13 August 2010	26.35	7.65	9.65	6.58	8	70	8.65	4.65	8.98	7	72
68	17 August 2010	31.25	19.65	16.32	9.65	15	51	14.32	12.32	9.65	12	61
70	19 August 2010	18.65	5.36	10.32	12.47	9	50	7.85	11.85	8.69	9	49
74	23 August 2010	24.97	10.26	14.32	6.56	10	58	9.64	10.45	7.98	9	63
78	27 August 2010	35.02	24.56	9.65	9.45	15	58	5.63	7.62	10.45	8	77
82	31 August 2010	19.65	14.32	12.32	8.64	12	40	4.86	6.35	9.65	7	65



Influent
Single-layer Effluent
Stratified Effluent
Concnetration PO4-P (mg L-1)
45
40
35
30
25
20
15
10
5
0
4
7
11
14
18
22
26
30
33
36
40
42
46
49
53
56
61
64
68
70
74
78
82
Time (Days)