RESEARCH REPORT

External Research Program

Sloping Sand Filters for On-Site Wastewater Treatment

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SLOPING SAND FILTERS FOR ON-SITE WASTEWATER TREATMENT

Report to:

Canada Mortgage and Housing Corporation

External Research Program

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June, 2009

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RESEARCH HIGHLIGHT

December 2009 Technical Series 09-112

Sloping Sand Filters for On-Site Wastewater Treatment

INTRODUCTION

Approximately 50% of Nova Scotia residents utilize on-site septic systems for wastewater treatment and disposal, however conventional treatment systems may be at greater risk of premature failure due to geologic conditions commonly found in the province, such as low permeability soils, shallow bedrock, and high water tables. To address these issues, sloping sand filters (SSF), or lateral flow sand filters (LFSF) as presented in figure 1.1, have been approved for use as remedial technology to replace failed conventional systems. While laboratory studies have indicated satisfactory performance very little field analysis has been undertaken.

PROJECT OBJECTIVES

This report presents findings from a two-year study examining the hydraulics and treatment performance of sloping sand filters (SSF), or lateral flow sand filters (LFSF), for on-site residential wastewater treatment. This study utilized, and expanded upon, an existing set of field scale SSFs that were installed at the Bio-environmental Engineering Centre (BEEC) in Truro, NS for experimental purposes. The overall objective of this research project was to assess current design guidelines for SSFs, and make recommendations for the expanded use, and optimization, of these types of systems. Specific objectives included: (i) assessing the hydraulic behaviour and performance of conventionally designed SSFs at loading rates greater than those allowed within NS technical guidelines, (ii) assessing the hydraulic behaviour and performance of SSFs that were

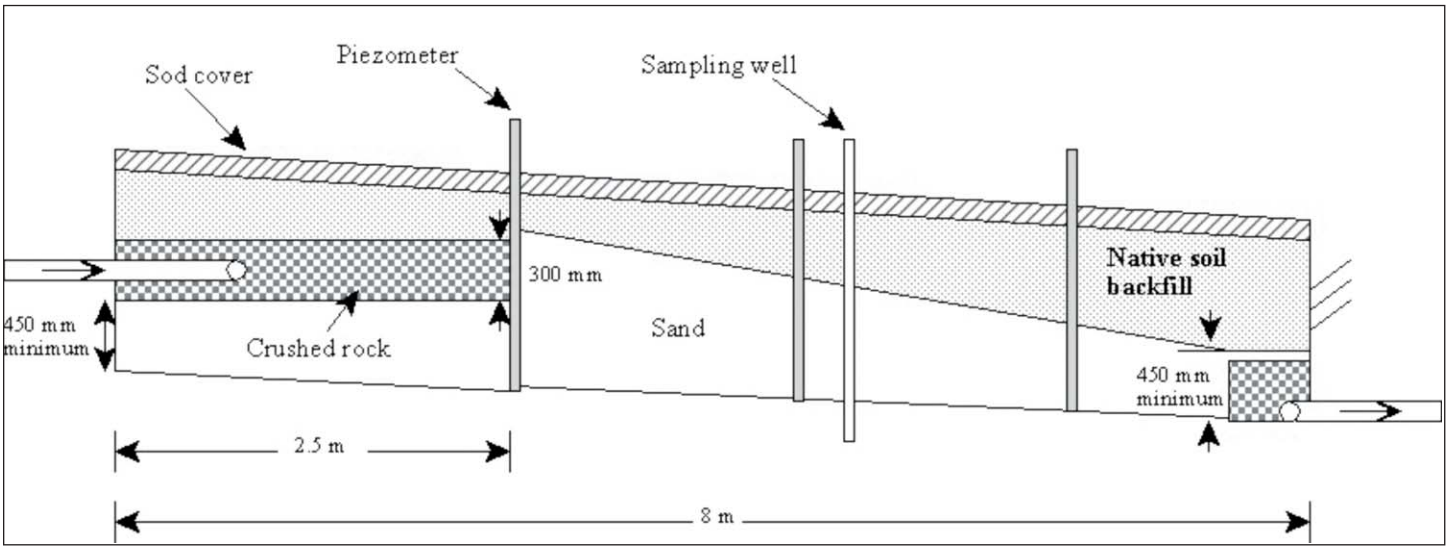

Figure 1 Schematic of a typical Lateral Flow Sand Filter used in Nova Scotia.

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substantially shorter than those required within NS technical guidelines, (iii) determining if current hydraulic models of SSF systems are appropriate.

METHODOLOGY

A total of eight pilot-scale SSF systems were installed at the BEEC, and continuously dosed with septic tank effluent. Filter construction encompassed the full range of sand sizes and slopes allowed within NS technical guidelines. Six of the SSFs were constructed according to NS technical guidelines but loaded at approximately double the recommended linear loading rate. Two replicate SSFs were constructed with downgradient lengths that were 50% of the length recommended in the NS technical guidelines, but were loaded according to the recommended linear loading rates. The hydrology and treatment performance of the systems were monitored over a 16-20 month period. A series of tracer studies were conducted within all eight filters over the course of the study. Tracer study data was fit to analytical residence time distribution models to assess the hydraulic functioning of the filters. Measured hydraulic characteristics were then compared to those predicted using theoretical models of porous media flow.

KEY FINDINGS

- External hydrologic factors can have a large influence on the flow characteristics of SSF systems. Outflows from the SSFs varied greatly, increasing by a factor of 4 during some precipitation events. However, the influence of precipitation on SSF hydrology is complex, and a strong function of antecedent moisture conditions.
- Observations from piezometers installed at several locations within each filter indicated that the filters were not fully saturated, even after the wastewater loading rate was increased.
- Observations from monitoring wells installed in the distribution trench of each filter indicated that the biomat within each filter was stable. Minor increases in ponding depths were observed in the distribution trench after wastewater loading rates were increased.
- In general, sand grain size had the greatest influence on residence time characteristics, as opposed to slope and wastewater loading rate. As expected, the fine grained filters have higher residence times compared to medium- and coarse-grained filters, presumably due to the smaller pore space for the wastewater to travel through. Residence times from medium and coarse grained filters were comparable.
- Tracer studies indicated that the residence time characteristics of the filters did not change after the wastewater loading rate was increased. This provided further evidence that biomat hydraulics have a large influence on the speed of wastewater movement through the filters.
- Comparison of measured mean residence times to theoretical residence times computed assuming saturated flow confirmed that saturated Darcy flow did not occur within the SSFs.
- In general the SSFs performed well over the monitoring period, producing average effluent five-day biochemical oxygen demand (BOD_5) concentrations below 10 mg/L, and average total suspended solids (TSS) concentrations below 15 mg/L.
- Median outlet *E. coli* levels were all below 10 CFU / 100 mL, indicating that the sand filters were generally effective at removing enteric bacteria. However, on several occasions levels of *E. coli* in filter effluent exceeded 100 CFU / 100 mL, illustrating variability in treatment performance. This indicated that effluent from SSF systems could not be surface discharged without additional disinfection.
- SSFs that were loaded at elevated rates, as compared to NS technical guidelines, performed well, providing a level of treatment that was similar to that observed at conventional loading rates.

- The shortened filters performed at the same level as a regular length filter under similar loading rate conditions. These results suggest that the majority of treatment occurs within the first part of the LFSF, and that treatment processes occurring within the biomat control the treatment efficiency of the system.
- Removal of Total Nitrogen (TN) was not affected by the increase in wastewater loading rate. The SSFs consistently removed between 40 – 50% of TN.
- A progressive reduction in phosphorus (P) removal was observed in each filter. After 3 years of effluent loading, several of the original six filters appear to be saturated with P. As expected, the coarse-grained filters saturate more quickly than fine-grained filters, as they would possess less surface area for adsorption. These results indicate that conventional sand-based disposal systems have virtually no long-term phosphorus removal capacity.

IMPLICATIONS FOR THE HOUSING INDUSTRY

This study has shown that current design loading rates for SSFs in NS are conservative, and provide an inherent safety factor. The SSF system was shown to be a reliable, relatively robust treatment system. However, sand-based systems such as these indicate variable *E. coli* removal and poor long-term phosphorous removal. Accordingly, consideration should be given to additional treatment and disinfection when utilized for surface discharge or for discharge into sensitive receiving bodies.

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LE POINT EN RECHERCHE

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Filtres à sable en pente servant d'installation d'assainissement sur place des eaux usées

INTRODUCTION

Environ 50 % des résidents de la Nouvelle-Écosse utilisent une installation septique sur place pour l'assainissement et l'élimination des eaux usées. Les installations classiques, toutefois, présentent un plus grand risque de défaillance prématurée en raison des conditions géologiques que l'on trouve communément dans la province, comme un sol à faible perméabilité, une roche de fond à faible profondeur ou une nappe d'eau élevée. Pour endiguer ces problèmes, des filtres à sable en pente (ou filtres à sable à écoulement latéral), illustrés à la figure 1.1, ont été approuvés à titre de technologie de rechange pour remplacer les installations classiques défectueuses. Bien que des essais en laboratoire aient donné des résultats satisfaisants, très peu d'analyses sur le terrain ont été entreprises.

OBJECTIFS

Le rapport dont il est ici question fait état des constatations d'une étude qui s'est déroulée sur deux ans et qui a porté sur l'examen des caractéristiques hydrauliques et de la performance en traitement des filtres à sable en pente, ou filtres à sable à écoulement latéral, servant d'installation d'assainissement sur place pour les habitations. L'étude a tiré parti d'une série d'installations de filtres à sable en pente qui ont été mises en place au Bioenvironmental Engineering Centre (BEEC), à Truro (N.-É.), à des fins expérimentales. L'objectif principal de la recherche consistait à évaluer les directives de conception actuelles des filtres à sable en pente et à formuler des recommandations quant à l'utilisation plus étendue de ce genre d'installation et leur optimisation. Les travaux de recherche avaient pour objectifs particuliers (i) d'évaluer le comportement hydraulique et la performance des filtres à

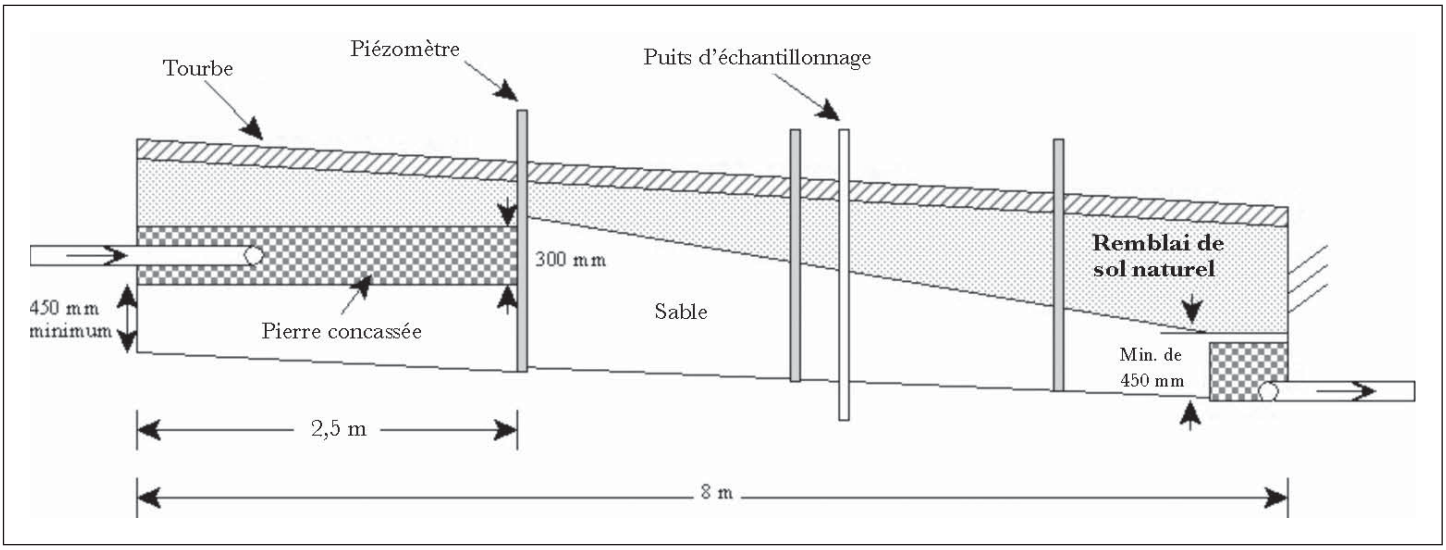

Figure 1 Schéma d'un filtre à sable à écoulement latéral type utilisé en Nouvelle-Écosse.

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sable en pente de conception courante fonctionnant à des taux de charge plus importants que ceux autorisés par les lignes de conduite de la N.-É., (ii) d'évaluer le comportement hydraulique et la performance des filtres à sable en pente qui étaient beaucoup plus courts que ceux exigés par les lignes de conduite techniques de la N.-É. et (iii) de déterminer dans quelle mesure les modèles hydrauliques actuels visant les installations de filtres à sable en pente sont adéquats.

MÉTHODE

Au total, on a aménagé huit installations pilotes de filtres à sable en pente au BEEC, lesquelles ont été alimentées en continu d'effluent de fosse septique. Pour la construction des filtres, on a fait appel à toute la gamme de granulométrie de sables et de pentes autorisées dans les lignes de conduite techniques de la Nouvelle-Écosse. Six des installations ont été construites selon les lignes de conduite techniques de la N.-É., mais à une charge hydraulique d'environ le double de la charge linéaire recommandée. Deux installations identiques de filtres à sable en pente ont été mises en place avec des longueurs de l'amont vers l'aval à 50 % de la longueur recommandée dans les lignes de conduite techniques, tout en recevant une charge conforme au taux de charge linéaire recommandé. Les aspects de l'hydrologie et de la performance en traitement des installations ont été suivis pendant 16 à 20 mois. Au cours des travaux, une série d'études par traceur a été menée dans les huit filtres à sable. Les données des études par traceur ont été comparées à des modèles de distribution analytiques en temps de séjour aux fins d'évaluation du fonctionnement des filtres à sable. Les caractéristiques hydrauliques mesurées ont par la suite été comparées à celles prévues par les modèles théoriques d'écoulement en milieux poreux.

CONSTATATIONS CLÉS

- Des facteurs hydrologiques externes peuvent avoir un impact important sur les caractéristiques d'écoulement des installations de filtres à sable en pente. Le débit de sortie a varié grandement, quadruplant lors de certains épisodes de précipitations. L'effet des précipitations sur l'hydrologie des filtres à sable en pente est toutefois complexe et dépend en grande partie des conditions antérieures d'humidité.
- Des observations tirées de piézomètres installés à divers endroits à l'intérieur de chaque filtre révèlent que les filtres ne sont pas entièrement saturés, même après augmentation du taux de charge en eaux usées.
- Des lectures tirées de puits d'observation installés dans la tranchée de distribution de chaque filtre indiquent que le film biologique à l'intérieur de chaque filtre était stable. On a observé un faible accroissement de la profondeur des accumulations de liquides dans la tranchée de distribution après avoir augmenté les taux de charge en eaux usées.
- En règle générale, c'est la taille des grains de sable qui influait davantage sur les caractéristiques de temps de séjour, par rapport à la pente ou au taux de charge en eaux usées. Comme prévu, les filtres à grain fin présentent des temps de séjour plus longs comparativement aux filtres à sable à grains moyens ou grossiers, sans doute à cause du plus faible espace interstitiel à travers duquel les eaux usées se déplacent. Les temps de séjour des filtres à grains moyens ou grossiers étaient du même ordre.
- Les études sur traceur révèlent que les caractéristiques de temps de séjour dans les filtres demeuraient inchangées même si le taux de charge en eaux usées était augmenté. Cette constatation constitue une autre preuve que les caractéristiques hydrauliques des films biologiques influent largement sur la vitesse d'écoulement des eaux usées à travers les filtres à sable.
- Une comparaison établie entre les temps moyens de séjour et les temps de séjour théoriques calculés, en supposant un écoulement saturé, a confirmé que l'écoulement dans les installations étudiées ne se faisait pas selon l'écoulement saturé de Darcy.
- En général, les filtres à sable en pente ont affiché une performance satisfaisante au cours de la période de suivi, produisant un effluent dont les concentrations moyennes en demande biochimique d'oxygène sur cinq jours (BOD_5) étaient inférieures à 10 mg/L, et dont les concentrations moyennes totales de solides en suspension (TSS) étaient inférieures à 15 mg/L.

- Les niveaux moyens de colibacilles dans l'effluent étaient tous inférieurs à 10 CFU/100 ml, ce qui indique que les filtres à sable étaient généralement efficaces en matière d'élimination d'entébactéries. À plusieurs occasions, toutefois, les niveaux de colibacilles dans l'effluent des filtres ont excédé 100 CFU/100 ml, illustrant ainsi la variabilité de la performance en traitement. Cette situation indique qu'il faut éviter d'acheminer l'effluent des filtres à sable en pente vers les surfaces de ruissellement sans désinfection préalable.
- Les filtres à sable en pente qui ont traité une charge élevée d'effluent comparativement aux lignes de conduite techniques de la Nouvelle-Écosse ont présenté une performance satisfaisante, c'est-à-dire qu'ils ont fourni un niveau de traitement semblable à celui observé à des taux de charge traditionnels.
- Les filtres à sable raccourcis ont affiché la même performance en traitement que les filtres de longueur courante dans des conditions de charge semblables. Ces résultats suggèrent que la majorité du traitement s'effectue dans la première partie du filtre à sable à écoulement latéral et que ce sont les processus de traitement qui ont cours dans le film biologique qui déterminent l'efficacité de l'installation.
- L'augmentation du taux de charge en eaux usées n'a pas influé sur l'élimination de l'azote total. Les filtres à sable en pente ont éliminé de façon constante entre 40 et 50 % de l'azote total.
- On a observé une réduction progressive du taux d'élimination du phosphore dans chacun des filtres. Après trois années de traitement de charge en effluent, plusieurs des six filtres d'origine semblent être saturés en phosphore. Comme on s'y attendait, les filtres à sable à grains grossiers se sont saturés plus rapidement que les filtres à grains fins, puisque les premiers présentent une surface d'adsorption moins étendue. Ces résultats révèlent que les installations d'assainissement courantes à base de sable ne possèdent aucune capacité à long terme d'élimination du phosphore.

CONSÉQUENCES POUR LE SECTEUR DE L'HABITATION

Cette étude a montré que les taux de charge actuellement utilisés lors de la conception de filtres à sable en pente en Nouvelle-Écosse sont prudents et comportent donc un facteur de sécurité inhérent. Il a été montré que le filtre à sable en pente constitue une installation d'assainissement fiable et relativement robuste. Cela dit, les installations à base de sable de ce type affichent des taux variables d'élimination des colibacilles et une piètre élimination à long terme du phosphore. C'est pourquoi il faudrait considérer la mise en œuvre de techniques de désinfection et de traitement additionnelles lorsque l'effluent de sortie est acheminé en surface du sol ou vers un milieu récepteur sensible.

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EXECUTIVE SUMMARY

This report presents findings from a two year study examining the hydraulics and treatment performance of sloping sand filters (SSF), or lateral flow sand filters (LFSF), for on-site residential wastewater treatment. Lateral flow sand filters have been used in Nova Scotia (NS) for several years as a remedial option for failed soil absorption fields. The use of these types of treatment systems could be greatly expanded in NS, and across Canada, however, the performance, and hydraulic behavior, of these types of systems is poorly understood. This study utilized, and expanded upon, an existing set of field scale SSFs that were installed at the Bioenvironmental Engineering Centre (BEEC) in Truro, NS for experimental purposes. The overall objective of this research project was to assess current design guidelines for SSFs, and make recommendations for the expanded use, and optimization, of these types of systems. Specific objectives included: (i) assessing the hydraulic behavior and performance of conventionally designed SSFs at loading rates greater than those allowed within NS technical guidelines, (ii) assessing the hydraulic behavior and performance of SSFs that were substantially shorter than those required within NS technical guidelines, (iii) determining if current hydraulic models of SSF systems are appropriate.

A total of eight pilot scale SSF systems were installed at the BEEC, and continuously dosed with septic tank effluent. Six of the SSFs were constructed according to NS technical guidelines but loaded at approximately double the recommended linear loading rate. Two replicate SSFs were constructed with downgradient lengths that were 50% of the length recommended in the NS technical guidelines, but were loaded according to the recommended linear loading rates. The hydrology and treatment performance of the systems were monitored over a 16-20 month period. A series of tracer studies were conducted within all eight filters over the course the study. Tracer study data was fit to analytical residence time distribution models to assess the hydraulic functioning of the filters. Measured hydraulic characteristics were then compared to those predicted using theoretical models of porous media flow.

In general, the results of the study provide further evidence that SSF systems are a relatively reliable, and robust, form of on-site wastewater treatment. Water level measurements within the SSF systems loaded at double the recommended linear rate revealed that filters largely remained unsaturated, and biomats hydraulics remained stable. Mean residence times did not appear to increase with increased loading rates. The treatment performance of the SSF systems loaded at double the recommended rate was not statistically different from those reported previously for these systems when loaded at the recommended rate. The treatment performance of the two shortened SSF systems was also similar to that reported for a comparable SSF system that possessed a sand toe that was twice as long. These findings confirm that existing technical guidelines for SSF design are conservative, and that the hydraulic behavior of these types of systems is not well represented as saturated darcy flow. An additional interesting observation from this study was the progressive reduction in phosphorus removal within all the monitored SSFs. Results from this study suggest that sand-based disposal fields become saturated with phosphorus within 3-5 years.

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1.0 BACKGROUND AND PROJECT OBJECTIVES

Approximately 50% of the population of Nova Scotia relies on an on-site system for wastewater treatment and disposal (Check 1992). A conventional system in Nova Scotia consists of a septic tank and absorption trench, constructed within native soil materials. Many of these systems are malfunctioning, resulting in contamination of surface waters, groundwater, shellfish areas and recreational areas. A septic system malfunction may include failure of the absorption field caused by saturated soil conditions or clogging due to sewage solids, effluent breaking through the ground surface, and sewage backups into toilets, tubs, or sinks. The associated health risks, environmental effects and costs to shellfish and tourist industries, property owners and taxpayers are substantial.

System failures can be due to a number of reasons; however, the installation of conventional leaching bed systems in areas where the soil and geologic conditions are not appropriate is a common occurrence. The presence of low permeability soils, shallow bedrock and high water tables are the most common site constraints in Nova Scotia. If sufficient depth of permeable soil is not present there is an increased risk of system malfunction and contamination of ground or surface water. Improper septic tank maintenance may also cause system malfunction.

Sand filtration has been used as a method for treating both drinking water and wastewater for many years. Typically, systems are operated as either single pass or recirculating vertical flow filters (Kristiansen 1981a; Pell and Nyberg 1989a; Harrison et al. 2000). Various studies have shown that single pass sand filters are effective in removing organic material, suspended solids, enteric microorganisms, and ammonia-nitrogen (NH_4-N) from domestic wastewater (Brandes 1980; Pell and Nyberg 1989a; Harrison et al. 2000; Rodgers et al. 2004). In these studies the studied sand filters were operating under unsaturated flow conditions, thus allowing for almost complete nitrification of all influent NH_4-N to nitrate-nitrogen (NO_3-N). Reported treatment efficiencies for phosphorus (P) within sand filters receiving domestic wastewater are variable, ranging from less than 50% (Pell and Nyberg 1989a) to greater than 80% (Rodgers et al. 2004).

In Nova Scotia, sand filters are approved for use as a remedial technology to replace a failed soil absorption field described as a malfunction (NSDEL 2005). The design of a typical sand filter currently used in Nova Scotia is provided in Fig. 1.1. The system is termed a Lateral Flow Sand-Filter (LFSF), or sloping sand filter (SSF), and is a variation of the commonly reported vertical flow sand filter design. Septic tank effluent enters a gravel filled distribution trench and flows vertically down into the sand medium (Fig. 1.1) until it reaches an impermeable base (bedrock or impermeable soil). It then flows laterally downslope through the sand filter. The length of the distribution trench is based on the design loading rate, the slope of the filter, and the hydraulic conductivity of the sand. The width of the gravel trench (length of sand filter in the downslope direction) must be at least 5 m and the areal loading rate for system must not exceed 33 L/m^2.

Although SSF systems have been in use in Nova Scotia for more than 20 years, very little data have been collected from field systems to evaluate their performance, and to determine if current design criteria are appropriate. The LFSF concept was studied by Check et al. (1994) using laboratory models. Within this laboratory study three 0.178 m wide x 5 m long filters were constructed. Each filter was constructed using a different sand medium, encompassing the range of permeability and sizes recommended in the Nova Scotia Department of Environment technical guidelines.

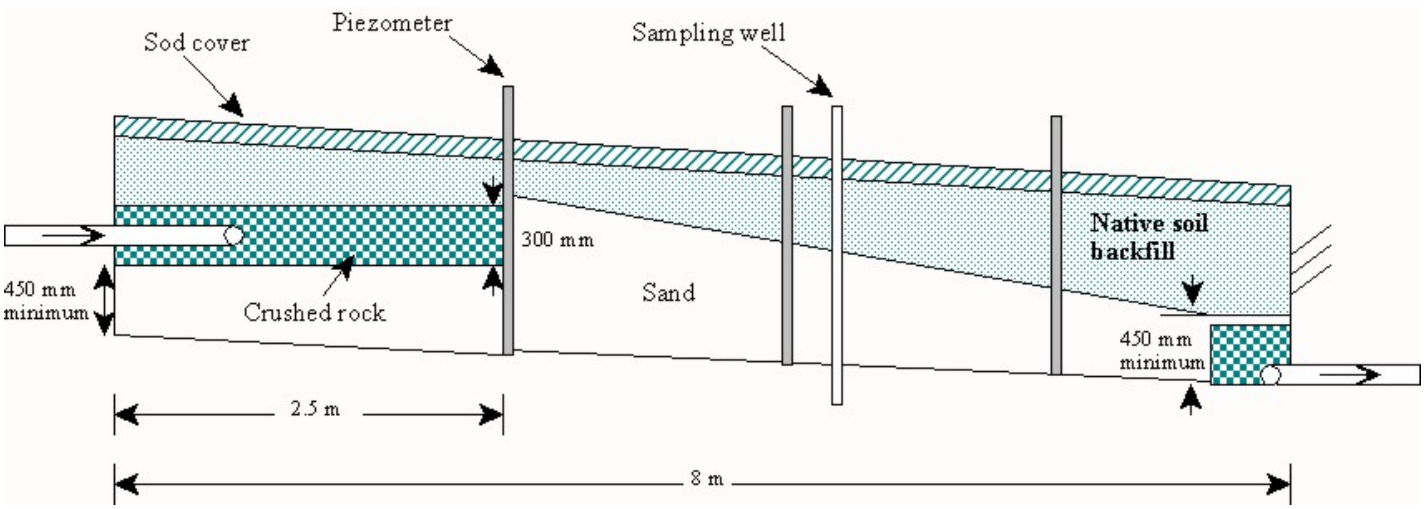


Figure 1.1. Schematic of a typical Lateral Flow Sand Filter used in Nova Scotia.

They found that treatment efficiencies for SSF systems were comparable to vertical flow filters. The SSF models provided sufficient removal of biochemical oxygen demand (BOD), total suspended solids (TSS), NH_4-N and enteric microorganisms. It was observed that P removal was satisfactory at the start of the experiment and then declined as the experiment progressed. The authors also recommended use of the coarsest sand size as the treatment performance of this filter was comparable to the two filters constructed with finer sand materials, and the coarser sand would be less likely to clog.

Although the work conducted by Check et al. (1994) showed that the SSF is capable of providing adequate treatment of septic effluent, data related to the performance of these systems under field conditions was not available. Also, the experiments were relatively short-term (6 months) and conducted under laboratory conditions. The influence of temperature and atmospheric processes (precipitation/evapotranspiration) could not be examined. The influence of other key design criteria, such as sand characteristics and slope, on system performance also required further study. To address these information gaps, an experimental facility was constructed in the summer of 2004 to evaluate the performance of SSFs under field conditions. The original facility consisted of six pilot scale SSFs designed in accordance with specifications for SSFs in the Nova Scotia On-site Technical Guidelines. The systems were constructed adjacent to the Bio-environmental Engineering Centre in Truro, Nova Scotia, Canada. Three filters, containing media that met specifications for mortar, concrete, and silica sands, were installed at a slope of 5%. Three others, containing the same sands, were installed at a 30% slope. These filters differ in the particle size of the sand, with coarse, medium or fine sands providing a range of hydraulic conductivity.

Each sand filter is 8 m long, 1.2 m wide and consists of a gravel bed at the head to evenly distribute the effluent across the top of the sand filter, and then a layer of sand tapering from approximately 1 m at the gravel to 0.45 m at the toe of the filter (Fig. 1.1). The filter bed is covered with 0.6 to 1 m of soil which is separated from the sand by geotextile material. Piezometers and a sampling well were installed to provide access for monitoring water levels and sampling effluent in the filter bed (Fig. 1.1). The sampling well was installed to a depth below the filter bottom to act as a sump for effluent collection. The sand filters were constructed within open plywood boxes (i.e. the top of the filter was open) lined

with plastic. Effluent was collected in a 100 mm perforated pipe running the width of the filter at the downslope end and directed into the outflow sampling hut through a solid 100 mm PVC pipe. The septic effluent for the sand filters is supplied by a PLC controlled pump to dose the sand filters once per hour to ensure a loading rate of 100 L d^{-1} (375 mm mth^{-1}) to each filter. The results from the first year of monitoring were reported in Havard et al. (2008). Average removal efficiencies for all SSFs met NSE requirements: biological oxygen demand (>98.5%), total suspended solids (>95.5%), and *E. coli* (>5.4 log reduction). Phosphorus removal ranged from 98% in the fine sand to 71.2% in the coarse sand filter. Nitrification was favored because the filters were operating under aerobic and unsaturated conditions. Therefore, denitrification was limited causing elevated nitrate effluent concentrations. Total nitrogen removal ranged from 60 to 66 %. The SSF provided consistent year round treatment and did not appear to be impacted greatly by slope, temperature or external hydrologic influences.

However, the hydraulic assumption on which the design of these systems is based, that flow occurs through a saturated media at the base of the system, apparently does not apply. Moisture measurements have indicated that the media in all of these systems is tension saturated, and that lateral flow occurs to some degree through much of the media depth. Therefore, it is likely that current provincial guidelines are resulting in over-designed systems.

1.1 Project Objectives

As stated previously, initial monitoring of pilot scale SSFs in the field produced promising results. The initial results also provided evidence that current design SSFs were conservative, and that more cost-effective designs could be developed. In addition, initial results suggested that the treatment efficiency of certain parameters, specifically phosphorus, could change as the filters mature. The principal objectives of this research were to:

1. Assess the hydraulic behavior and performance of conventionally designed SSFs at loading rates greater than those allowed within NSE technical guidelines

2. Assess the hydraulic behavior and performance of SSFs that were substantially shorter lengths than those required within NSE technical guidelines

3. Determine if current hydraulic models of SSF systems are appropriate

2.0 METHODOLOGY

2.1 LFSF Construction and Loading Regimes

The research utilized the existing infrastructure at the BEEC. To assess the performance of conventional SSFs at increased loading rates the hydraulic loading rates applied to the original six SSF systems (Fig. 2.1) was approximately doubled. The flow rates to these filters (Filters 1 -6) was increased in February of 2007. In order to address Project Objective 2, the project team had originally planned to install suction lysimeters at varying distances throughout the existing SSF systems. This was attempted during the summer of 2007, however, due to the low moisture contents, and coarse grained nature of the sand material within the filters, it was not possible to obtain a representative water quality samples using suction lysimeters. To address this issue the project team constructed an additional two SSF systems (Filters 7 and 8) which possessed sand toes which were reduced to 3 m in length (Fig. 2.1). The effluent leaving the filters was collected in the same manner as for the original six SSFs and directed to the heated sampling hut. The two new shortened SSFs were both constructed on a 5% slope with a medium grained sand (Table 2.1). Therefore the two new filters were identical to Filter 2, except they possessed a shorter sand toe. The two new filters were loaded at the recommended rate of 100 L d^{-1}. Construction of these filters was completed in July, 2007 and they began receiving wastewater in August, 2007.

Table 2.1. Physical characteristics of the filter sands.

Sand Type	d_{10} (mm)	Uniformity Coefficient (d_{60}/d_{10})	Hydraulic Conductivity (m s^{-1})
Fine	0.15	8	1.5×10^{-4}
Medium	0.17	5.6	5.0×10^{-4}
Coarse	0.30	1.8	1.0×10^{-3}

2.2 Hydrologic Monitoring

Flow data from each sand filter was measured using calibrated tipping buckets and recorded every 10 minutes on a CR510 data logger (Campbell Scientific, Edmonton, AB). Meteorological conditions (precipitation, solar radiation, air temperature, and relative humidity) were continuously monitored and recorded using a Campbell Scientific CR10 datalogger (Edmonton, AB). The data were sampled every 60 s and 60 min averages were recorded. Precipitation was measured using a heated rain gauge (Campbell Scientific, Edmonton, AB). Temperatures within the filters were measured using copper constantan thermocouples.

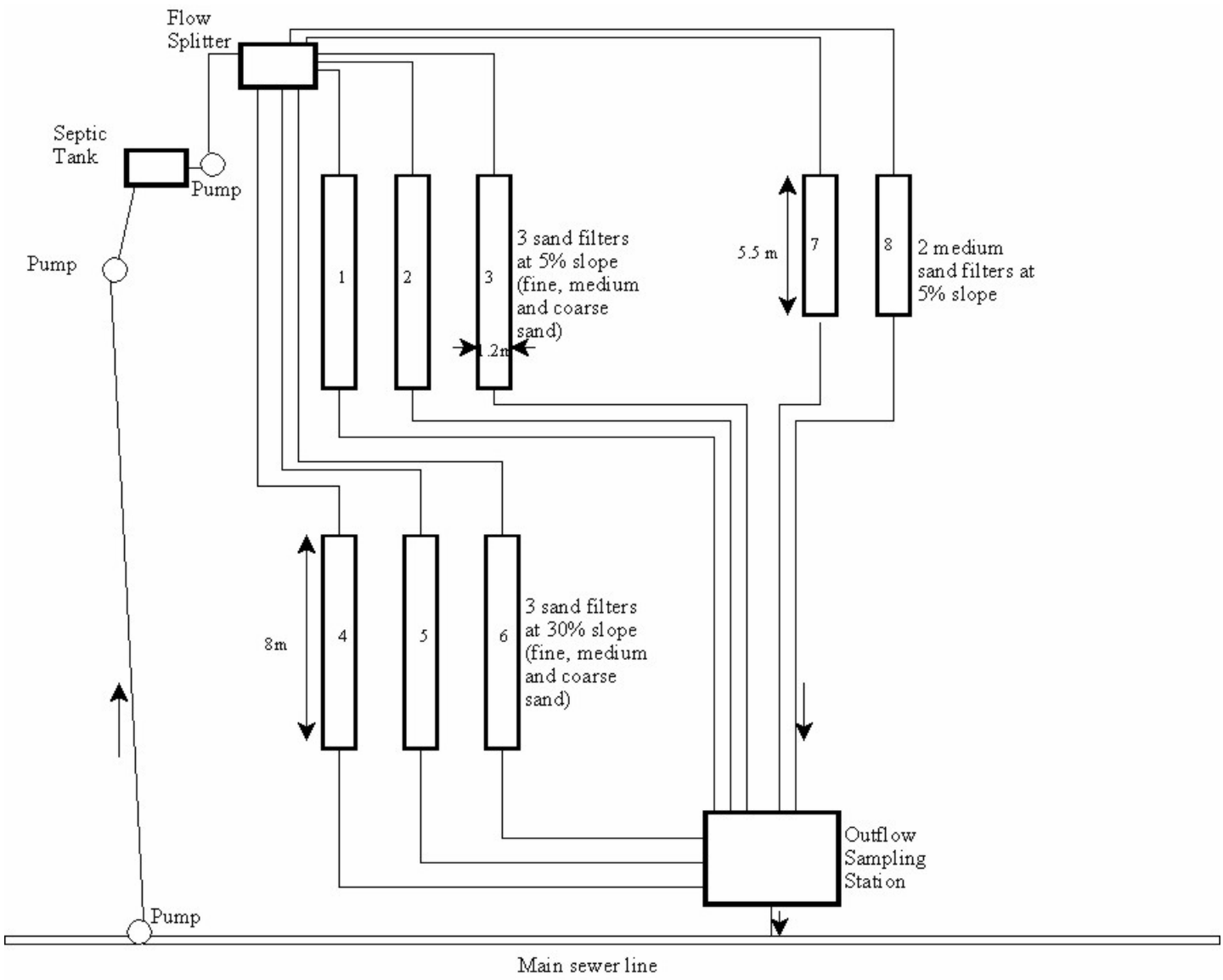


Figure 2.1. Layout of the SSF field experimental facility at the Bio-environmental Engineering Centre in Truro, NS. The site consists of six 8 m long SSFs (Filters 1-6) and two 5.5 m SSFs (Filters 7 and 8). Filters 7 and 8 were constructed with a medium grained sand and are therefore comparable Filter 2.

2.3 Hydraulic Assessment and Modeling

A series of tracer studies were conducted within the 8 filters several times during the course of the study. Rhodamine tracer studies were conducted within the eight SSFs a total of 4 times and included both warm and cool season climatic conditions. Within each tracer experiment 10 mL of rhodamine dye (20 wt/wt) was injected into the inlet pipe of each filter. Grab samples were collected at the outlet of each filter at time intervals ranging from 2 – 48 h over a 28 day period. Concentrations of rhodamine dye within effluent samples were determined on a UV/VIS spectrophotometer. Data obtained from the rhodamine tracer studies were fit to analytical models which were used to determine the mean residence time, and longitudinal dispersion coefficient, for each sand filter (Fogler 1992). The function E(t) represents the residence time distribution (RTD) function which describes the amount of time that a particular fluid element spends in the system (Fogler 1992):

(1)

$$E(t) = \frac{C(t)}{\int C(t)dt}$$

Where C(t) represents the effluent tracer concentration at time, t, and the integral in the denominator is the area under the C(t) curve. The mean residence time, t_m, can then be calculated by taking the first moment of the RTD function, as follows:

(2)

$$t_m = \int tE(t)dt$$

Variance (σ^2), or the square of the standard deviation, was then calculated to obtain a measure of the degree of "spread" of the data distribution. Variance was determined by taking the second moment about the mean residence time (Fogler 1992):

(3)

$$\sigma^2 = \int (t - t_m)E(t)dt$$

Variance was calculated for each sand filter and was then used to calculate a dispersion coefficient. Variance as calculated above is in units of time; this must be converted to variance in space before calculating dispersion (Apello and Postma 1993):

(4)

$$\sigma_x{}^2 = \frac{\sigma^2 x^2}{t_m{}^2}$$

where x is the filter length (8 or 5.5 m). Variance in space was then used to calculate a longitudinal dispersion coefficient for each sand filter (Apello and Postma1993):

(5)

$$D_L = \frac{\sigma_{x2}}{2t_m}$$

The dispersivity, α_L, for each sand filter was then computed as:

(6)
$$\alpha_L = \frac{D_L}{v}$$

where; v is velocity (filter length /mean residence time). The theoretical time of travel within a SSF, assuming saturated flow can be modeled using Darcy's Law. The true horizontal velocity, v_h, can be computed as:

(7)
$$v_h = \frac{K}{n}\frac{dH}{dL}$$

Where K is the hydraulic conductivity of the sand (m/d), n is the porosity of the sand, and dH/dL is the hydraulic gradient within the sand filter. When designing a SSF it is assumed that the hydraulic gradient is equal to the slope of the filter. The porosity of the sand was estimated to be 0.30 (Freeze and Cherry, 1979). The average theoretical travel time, t_T of a conservative particle within the filter could then be computed as:

(8)
$$t_T = \frac{dL}{v_h}$$

Water levels in mini-piezometers installed within both the distribution trench and filter sand in all filters were also measured on a monthly basis to assess level of saturation.

2.4 Performance Monitoring

The influent wastewater, and effluent from each filter, was sampled on monthly basis for the duration of the study. Filters 7 and 8 were allowed to mature for 2 months before sampling was initiated. During each monthly sampling event autosamplers were deployed for a 24 h period to collect a composite sample of influent wastewater. Two ISCO 6712 autosamplers (ISCO Inc., Montreal, PQ), with multiplexers, were used to collect time weighted (100 mL/h) composite samples over a 24 h period from the outlet of each filter system. These composite samples were analyzed at the Nova Scotia Agricultural College's Department of Environmental Sciences, Water Quality Research Laboratory. Analysis included total suspended solids (TSS) (Std. Method 2540D), five-day biological demand (BOD_5) (Std. Method 5210B), total phosphorus (TP) (Std. Method 4500-P, Phosphorus - 1999 revision and ascorbic acid method), total kjeldahl nitrogen (TKN) (Std. Method 4500-N_{org} B) and NH_4-N (Std. Method 4500-NH_3). The anions phosphate-P (SRP) and NO_3-N were quantitated according to Std. Method 4110 (2000 version). All procedures are outlined in Standard Methods for the Examination of Water and Wastewater (Clesceri et al. 1998). Individual grab samples of the influent wastewater and effluent from each filter were collected and analyzed for *Escherichia coli* using the membrane filtration technique in conjunction with m-Coliblue24 culture media (HACH 1999). The performance of the eight filters was evaluated in several manners. Percent removal, on a concentration basis, was computed for each water quality variable for each month. Total influent and effluent nitrogen concentrations were determined on a monthly basis by adding the TKN and NO_3-N concentrations. T-tests were used to assess differences in treatment performance.

3.0 RESULTS AND DISCUSSION

3.1 Flow Characteristics

Hydrology plays a significant role in the performance of SSFs. To evaluate this influence, flow characteristics such as daily flow from the low and high loading rate periods, the relationship between external hydrological events, and seasonal trends were examined. Filters 1 through 6 were installed in the summer of 2004 and began receiving wastewater in September 2004. Each filter's daily loadin rate capacity was to be 100 L/day, as determined by the current provincial guidelines. Preliminary findings indicated little to no ponding of water in the filters, an indication of saturation, so daily wastewater loading was increased to 200 L/day in January 2007. It took approximately three months to calibrate loading rates and address for pump failures and mechanical problems. Shorter filters 7 and 8 were constructed in July 2007 and started receiving 100 L/day in August 2007.

Table 3.1 provides average daily outflow for SSF1-6. From February 2006 to December 2006, SSF1-5 averaged approximately 100 L/day and SSF6 averaged 55.6 L/day. Flow ranges from 0 L/day to 380.8 L/day. Values of 0 L/day were recorded during periods of pump failures. High loading rate data, taken from April 2007 to December 2008, ranges from 0 L/day to 1092.7 L/day. Average daily flows are under 200 L/day. The range in flows is indicative of real events where the SSF would be in high usage and/or during heavy rainfall events and spring thaws. Since their operation in August 2007, SSF7-8 achieved daily average outflows of 90.4 L/day and 65.9 L/day, shown in Table 3.2. Filter 8 underwent some clogging issues with the flow adapter which explains the lower daily outflow average. Flows range from 672.6 L/day to 0 L/day.

External hydrological events such as rainfall and snowfall (total precipitation) have an impact on flow. The relationship is a multi-variable one; flow is a function of the history of precipitation events and antecedent moisture conditions. When the filters are more unsaturated, response to external hydrological events will not be as great. The filters are not steady state hydrological systems and are subject to variable conditions. Figures 3.1, 3.2, and 3.3 represent this graphically where peaks in total precipitation correspond with peaks in daily flow from the filters.

To better illustrate how the pre-existing moisture status of the soil and precipitation events influence the flow responses of the filters, the period of mid-July 2008 to the end of September 2008 was examined (Figures 3.4 – 3.6). There were few precipitation events occurring during the last two weeks of July; all were comparatively small. As such, the filter soil was dry. Subsequently the flow responses occurring after the precipitation events in early August are dampened. However, precipitation events in early September trigger a greater response in the filters due to moisture in the soil from early August.

Water level measurements conducted in Filters 1-6 after the loading rate was increased indicated that ponding of water in the distribution trench was occurring, however no water was detected in any piezometers located within the sand bed. The hydraulic characteristics of the biomat appeared stable, as ponded water levels did not increase significantly during the experiment.

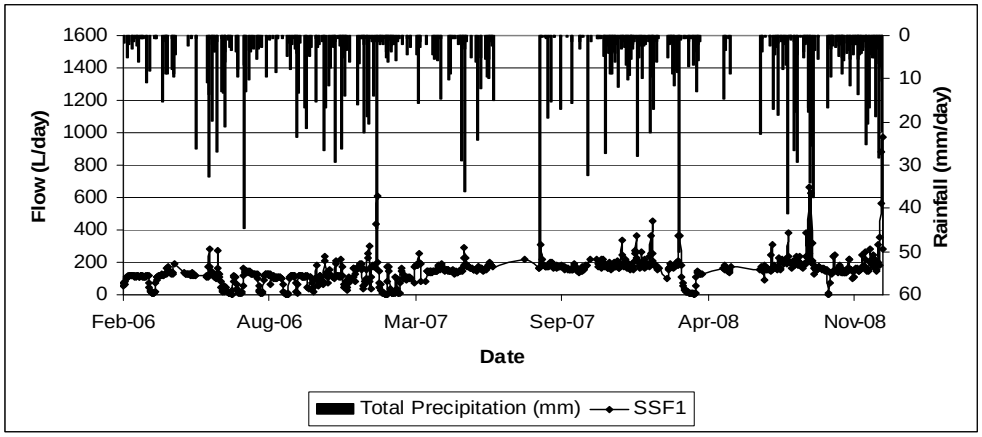
Table 3.1. Descriptive Statistics for SSF1-6, including Average Daily Flow, Standard Deviation, Minimum and Maximum Flows.

Parameters	SSF1	SSSF2	SSF3	SSF4	SSF5	SSF6
			Low Flow (L/day)			
Average Daily Flow (ADF)	101.7	99.1	104.7	103.5	101.0	55.6
Standard Deviation (STD)	48.9	50.0	51.6	47.8	52.0	51.4
Minimum (MIN)	2.5	1.9	1.1	1.4	0.9	0.0
Maximum (MAX)	280.5	311.1	297.9	239.9	380.8	237.4
			High Flow (L/day)			
ADF	176.8	181.9	170.4	180.4	175.1	164.3
STD	81.3	76.2	54.5	79.4	96.8	58.5
MIN	0.0	0.0	0.0	0.0	0.0	2.8
MAX	974.6	1077.4	549.9	1002.5	1092.2	709.7

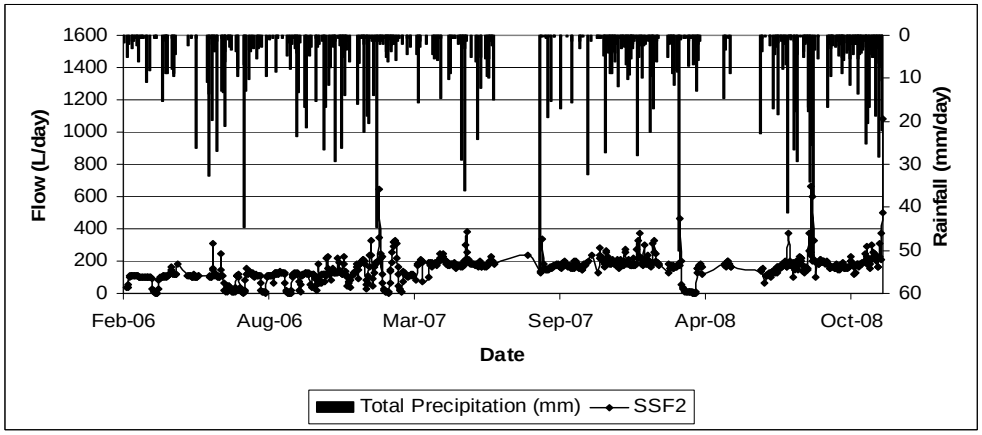
Table 3.2. Descriptive Statistics for SSF7-8, including Average Daily Flow, Standard Deviation, Minimum and Maximum.

Parameters	SSF7	SSF8
ADF (L/day)	90.4	65.9
STD (L/day)	59.5	44.5
MIN (L/day)	1.2	0.0
MAX (L/day)	672.6	623.7

(a)



(b)



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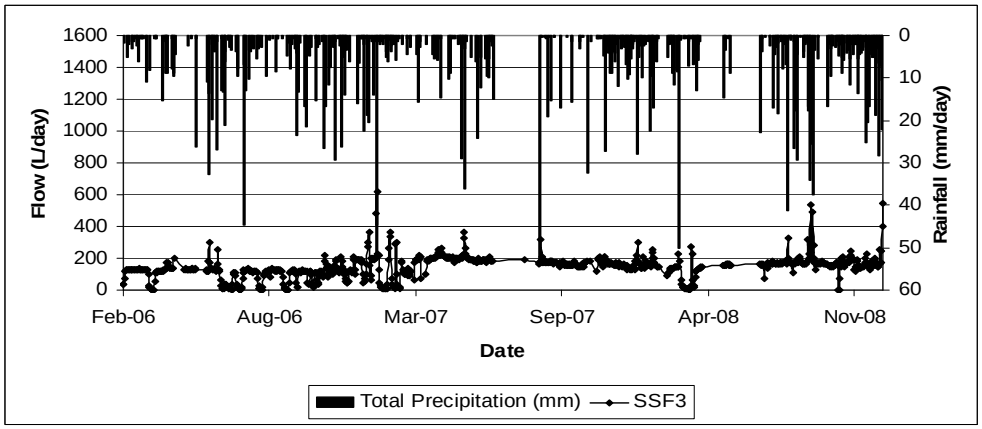
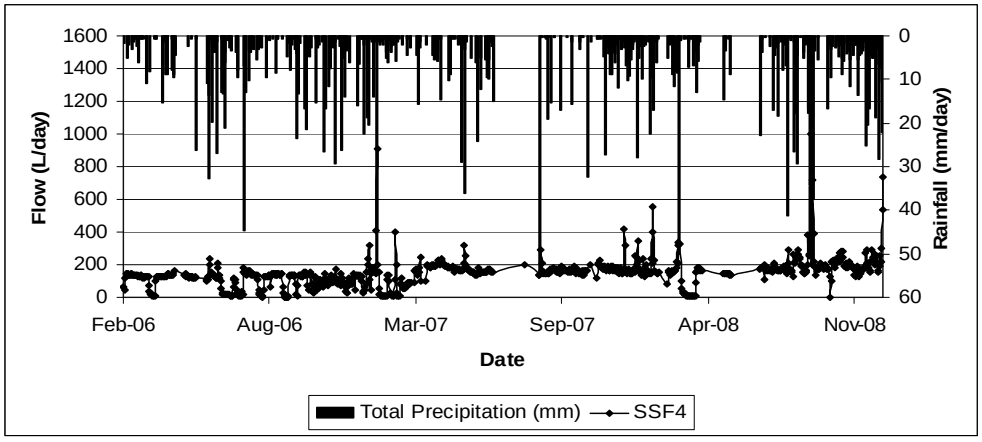
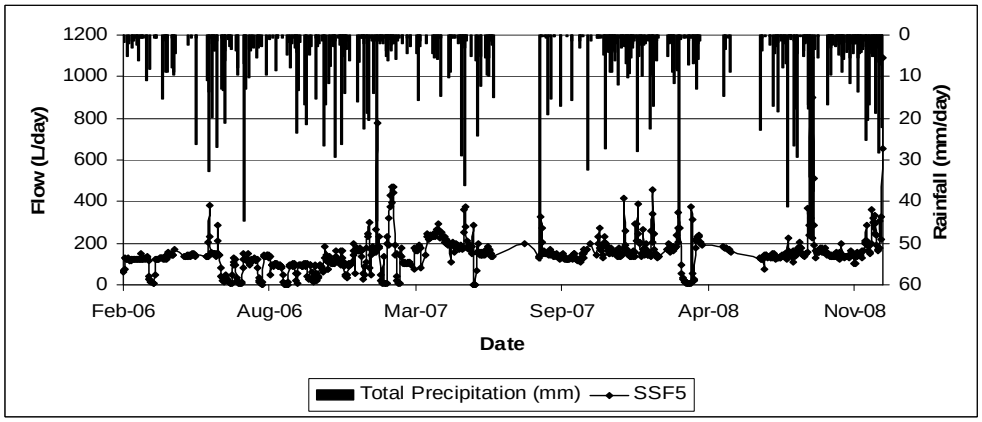


Figure 3.1. Total Precipitation and Daily Flow for SSF1 (a), SSF2 (b) & SSF3 (c) from February 2006 to December 2008

(a)



(b)



(c)

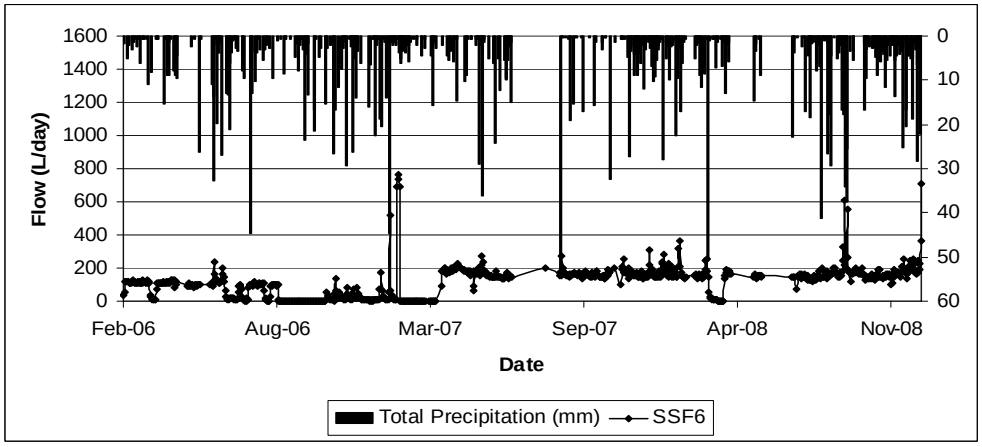
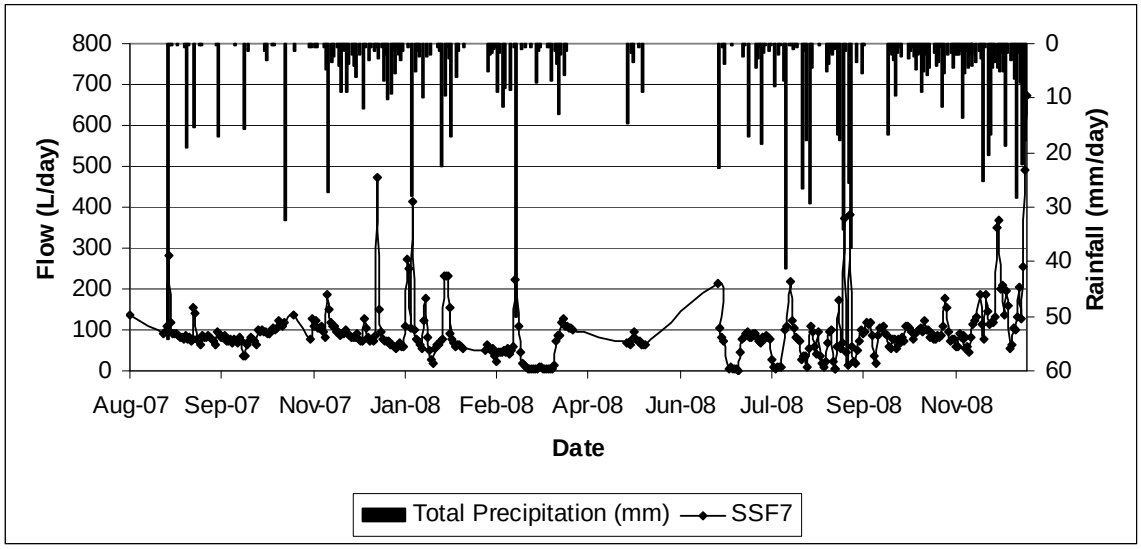


Figure 3.2. Total Precipitation and Daily Flow from SSF4 (a), SSF5 (b) & SSF6 (c) from February 2006 to December 2008

(a)



(b)

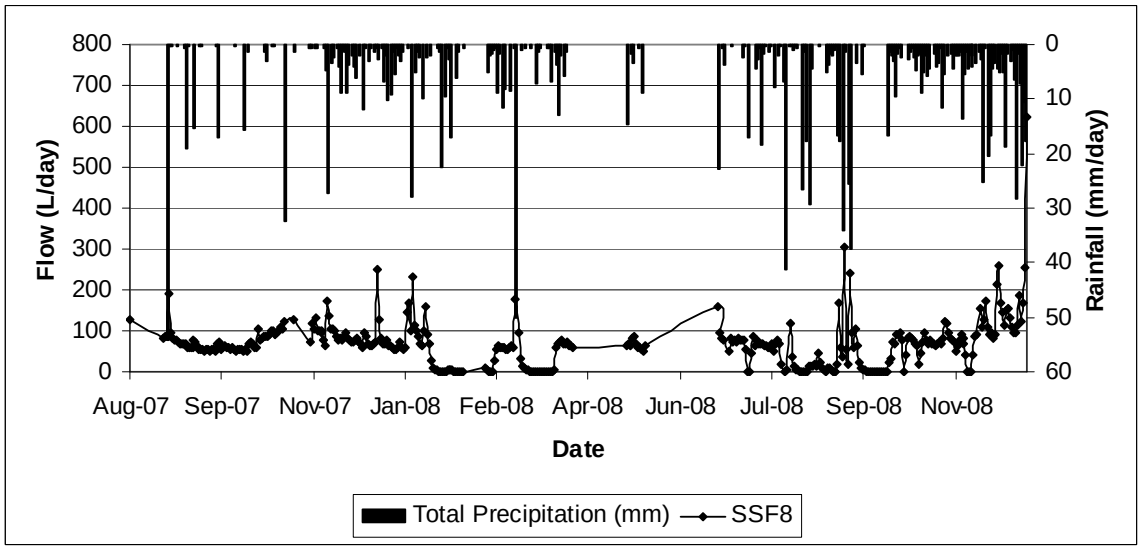
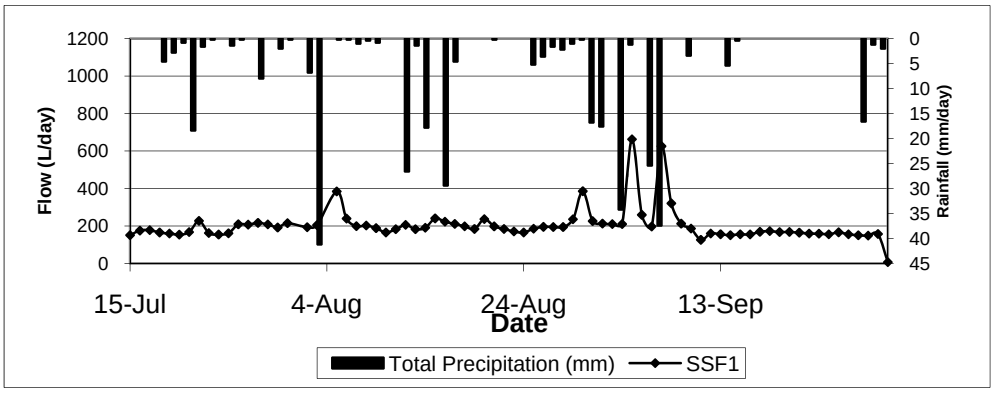
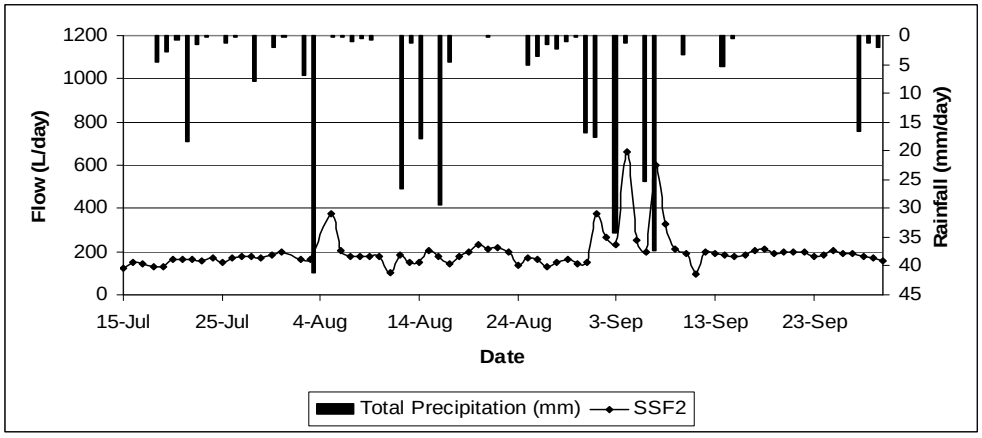


Figure 3.3. Total Precipitation and Daily Flow for SSF7 (a) & SSF8 (b) from August 2007 to December 2008

(a)



(b)



(c)

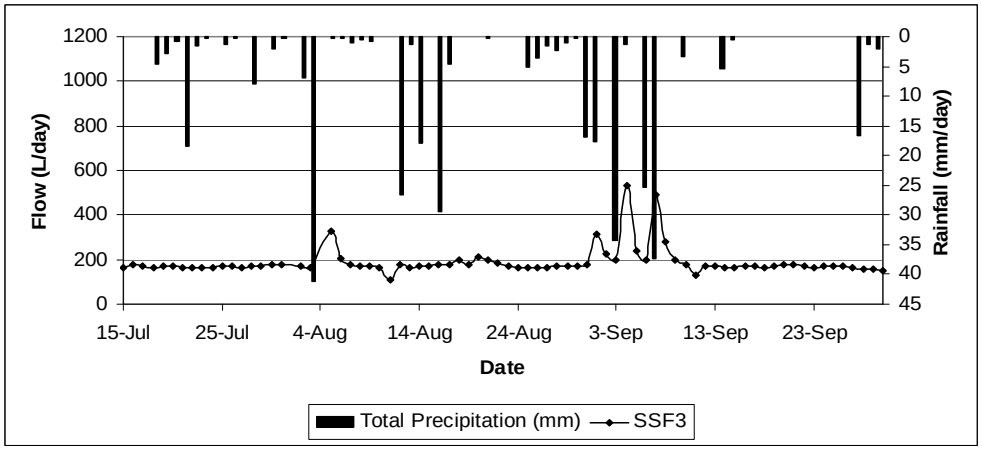
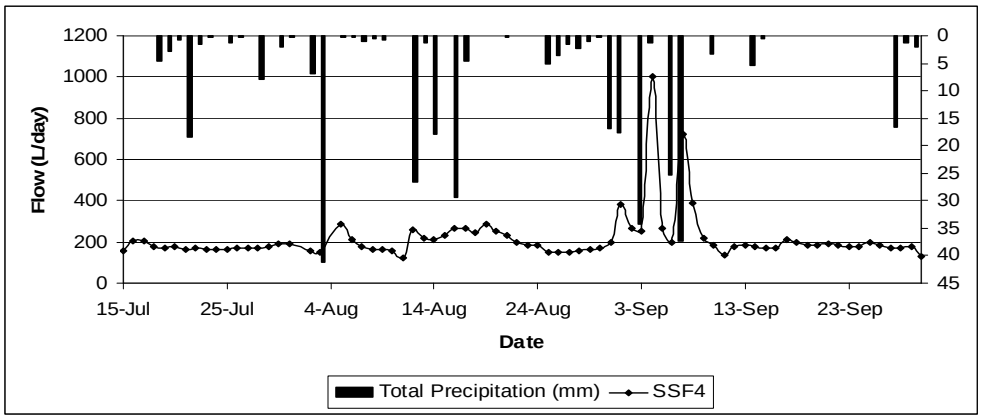
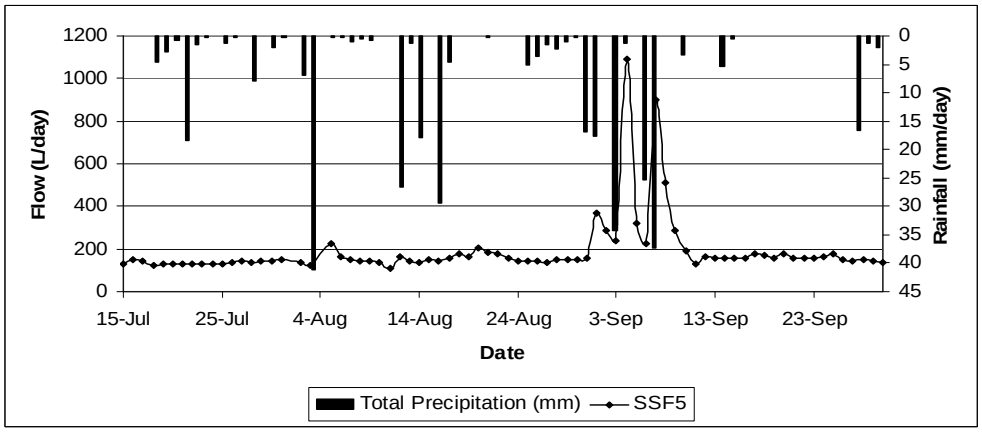


Figure 3.4. Total Precipitation and Daily Flow for SSF1 (a), SSF2 (b) & SSF3 (c) from July 15, 2008 to September 30, 2008

(a)



(b)



(c)

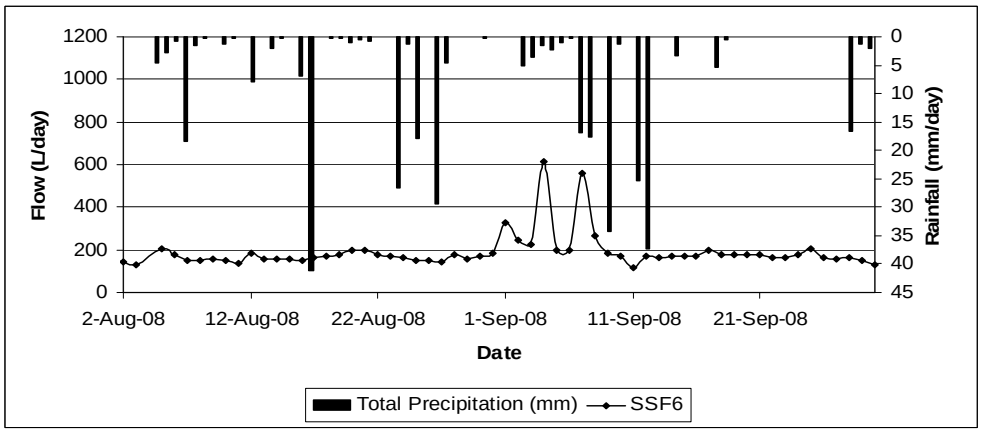
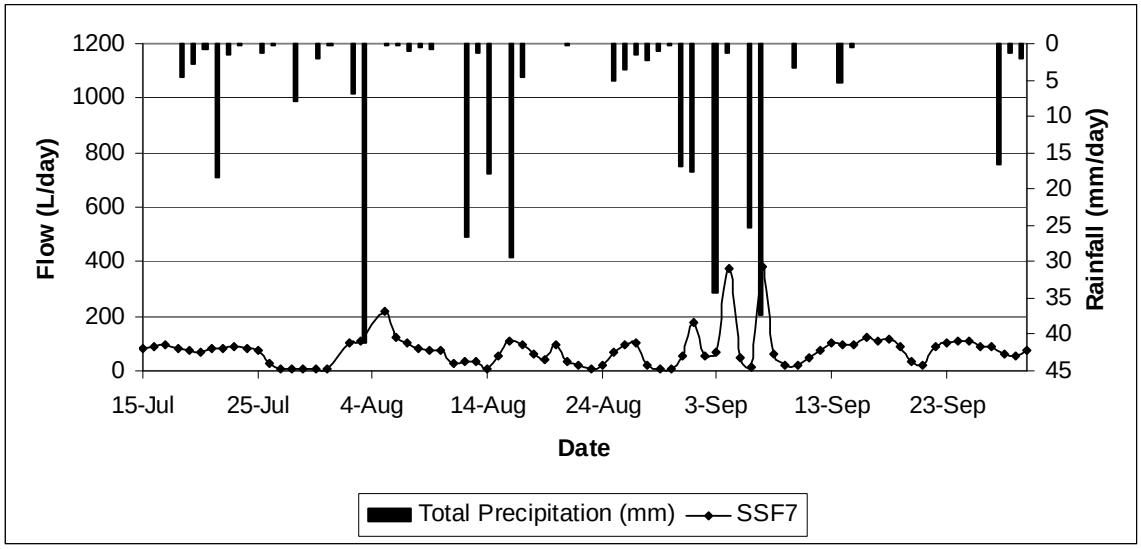


Figure 3.5. Total Precipitation and Daily Flow for SSF4 (a), SSF5 (b) & SSF6 (c) from July 15, 2008 to September 30, 2008

(a)



(b)

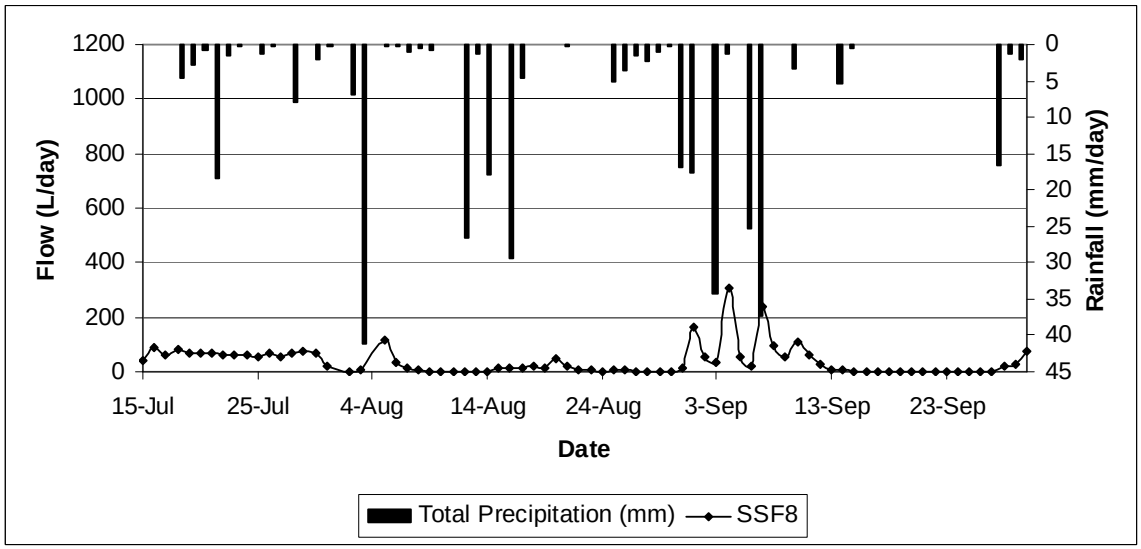


Figure 3.6. Total Precipitation and Daily Flow for SSF7 (a) & SSF8 (b) from July 15, 2008 to September 30, 2008.

3.2 Hydraulic Assessment and Modeling

Tracer studies were conducted within each filter to determine hydraulic characteristics and residence times within each system. These results explore the relationship between the hydraulic responses of individual filters and variables including filter length, slope, grain size, biomat development, loading rate and precipitation. A comparison of previous t_m results from 2005 to subsequent tracer studies performed in 2007 and 2008 are shown in Table 3.3.

Table 3.3. Hydraulic parameters generated from tracer studies on SSF1-8.

	SSF1	SSF2	SSF3	SSF4	SSF5	SSF6	SSF7	SSF8
Slope	5%	5%	5%	30%	30%	30%	5%	5%
Grain Size	Fine	Medium	Coarse	Fine	Medium	Coarse	Medium	Medium
Summer 2005								
t_m (hrs)	150.2	97.5	91.4	153.5	94.4	62.0	-	-
σ (hours)	104.2	97.6	86.4	94.6	80.9	66.5	-	-
D (cm^2/s)	0.29	0.91	0.87	0.22	0.69	1.65	-	-
Summer 2007								
t_m (hrs)	138.8	51.8	106.2	99.2	66.4	48.2	-	-
σ (hours)	52.1	258.9	43.0	27.7	32.4	31.9	-	-
D (cm^2/s)	0.090	42.9	0.137	0.070	0.319	0.805	-	-
Summer 2008								
t_m (hrs)	187.6	76.6	66.7	115.1	90.8	64.3	210.5	91.3
σ (hours)	49.1	223.5	35.5	37.4	27.6	22.1	52.3	44.8
D (cm^2/s)	0.033	9.903	0.377	0.082	0.090	0.163	0.012	0.111
Autumn 2008								
t_m (hrs)	201.4	65.2	55.0	116.4	110.4	57.0	56.5	81.8
σ (hours)	57.2	218.5	26.4	49.3	47.4	25.4	29.1	23.5
D (cm^2/s)	0.036	15.3	0.373	0.137	0.151	0.309	0.196	0.040

Mean residence times vary between filters, ranging from 48.2 hours (SSF6, summer 2007) to 210.5 hours (SSF7, summer 2008). Temporal changes in t_m are shown in Figure 3.7. Generally, t_m decreases from 2005 to 2007, possibly due to the doubling of the loading rate from 100 L/day to 200 L/day. The exception to this is SSF3; however the increase in t_m is small, from 91 hours to 106 hours. Fine grained filters have higher residence times compared to medium and coarse grained filters, presumably due to the smaller pore space for the wastewater to travel through. Residence times from medium and coarse grained filters are comparable; SSF6 has the fastest t_m, which is due to its coarse grain size and 30% slope.

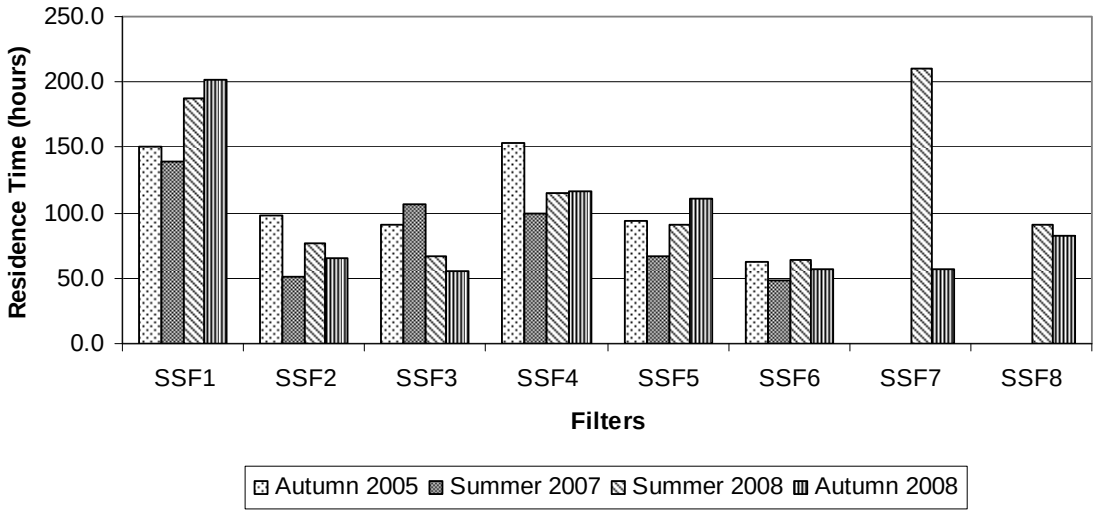


Figure 3.7. Residence times from tracer studies from 2005-2008 on SSF1-8.

Filter 2 appeared to be short circuiting during the tracer study in summer 2007 because t_m decreases by half. Figure 3.8 (a) shows SSF2 reaching a concentration peak earlier than SSF1, which is unusual because SSF3 is coarse grained and should therefore should peak first. An analysis of the flow and precipitation data in Figure 3.8 (b) indicates that excess flow and precipitation to SSF2 were not the cause of this occurrence. Therefore, the short circuiting in SSF2 may be due to preferential flow patterns within the filter during that tracer study. Subsequent tracer studies show that this was an isolated incident as SSF2 does not short circuit again.

From Figure 3.9 (a) we note that SSF5-6 achieve higher concentration peaks than SSF2-3 (Figure 3.8 (a)). This may be due to the difference in slopes. However, the magnitude of the concentration peak for SSF4 is comparable to SSF1. Both filters are fine grained, leaving less pore space for the wastewater to travel through. Another cause for lower concentration peaks and greater residence times for the fine grained filters (SSF1, SSF4) may be due to the development of the biomat, which is known to control the rate of infiltration of wastewater into the filters (Crites & Tchobanoglous, 1998). From this we can infer that slope does not play as significant a role as filter grain size in hydraulic characteristics of SSFs.

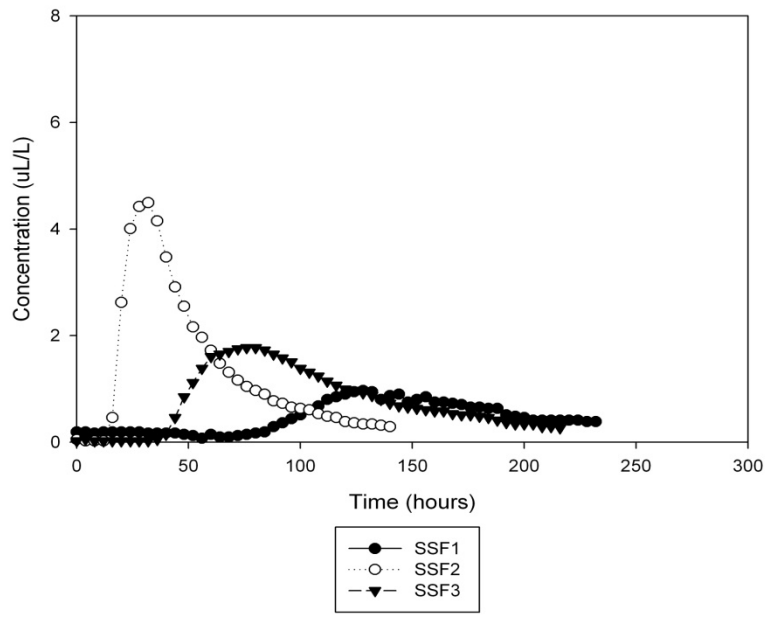
The concentration peaks are lower in summer 2008 than in summer 2007, shown in Figure 3.10 (a). This may be due to the lack of precipitation events that occurred during this study, as seen in Figure 4

(b). Note that SSF2 is not short circuiting anymore as it peaks in between SSF1 and SSF3. These filters behave as expected.

Filters 5 and 6 achieved lower concentration peaks than in previous studies (Figure 3.11 (a)). This may be due to the lack of precipitation events that occurred during this study. Concentration peaks for SSF6 are comparable to previous studies. It was expected that results from the first Rhodamine tracer study from SSF7-8 would be similar. However, SSF8 reaches a higher concentration peak earlier than SSF7, shown in Figure 3.12 (a). Filter 7 has a t_m of over 210.5 hours compared to that of SSF8 at 64.3 hours. Corresponding flow and precipitation data shown in Figure 3.12 (b) during this period indicate the filter received little to no wastewater loading during the first 150 hours of the study. This is due to clogging of the orifice plate of the filter. Notably, at approximately the 210 hour point, SSF7 begins receiving more flow and SSF8 receives none. This indicates a problem with the proper distribution of flow between the filters. An adjusted t_m from this tracer study for SSF7 was calculated using the start time of the tracer study at t = 150 hours. The adjusted t_m is 61.5 hours (Figure 3.13). After the adjustment is made for t_m for SSF7 in summer 2008, in general, mean residence times from SSF7-8 are comparable to those of SSF5, a medium-grained filter located on a 30% slope. This suggests that slope and filter length play lesser roles in the hydraulic characteristics of SSFs.

Results are as expected for SSF1-6 for the Rhodamine tracer study conducted in autumn 2008 (Figures 3.14-3.15). There is more rainfall than in previous studies, and variations in flow, which produced little influence on the hydraulic response of the filters. Flow data from Figure 3.15 (b) shows that SSF4 received over 200 L/day for the first 250 hours of the study, yet there is little impact on the residence time or the concentration peak. Notably, SSF1 has a very low concentration peak and the greatest t_m of any previous tracer study. Therefore, we can infer that SSF1-6 have well established biomats, specifically SSF1 and SSF4 (both fine grained filters). External precipitation events and variations in flow do not appear to influence hydraulic response from filters with well-established biomats. In comparison, results from the autumn 2008 tracer studies on SSF7-8, filters with less established biomats, showed the highest magnitude of concentration peaks in any tracer study to date (Figure 3.16 (a)). Flow and precipitation data shown in Figure 3.16 (b) indicate that SSF8 received reduced flows during the first hours of the study. This is due to clogging and can explain the slight delay in concentration peak and greater t_m compared to SSF7.

(a)



(b)

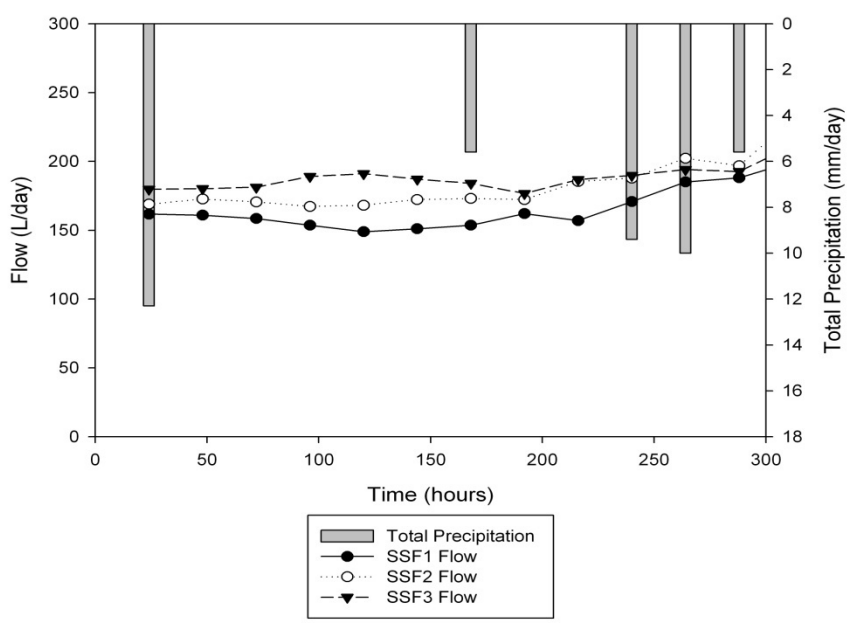
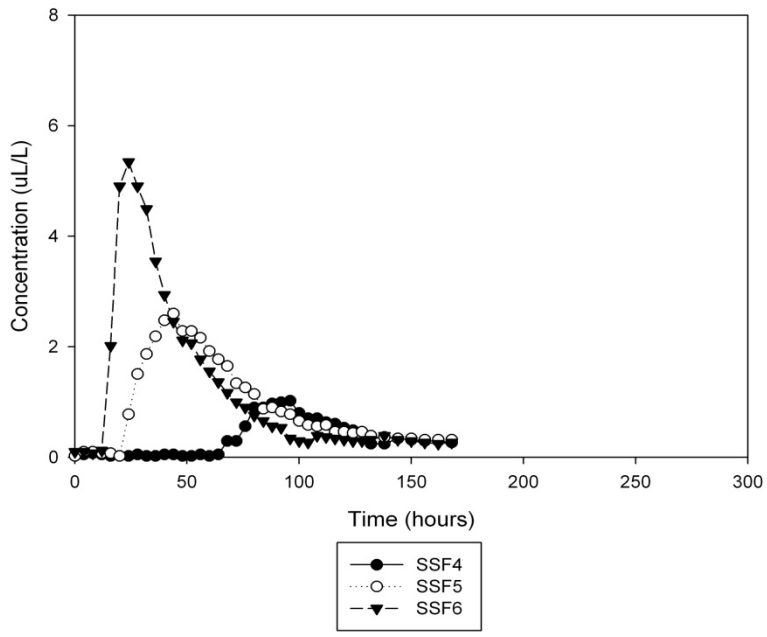


Figure 3.8. Rhodamine tracer study concentration series for SSF1-3 from summer 2007 (a) and Flow and precipitation data during tracer study, June 11-19, 2007 (b).

(a)



(b)

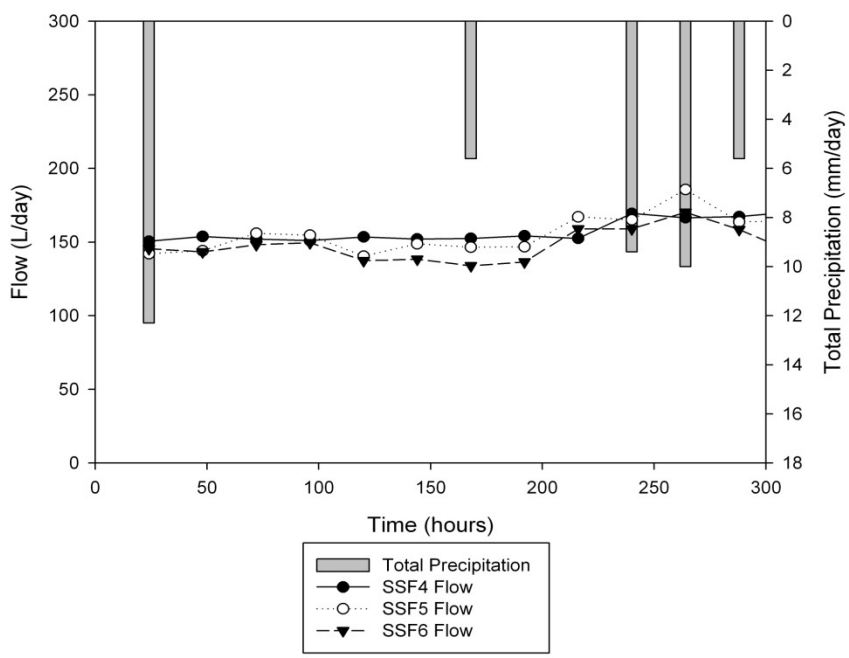
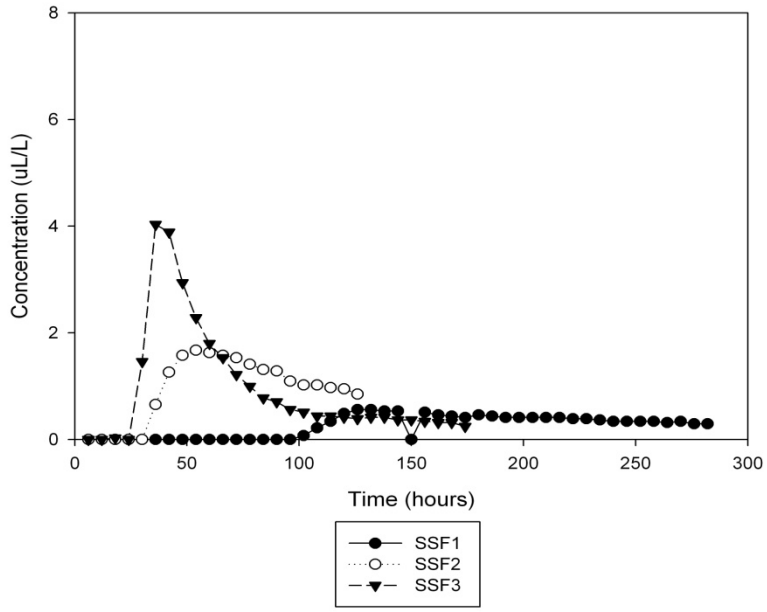


Figure 7.9. Rhodamine tracer study concentration series for SSF4-6 during summer 2007 (a) and Flow and precipitation data during tracer study, June 11-19, 2007 (b).

(a)



(b)

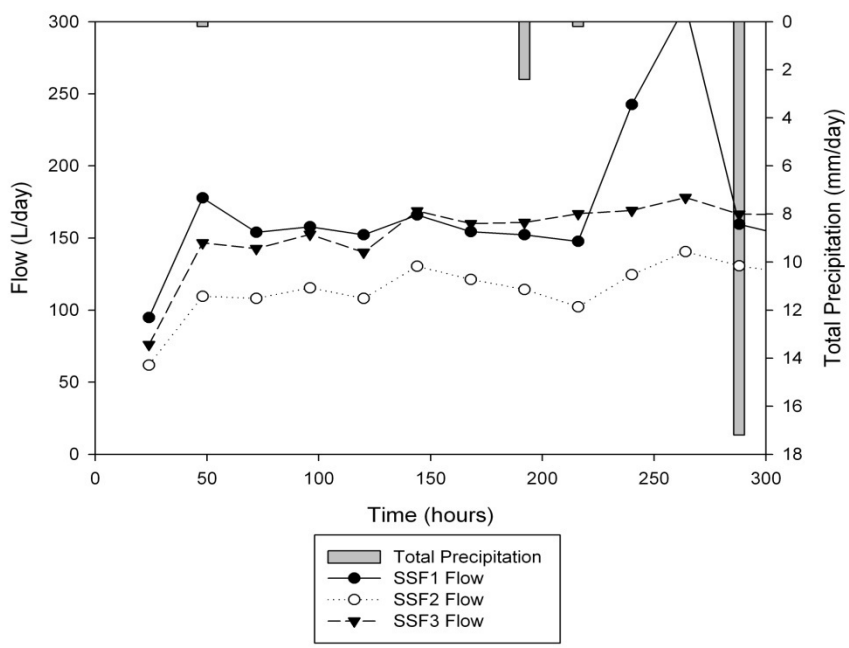
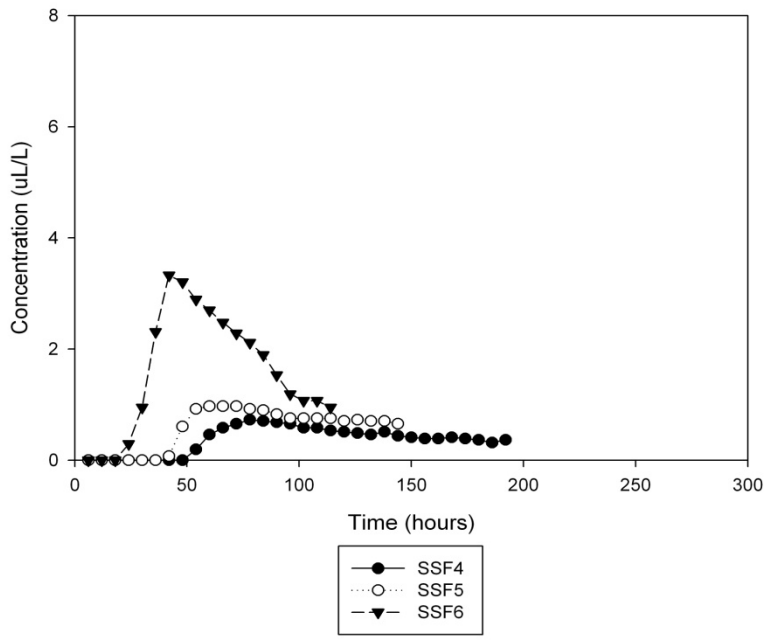


Figure 3.10. Rhodamine tracer study concentration series for SSF1-3 during summer 2008 (a) and Flow and precipitation data during tracer study, July 3-11, 2008 (b).

(a)



(b)

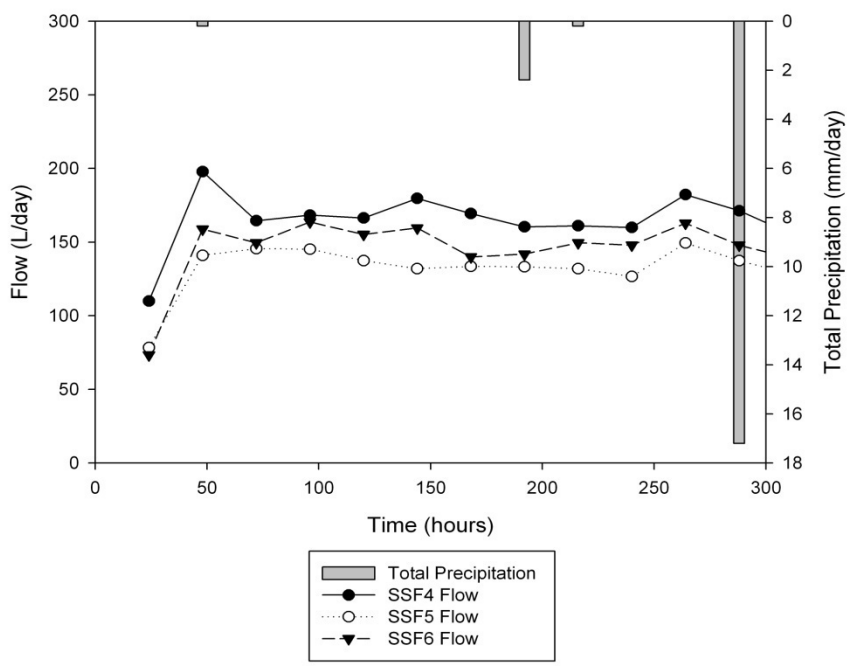
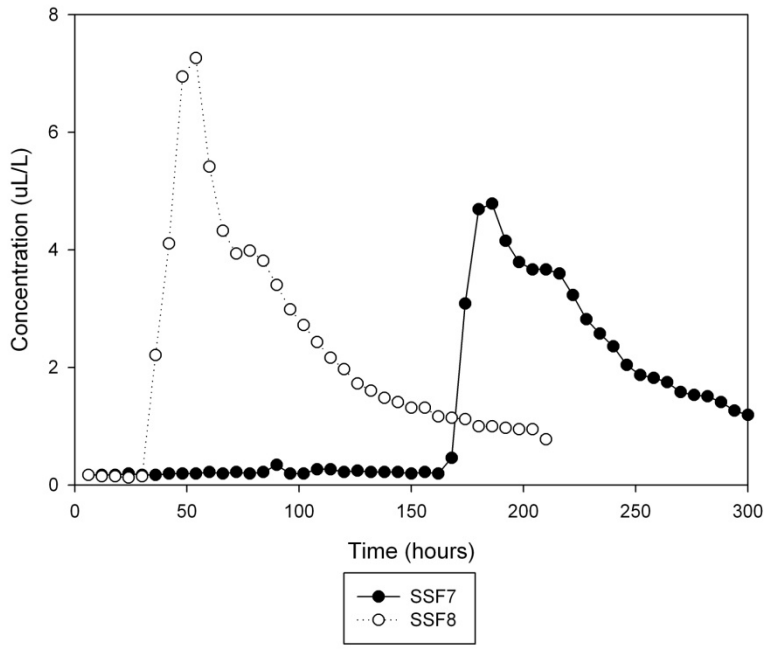


Figure 3.11. Rhodamine tracer study concentration series for SSF4-6 during summer 2008 (a) and Flow and precipitation data during tracer study, July 3-11, 2008 (b).

(a)



(b)

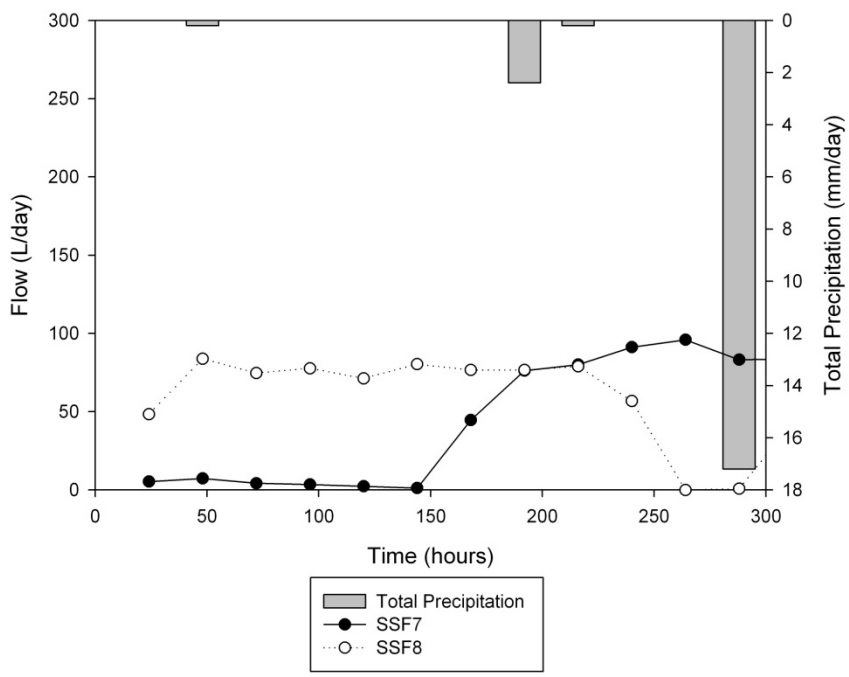


Figure 3.12. Rhodamine tracer study concentration series for SSF7-8 during summer 2008 (a) and Flow and precipitation data during tracer study, July 3-11, 2008 (b).

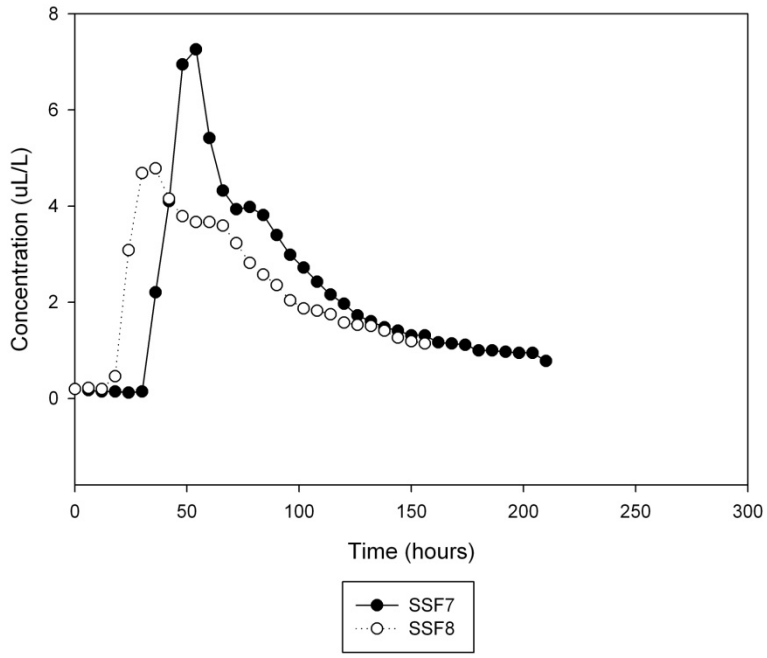
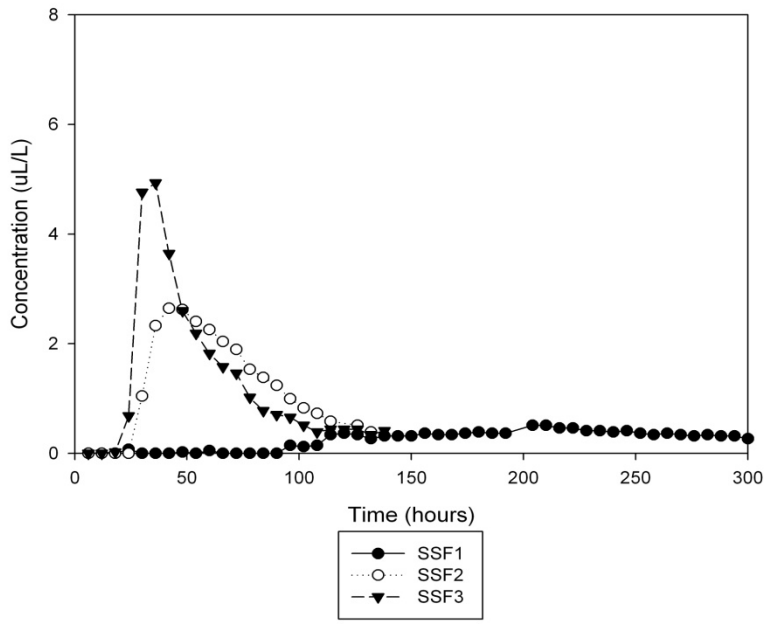


Figure 3.13. Rhodamine tracer study concentration series for SSF7-8 from summer 2008 with adjusted t_m.

(a)



(b)

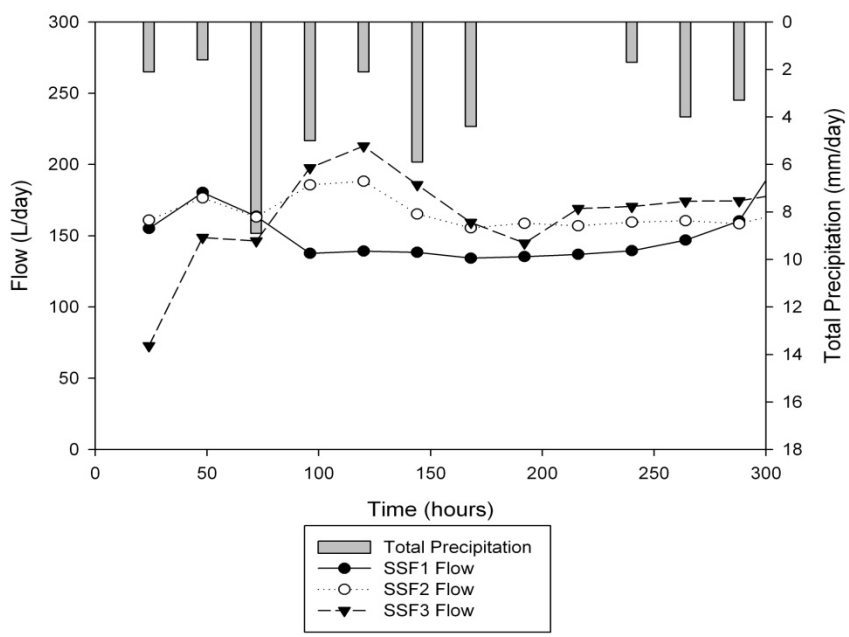
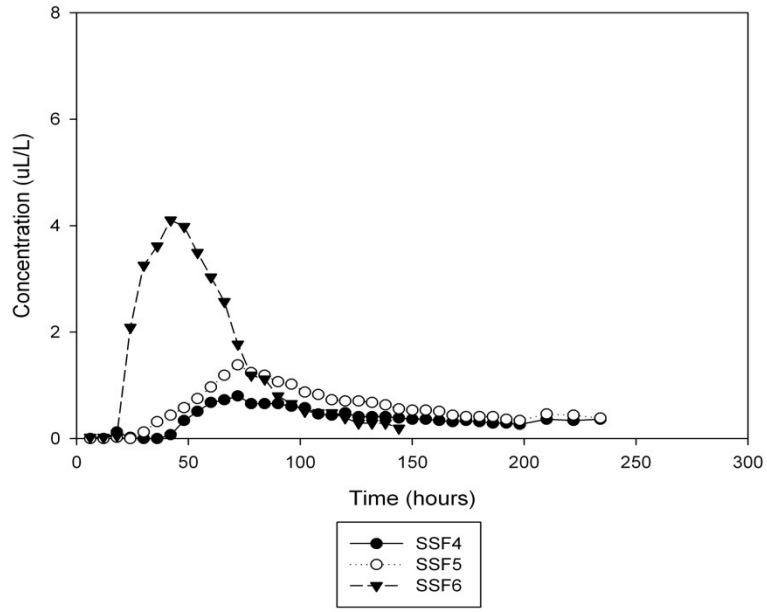


Figure 3.14. Rhodamine tracer study concentration series for SSF1-3 during autumn 2008 (a) and Flow and precipitation data during tracer study, October 14-22, 2008 (b).

(a)



(b)

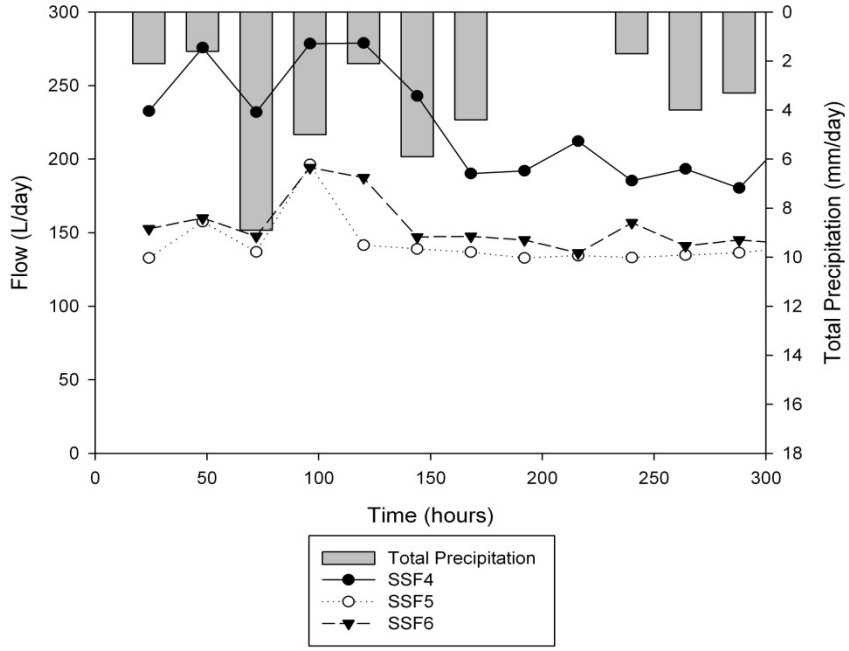
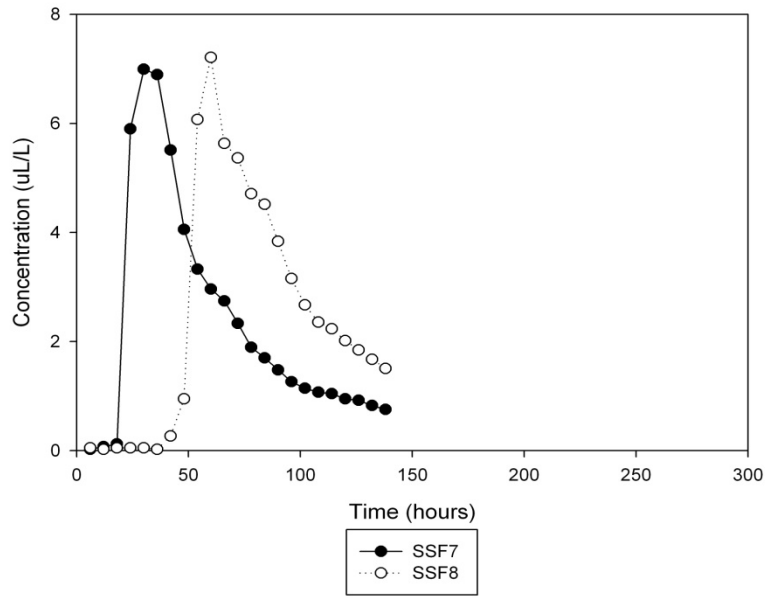


Figure 3.15. Rhodamine tracer study concentration series for SSF4-6 during autumn 2008 (a) and Flow and precipitation data during tracer study, October 14-22 2008 (b).

(a)



(b)

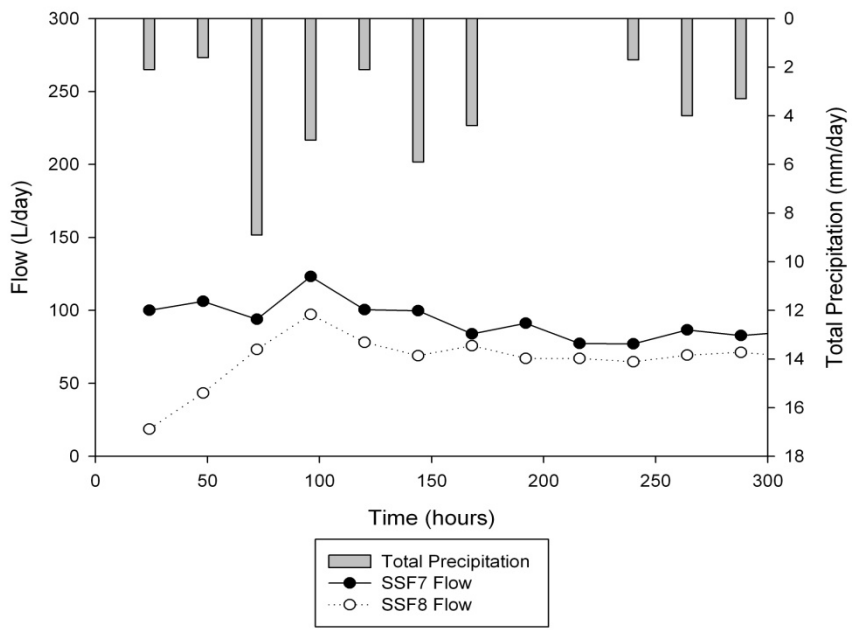


Figure 3.16. Rhodamine tracer study concentration series for SSF7-8 from autumn 2008 (a) and Flow and precipitation data from October 14-22, 2008 (b).

From these tracer studies, it has been shown that a number of factors influence the hydraulic characteristics of individual filters. There is variability in residence times between each filter. Through the course of four tracer studies conducted from 2005 to 2008, there appears to be no difference in response when wastewater loading was doubled. Grain size has an influence; fine grained filters had increased residence times which also may be due to greater biomat development. However, there was very little difference between medium grained and coarse grained filters. Filters 7 and 8, which do not have as well established a biomat as others, saw higher concentration peaks than other filters, which may be due to the short length of the filter and a less mature biomat. However, residence times from these filters, composed of medium grained sand and located on a 5% slope, are comparable to SSF5, a medium-grained filter located on a 30% slope. This suggests that filter slope and length does not play a large role in hydraulic behavior of filters. Precipitation played an insignificant role in filter hydraulic response because there were few rainfall events that occurred during the studies (the greatest rainfall event was 17.2 mm during the last hours of the summer 2008 study).

Theoretical hydraulic retention times were simulated using Darcy's Law and are provided in Table 3.4. The theoretical retention times were much smaller than those measured in the tracer studies (Table 3.3). This result, in combination with the water level measurements, confirm that saturated flow is not occurring with the LFSF systems. The larger measured retention times indicate that the biomat may be controlling residence time characteristics within the filters. The fact that a saturated zone does not exist at the bottom of the filters also suggests unsaturated flow may be occurring within a larger component of the sand than previously assumed.

Table 3.4. Theoretical residence times (t_T, hours) for each LFSF.

	SSF1	SSF2	SSF3	SSF4	SSF5	SSF6	SSF7	SSF8
Slope	5%	5%	5%	30%	30%	30%	5%	5%
Grain Size	Fine	Medium	Coarse	Fine	Medium	Coarse	Medium	Medium
t_T (hrs)	90	27	13	15	5	2.5	13	13

3.3 Treatment Performance

3.3.1 Statistical Summary: The treatment performance of key parameters such as *E. coli*, TC, BOD_5, TSS and nutrients over time provided essential information about the long term performance of SSFs. In this study, primary comparisons were made between low and high wastewater loading rate periods, and between regular length and shortened filters. As well, the influence of external hydrological factors on treatment performance was also assessed. The low loading rate (~100 L/day) period extends from January 2005 to November 2006 for filters 1-6. The filters were given three months to acclimate to the doubling of the loading rate. The high loading rate period occurs from March 2007 to December 2008.

In Table 3.5, a statistical summary of the average monthly influent and effluent concentrations for all filters from 2004 to 2008 is presented. In general the six original filters performed well over this four year period, producing average effluent BOD_5 concentrations below 10 mg/L, and average TSS concentrations below 15 mg/L. Some variability in effluent concentrations of BOD_5 and TSS were observed, as evidenced by the maximum concentrations shown in Table 3.5. As will be shown later, these spikes in BOD_5 and TSS can be attributed to excessively high solids and organic loading to the filters which occurred in the fall of 2006. This was due to solids accumulation in the septic tank, which was remediated in January, 2007. Median *E. coli* levels were all below 10 CFU / 100 mL, indicating that the sand filters were generally effective at removing enteric bacteria. However, on several occasions levels of *E. coli* in filter effluent exceeded 100 CFU / 100 mL, illustrating variability in treatment performance.

Average removal efficiencies and effluent concentrations for each of the six filters for the low and high loading rate periods are provided in Table 3.6 and 3.7, respectively. A summary of statistical testing, comparing effluent concentrations from low and high loading rate periods for each water quality parameter in each filter is provided in Table 3.8. Results from t-tests comparing low to high loading rate performance results indicate that there were no difference in treatment of TN, NO_3-N and TSS. Other parameters have mixed results. With respect to BOD_5, the results indicated that effluent concentrations were significantly higher during the low loading rate period. However, this is largely attributable to the elevated organic loading observed during the end of this period. With these values removed there is no significant difference in effluent BOD_5 concentrations between the high and low loading rate periods. Two of the filters were statistical different with respect to *E. coli* effluent concentrations, but these differences were small. The statistical test results for TP show that TP concentrations were statistically higher in filters 1, 4, and 4 during the high loading rate period. However, these results should be viewed with caution as the TP removal efficiency of the sand filters is progressively reduced with time due to saturation of adsorption sites. In general the increase in loading rate did not appear to affect the treatment efficiency of the SSFs.

Table 3.5. Statistical summary of filter performance (SSF1-6) from November 2004 to December 2008

	Parameter	Influent	1	2	3	4	5	6
Mean	*E. coli*	2.2E+06	6.9E+01	4.5E+01	2.5E+01	1.1E+01	1.9E+01	5.8E+01
Median	(CFU/100	1.6E+06	3.0E+00	7.0E+00	3.5E+00	2.0E+00	2.0E+00	4.0E+00
Maximum	mL)	1.7E+07	1.2E+03	6.0E+02	3.0E+02	3.0E+02	3.0E+02	9.0E+02
Minimum		1.0E+04	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Stdev		2.8E+06	2.3E+02	1.1E+02	6.5E+01	4.3E+01	6.0E+01	1.7E+02
Mean	TSS	522.3	14.3	10.4	9.2	7.7	5.5	7.1
Median	(mg/L)	52.4	4.8	3.2	5.3	2.6	2.2	2.0
Maximum		5200.0	114.0	95.0	59.8	30.6	51.6	78.4
Minimum		6.5	2.0	2.0	2.0	2.0	2.0	2.0
Stdev		1198.6	21.5	18.4	11.2	7.7	7.8	13.7
Mean	BOD_5	278.0	2.7	2.9	3.6	2.7	2.7	3.0
Median	(mg/L)	95.7	2.4	2.4	2.4	2.4	2.4	2.4
Maximum		1878.0	5.2	10.7	35.7	5.0	4.7	7.9
Minimum		29.6	2.4	2.4	2.1	2.4	2.4	2.4
Stdev		457.6	0.7	1.3	4.9	0.6	0.7	1.2
Mean	TP (mg/L)	8.3	0.9	1.3	2.4	1.0	1.1	2.3
Median		3.1	0.7	1.0	2.2	0.7	1.0	2.2
Maximum		55.8	3.8	5.2	6.2	2.9	3.0	5.1
Minimum		0.8	0.1	0.1	0.1	0.1	0.1	0.1
Stdev		10.6	0.9	1.0	1.3	0.8	0.7	1.1
Mean	NH_4-N	20.1	0.4	0.3	0.3	0.2	0.2	0.4
Median	(mg/L)	17.5	0.1	0.1	0.1	0.1	0.1	0.1
Maximum		69.5	2.6	2.0	1.8	1.0	2.2	4.8
Minimum		1.7	0.1	0.1	0.1	0.1	0.1	0.1
Stdev		13.1	0.6	0.4	0.4	0.2	0.4	0.8
Mean	NO_3-N	0.9	14.9	16.4	16.5	15.6	14.5	14.5
Median	(mg/L)	0.2	14.4	15.0	15.4	14.1	13.0	13.1
Maximum		20.0	48.8	45.6	37.2	33.9	38.7	32.8
Minimum		0.0	0.3	5.5	4.2	3.8	0.2	3.0
Stdev		3.0	7.9	7.7	7.7	7.2	8.0	7.1
Mean	TN (mg/L)	43.1	16.8	17.9	18.7	17.0	16.0	15.5
Median		29.3	51.5	16.2	16.4	15.5	14.0	14.0
Maximum		236.8	2.2	48.3	46.6	34.4	40.3	33.3
Minimum		8.4	2.2	6.6	5.9	3.9	0.6	2.1
Stdev		41.7	8.8	8.3	9.5	15.5	8.6	8.4

Table 3.6. Summary of treatment performance during the low loading rate period for filters 1-6.

			Filter					
Parameter	Influent		Fine (5%) SSF1	Medium (5%) SSF2	Coarse (5%) SSF3	Fine (30%) SSF4	Medium (30%) SSF5	Coarse (30%) SSF6
E. coli (CFU/100	1.5E+06	Outlet Log removal	3.2E+00 5.58	4.4E+01 5.05	2.7E+01 5.21	1.5E+01 5.28	2.0E+01 5.29	4.7E+01 5.25
TSS (mg/L)	910.1	Outlet % removal	21.0 91.9%	13.2 93.1%	13.4 93.2%	9.9 94.0%	7.9 93.3%	10.0 94.6%
BOD_5 (mg/L)	426.8	Outlet % removal	2.8 97.8%	3.0 97.8%	4.3 97.6%	2.8 97.7%	2.8 97.6%	3.1 97.4%
TP (mg/L)	9.1	Outlet % removal	0.6 87.0%	1.1 74.9%	2.2 56.9%	0.6 85.8%	0.8 82.7%	2.1 59.1%
NH_4-N (mg/L)	22.4	Outlet % removal	0.3 97.3%	0.3 97.2%	0.3 97.2%	0.2 98.0%	0.2 97.9%	0.6 96.8%
TKN (mg/L)	52.8	Outlet % removal	2.3 93.8%	2.3 93.6%	2.6 92.9%	1.8 94.7%	1.8 95.5%	1.9 95.1%
NO_3-N	1.5	Outlet	14.6	16.7	16.0	15.3	14.2	14.0
TN (mg/L)	54.3	Outlet % removal	16.9 55.2%	18.9 47.5%	18.6 48.1%	17.1 50.7%	15.9 56.8%	15.4 54.8%

Table 3.7. Summary of treatment performance during the high loading rate period for filters 1-6.

			Filter					
Parameter	Influent		Fine (5%) SSF1	Medium (5%) SSF2	Coarse (5%) SSF3	Fine (30%) SSF4	Medium (30%) SSF5	Coarse (30%) SSF6
E. coli (CFU/100	3.1E+06	Outlet	1.5E+02	4.3E+01	2.4E+01	6.6E+00	1.9E+01	5.0E+01
		Log removal	4.87	5.16	5.28	5.59	5.52	5.10
TSS (mg/L)	65.5	Outlet	6.9	8.1	4.3	4.5	2.8	4.3
		% removal	89.2%	92.4%	90.0%	91.2%	92.4%	91.8%
BOD_5 (mg/L)	91.2	Outlet	2.7	2.9	2.5	2.5	2.5	2.6
		% removal	95.7%	95.9%	96.6%	96.4%	96.3%	96.2%
TP (mg/L)	4.3	Outlet	1.3	1.6	2.8	1.5	1.4	2.6
		% removal	53.9%	42.8%	2.1%	47.6%	48.9%	9.5%
NH_4-N (mg/L)	17.9	Outlet	0.4	0.1	0.1	0.1	0.2	0.2
		% removal	97.2%	99.2%	99.1%	99.2%	98.8%	98.9%
TKN (mg/L)	30.5	Outlet	1.2	0.8	0.4	1.0	0.6	1.0
		% removal	95.5%	96.7%	98.4%	96.1%	97.8%	95.9%
NO_3-N	0.3	Outlet	15.6	16.2	17.3	15.8	14.7	14.9
TN (mg/L)	30.7	Outlet	16.6	16.6	17.5	16.9	15.7	14.9
		% removal	40.4%	40.7%	36.8%	39.0%	43.4%	45.1%

Table 3.8 Summary of p-values comparing low to high loading rate performance results for filters 1-6.

Filter	*E.Coli*	BOD_5	TSS	TP	NH_4-N	TKN	NO_3-N	TN
SSF1	*NS*	0.021	*NS*	0.031	*NS*	0.014	*NS*	*NS*
SSF2	0.000	*NS*	*NS*	*NS*	0.016	0.006	*NS*	*NS*
SSF3	0.001	0.003	*NS*	*NS*	0.031	0.030	*NS*	*NS*
SSF4	*NS*	0.009	*NS*	0.000	*NS*	*NS*	*NS*	*NS*
SSF5	*NS*	0.022	*NS*	0.004	*NS*	0.003	*NS*	*NS*
SSF6	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*	*NS*

Where *NS* = Not significant ($p > 0.05$)

A statistical summary comparing performance results from SSF2 during the low loading rate period and the shortened filters (SSF7-8) are presented in Table 3.9. This is followed by Table 3.10 which lists the results from t-tests comparing performance results between the filters. There are no significant differences between results from SSF7 and SSF8. The only parameters which indicate differences between the levels of treatment provided are TKN and NH4-N (only in SSF8). Thus, the shortened filters are performing at the same level as a regular length filter under similar loading rate conditions. These results suggest that the majority of treatment occurs within the first part of the LFSF, and that treatment processes occurring within the biomat control the treatment efficiency of the system.

Table 3.9. Statistical summary comparison between SSF2, a regular length filter during the low loading (~100 L/day) period (January 2005-November 2006) and shortened filters, SSF7-8, from November 2007 to December 2008.

	Parameter	Influent concentration (Jan '05 – Nov '06)	Medium (5%, 8 m) SSF2	Influent concentration (Nov '07 – Dec '08)	Medium (5%, 5.5 m) SSF7	Medium (5%, 5.5 m) SSF8
Mean	*E. coli* (CFU/100 mL)	1.5E+06	4.44E+01	3.7E+06	4.8E+01	6.6E+01
Median		1.4E+06	4.00E+00	1.5E+06	8.0E+00	1.4E+01
Maximum		3.5E+06	6.00E+02	1.7E+07	2.8E+02	6.0E+02
Minimum		3.0E+04	0.00E+00	1.0E+04	0.0E+00	2.0E+00
Stdev		9.5E+05	1.30E+02	5.0E+06	9.3E+01	1.6E+02
Mean	TSS (mg/L)	910.1	13.2	49.5	11.0	13.7
Median		273.0	4.9	34.1	7.0	13.6
Maximum		5200.0	63.5	197.0	36.8	41.4
Minimum		6.5	2.0	21.4	2.0	2.0
Stdev		1532.2	17.4	49.9	9.9	9.9
Mean	BOD_5 (mg/L)	426.8	3.0	66.6	2.7	2.7
Median		156.0	2.6	68.4	2.4	2.4
Maximum		1878.0	5.0	113.0	6.2	5.7
Minimum		38.5	2.4	29.6	2.4	2.4
Stdev		574.6	0.8	27.4	1.0	0.9
Mean	TP (mg/L)	9.1	1.1	3.2	1.0	0.9
Median		6.2	0.7	2.9	1.0	0.9
Maximum		33.1	5.2	9.2	1.4	1.7
Minimum		0.8	0.2	1.4	0.5	0.1
Stdev		8.9	1.1	2.1	0.2	0.4
Mean	NH_4-N (mg/L)	22.4	0.3	16.4	0.2	0.1
Median		17.6	0.1	17.3	0.1	0.1
Maximum		69.5	1.9	29.6	0.9	0.1
Minimum		1.7	0.1	5.8	0.1	0.1
Stdev		15.9	0.5	8.1	0.2	0.0
Mean	NO_3-N (mg/L)	1.5	16.7	0.05	14.0	17.8
Median		0.4	13.8	0.04	14.2	15.2
Maximum		20.0	45.6	0.08	25.6	28.2
Minimum		0.0	5.5	0.04	7.2	9.3
Stdev		4.0	9.3	0.02	5.9	6.3
Mean	TN (mg/L)	54.3	18.9	30.5	14.8	18.6
Median		41.5	16.3	26.7	14.5	16.6
Maximum		236.8	48.3	90.1	25.7	28.8
Minimum		8.4	6.6	15.2	7.3	9.7
Stdev		52.6	9.8	20.6	5.7	6.5

Table 3.10. Summary of p-values comparing performance results from SSF2 from January 2005 to November 2006 to SSF7 to SSF8 from November 2007 to December 2008.

Parameter	SSF2 vs. SSF7	SSF2 vs. SSF8	SSF7 vs. SSF8
E. Coli (CFU/100 mL)	*NS*	*NS*	*NS*
TSS (mg/L)	*NS*	*NS*	*NS*
BOD_5 (mg/L)	*NS*	*NS*	*NS*
TP (mg/L)	*NS*	*NS*	*NS*
NH_4-N (mg/L)	*NS*	0.015	*NS*
TKN (mg/L)	0.035	0.003	*NS*
NO_3-N (mg/L)	*NS*	*NS*	*NS*
TN (mg/L)	*NS*	*NS*	*NS*

Where *NS* = Not significant ($p > 0.05$)

3.3.2. Temporal Trends in Treatment Performance: Influent concentrations appear to vary when comparing high to low loading period averages in Tables 3.6 and 3.7 (910.1 mg/L to 65.5 mg/L, respectively). However, peak values shown in Figure 3.17 occurring in February, June, August and September 2006 due to mechanical issues with the pump are an explanation for the inflated low loading period averages. This is evident when comparing inlet concentrations (Figure 3.17) to outlet concentrations for SSF1-6 (Figure 3.19, a-b): spikes in influent are matched by increased outlet concentrations, specifically in late summer 2006. However, it is important to note that increased influent concentrations did not affect TSS removal %. Statistically, each filter is achieving over an 89% TSS removal rate. Average outlet concentrations for the high loading rate period range from 2.8 mg/L (SSF5) to 8.1 mg/L (SSF2). Each filter performed very well with respect to TSS removal.

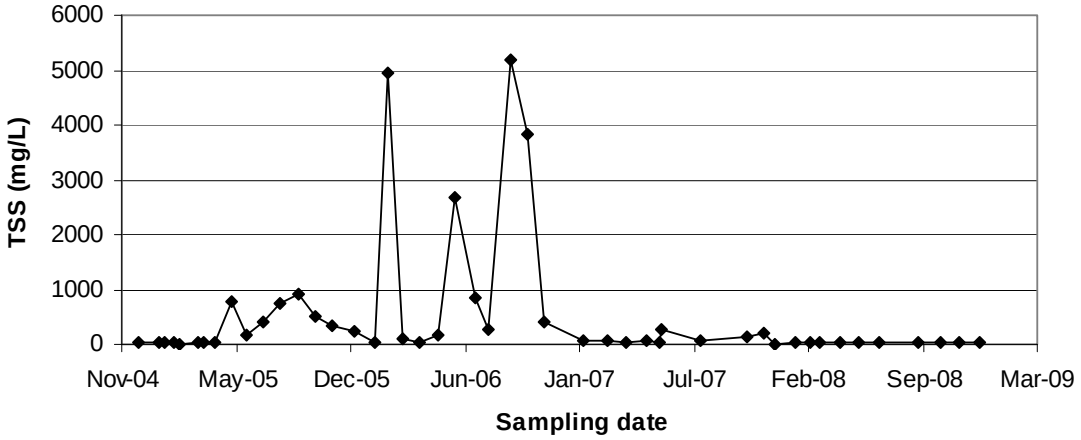


Figure 3.17. TSS inlet concentrations from November 2004 to December 2008.

Results for BOD_5 treatment are similar to TSS removal. Filters demonstrate an ability to dampen out variability in influent concentrations. Outlet concentrations from the high loading rate period range from 2.5 mg/L (SSF3, SSF4) to 2.9 mg/L (SSF2). Temporal trends of effluent BOD_5 concentrations show that the systems consistently produce levels less than 10 mg/L.

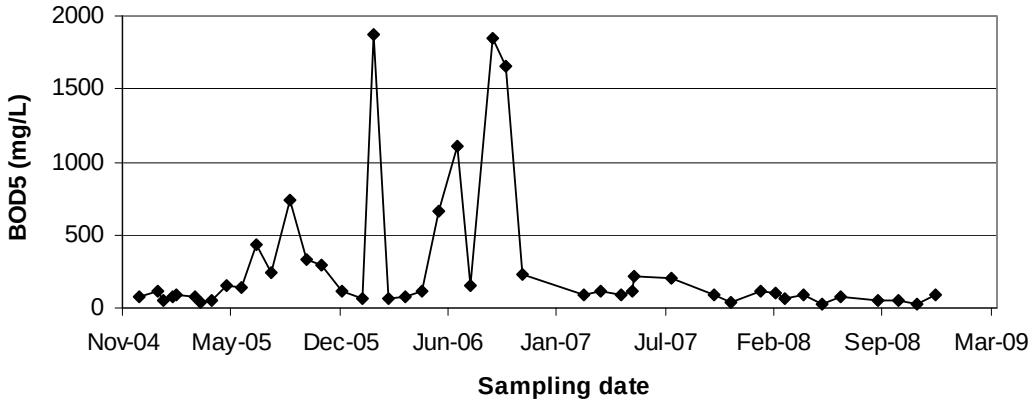
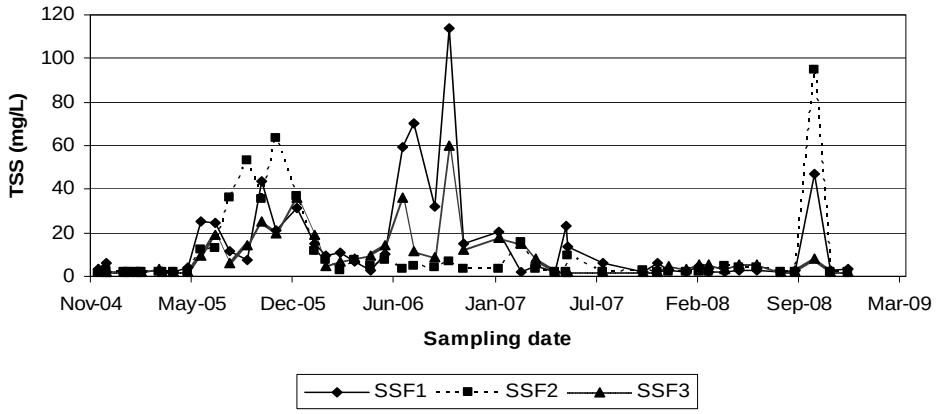
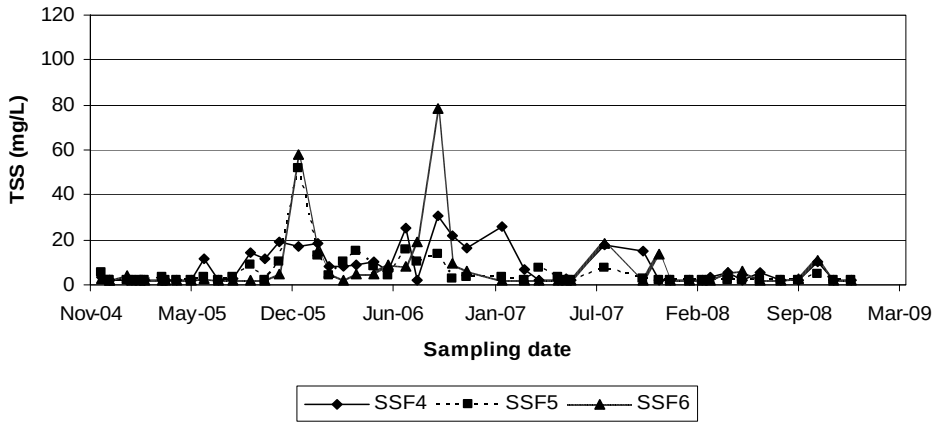


Figure 3.18. BOD_5 inlet concentrations from November 2004 to December 2008.

(a)



(b)



(c)

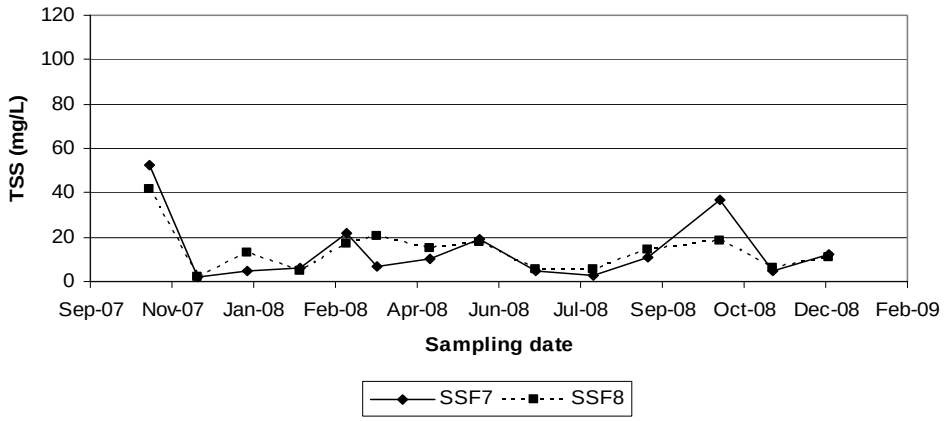
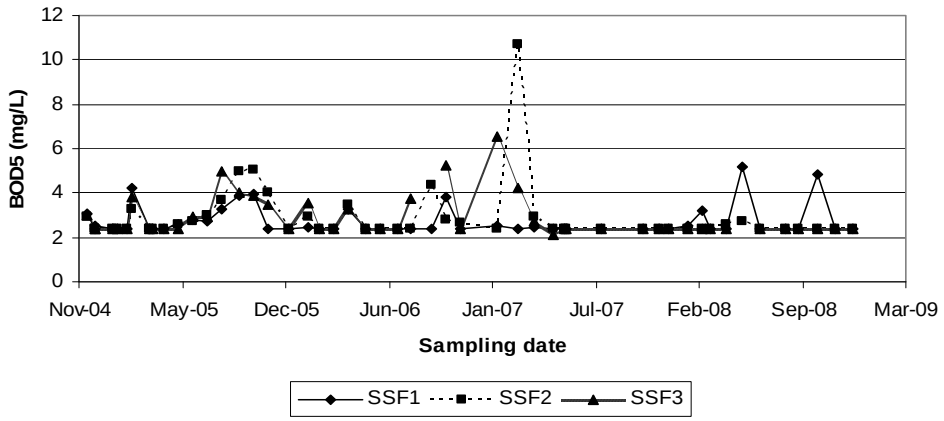
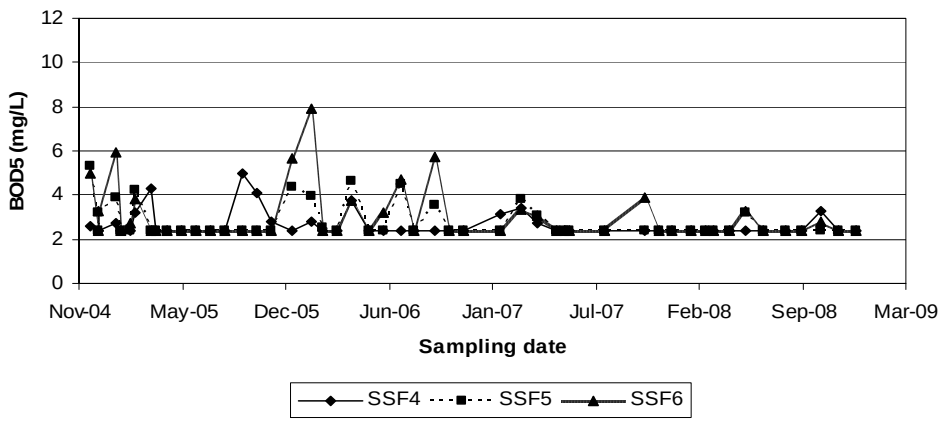


Figure 3.19. Outlet TSS concentrations for SSF1-3 (a) and SSF4-6 (b) from November 2004 to December 2008 and for SSF7-8 (c) from October 2007 to December 2008.

(a)



(b)



(c)

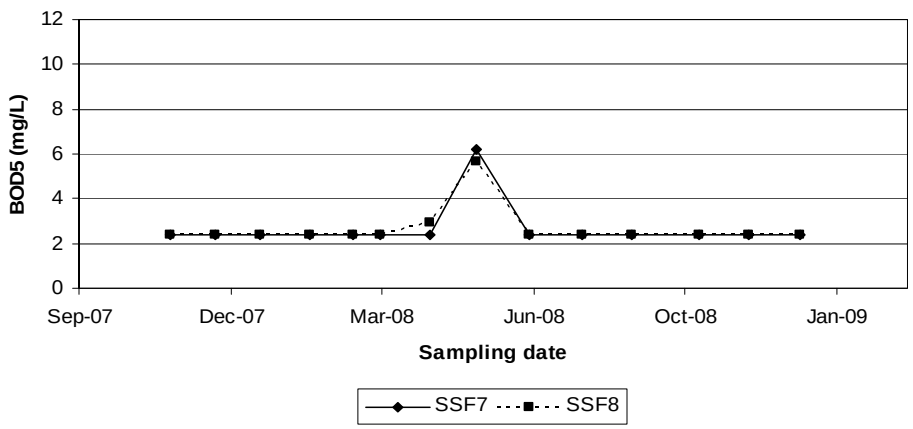


Figure 3.20. Outlet BOD_5 concentrations for SSF1-3 (a) and SSF4-6 (b) from November 2004 to December 2008 and SSF7-8 (c) from October 2007 to December 2008.

Influent bacteria counts have remained constant over time from 2004 to 2008 with occasional spikes which simulate realistic variability (Figure 3.21). With respect to *E. coli*, outlet concentrations did not change from low to high loading periods, except for SSF1 which increased by a magnitude of 2. Accordingly, log removal for that filter fell from 5.58 to 4.87. Except for SSF1, each filter achieves at least a 5-log removal rate of *E. coli*. Temporal variations in bacteria outlet concentrations (Figure 3.22-3.24) represent a level of variability which may not be acceptable for surface discharge, due to the possible health hazard associated with such levels.

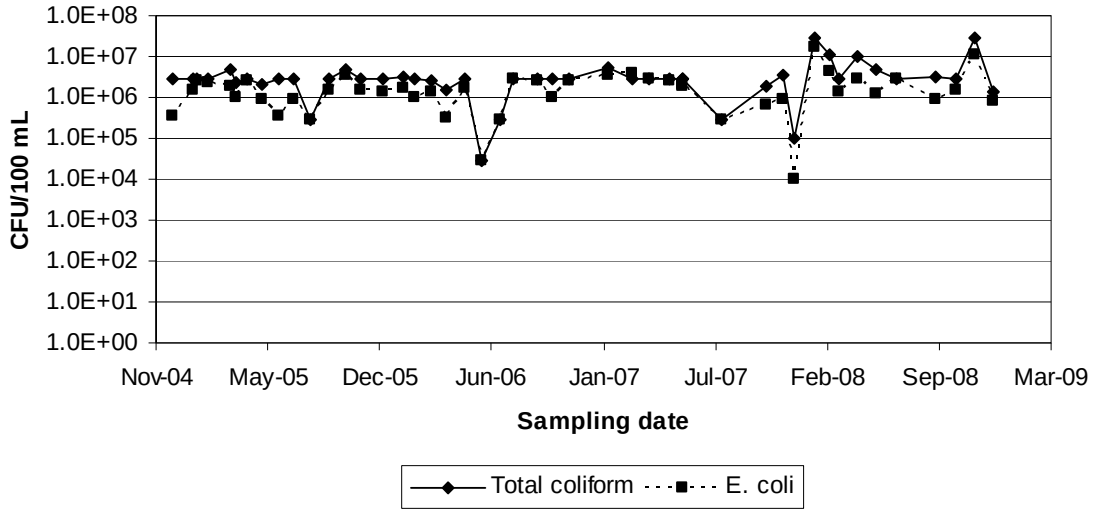
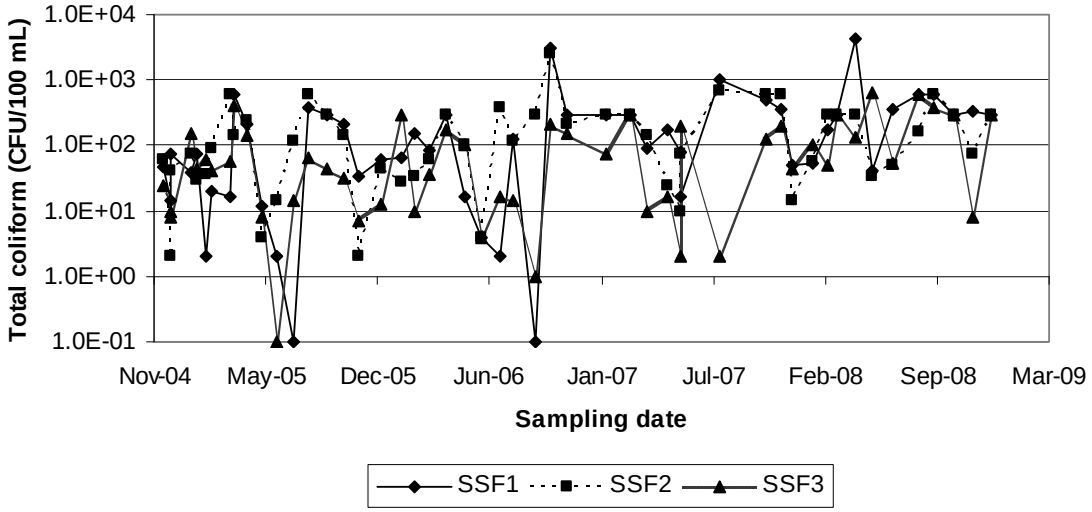


Figure 3.21. Inlet TC and *E. coli* concentrations from November 2004 to December 2008 in CFU/100 mL.

Temporal trends in TP removal efficiencies are illustrated in Figure 3.25. The TP removal efficiency of each filter is progressively decreasing with time. All eight filters initially removed close to 100% of the influent TP, but after a relatively short period of time (1 year) the treatment efficiency begins to decrease. This reduction in treatment efficiency happened much quicker in filters 7 and 8 due to the smaller flow path lengths. After 3 years of effluent loading, several of the original six filters appear to be saturated with phosphorus. As expected, the coarse-grained filters saturate more quickly than fine-grained filters, as they would possess less surface area for adsorption. These results indicate that conventional sand-based disposal systems have virtually no long-term phosphorus removal capacity.

(a)



(b)

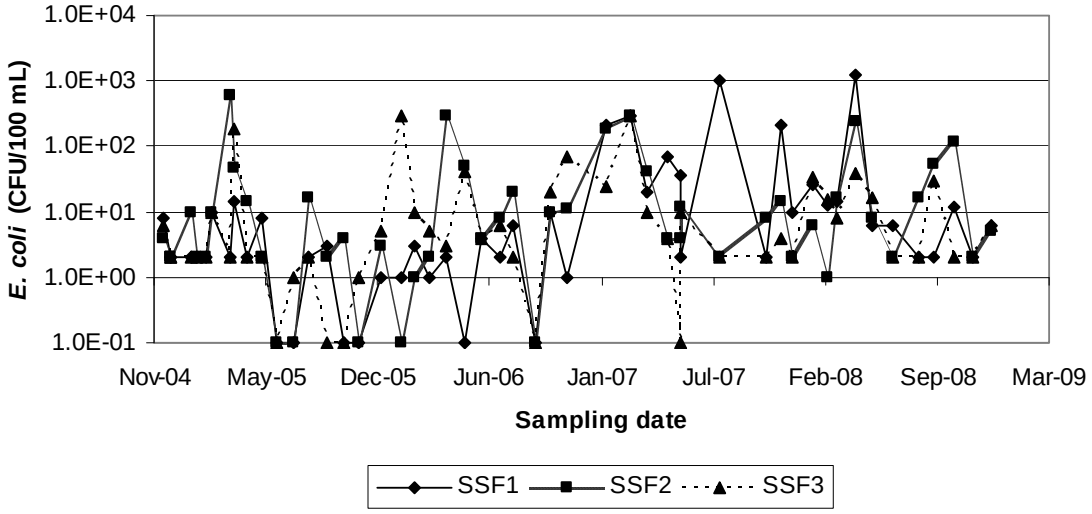
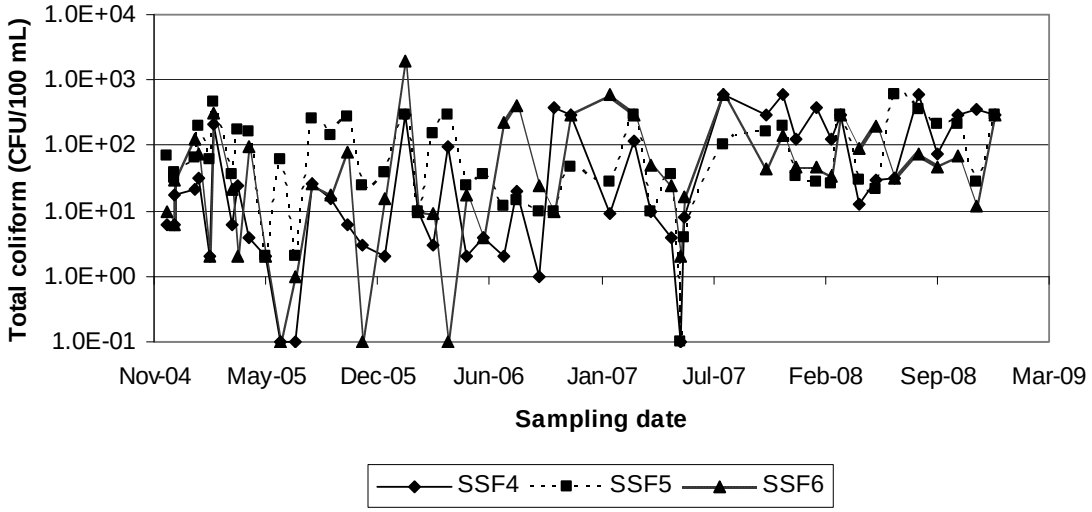


Figure 3.22. Outlet TC concentrations (a) and *E. coli* concentrations (b) for SSF1-3 from November 2004 to December 2008 in CFU/100 mL.

(a)



(b)

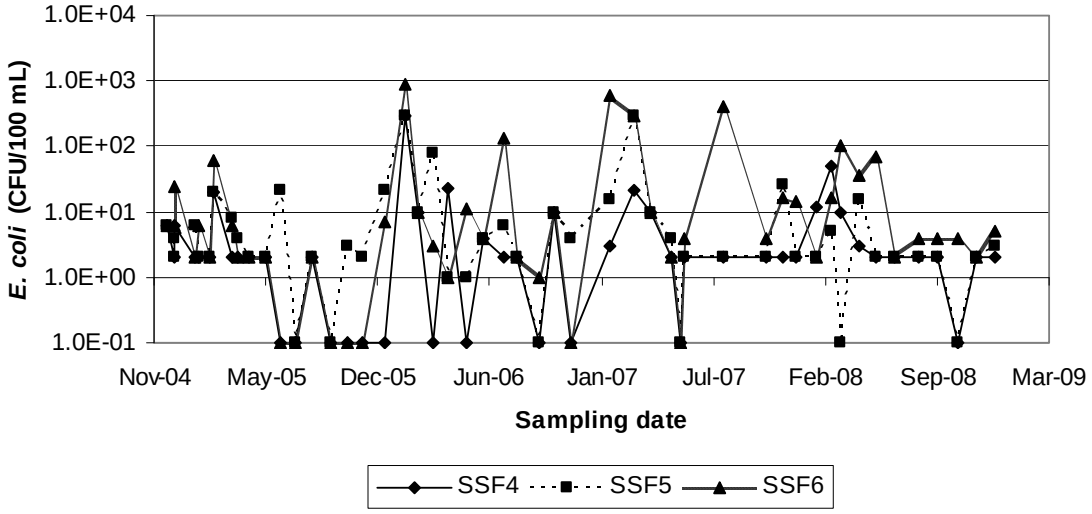
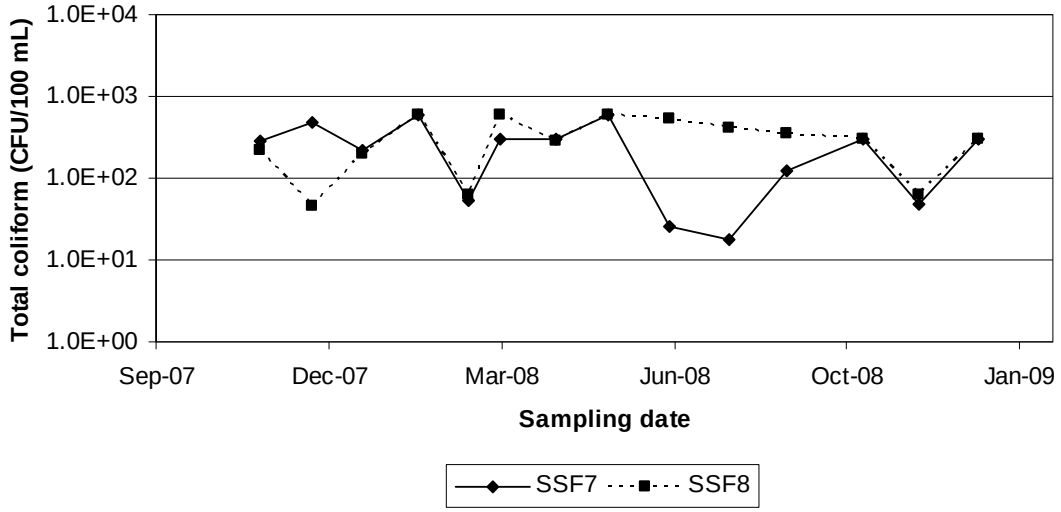


Figure 8.23. Outlet TC concentrations (a) and *E. coli* concentrations (b) for SSF4-6 from November 2004 to December 2008 in CFU/100 mL.

(a)



(b)

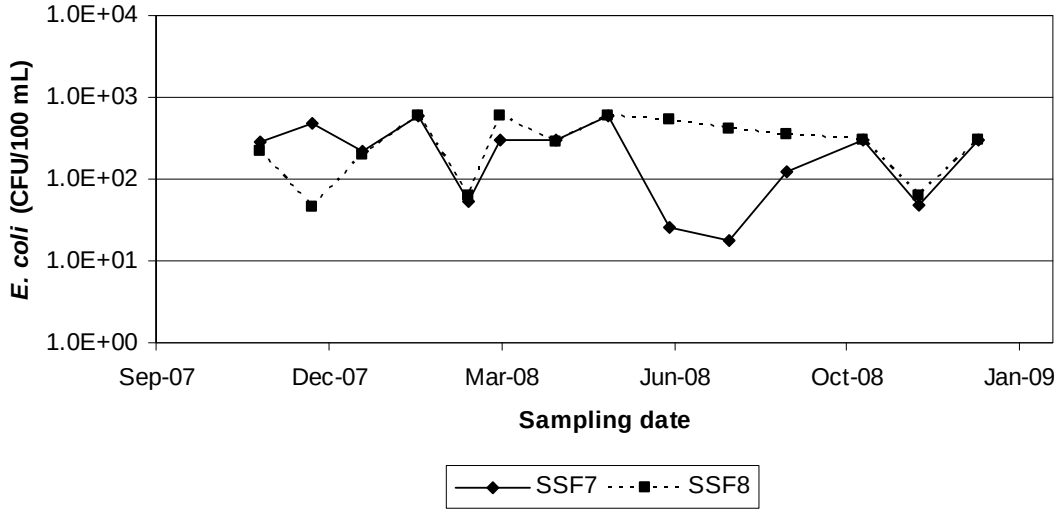
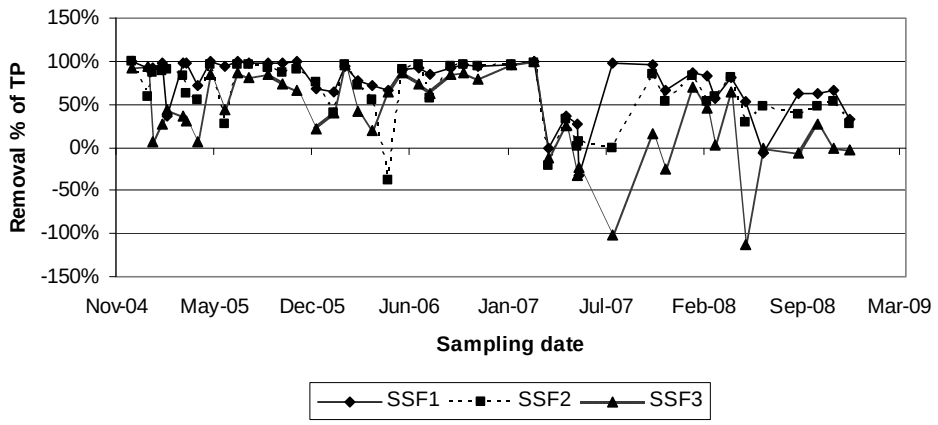
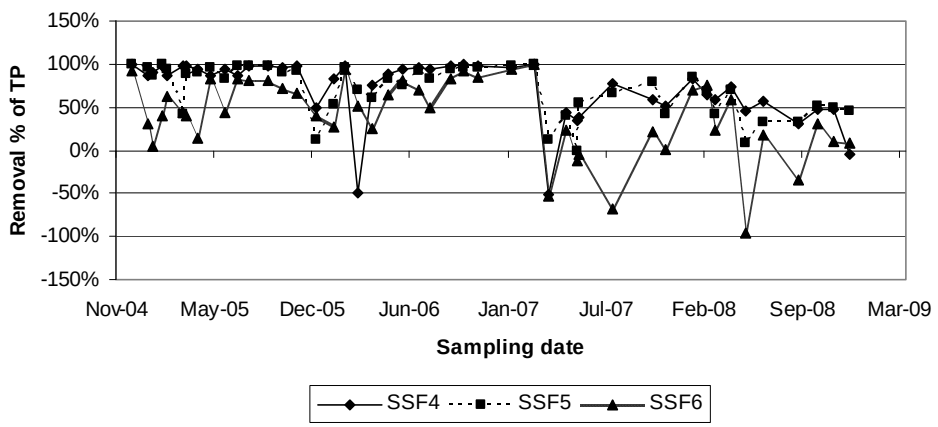


Figure 3.24. Outlet TC concentrations (a) and *E. coli* concentrations (b) for SSF7-8 from October 2007 to December 2008 in CFU/100 mL.

(a)



(b)



(c)

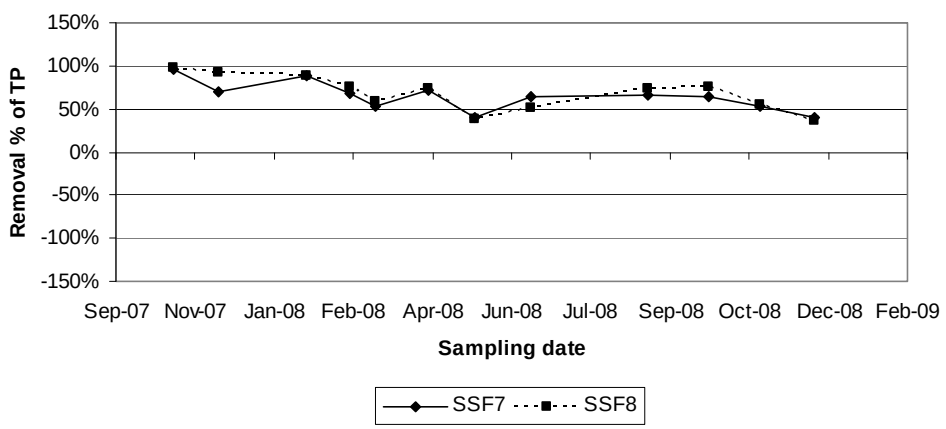


Figure 3.25. Removal % of TP for SSF1-3 (a) and SSF4-6 from November 2004 to December 2008 and SSF7-8 (c) from October 2007 to December 2008.

4.0 SUMMARY AND CONCLUSIONS

This report presents results from a detailed field scale analysis of the performance and hydraulic functioning of sloping sand filter systems receiving septic tank effluent. A total of eight SSFs, constructed using varying slopes, sand types, lengths, and loaded at varying rates, were intensively monitored over a 20 month period. The SSF system was shown to be a reliable, relatively robust treatment system. SSFs that were loaded at elevated rates, as compared to NS technical guidelines, performed well, providing a level of treatment that was similar to that observed at conventional loading rates. The treatment performance of two identical SSF systems that were substantially shorter than that recommended in the NS technical guidelines also performed well. The two shortened SSFs produced effluent concentrations of all primary water parameters that were similar to those achieved by a conventional length SSF possessing similar sand and slope characteristics.

Several tracer studies, using rhodamine dye as a conservative tracer, were conducted on all filters during the study period. Tracer study data was fit to analytical residence time distribution models to assess the hydraulic functioning of the filters. Measured hydraulic characteristics were then compared to those predicted using theoretical models of porous media flow. The increase in flow to the original six SSFs did not cause a noticeable change in the mean residence time characteristics of the filters. Water level measurements from piezometers installed throughout the sand bed in each filter confirmed that the filters remained unsaturated after the loading rates were increased. Ponding of water in the distribution trench was observed, but biomat hydraulics appeared to be stable. A comparison of tracer generated residence times with those predicted using theoretical porous media flow models provide further evidence that saturated darcy flow does not exist within the SSF systems, even at elevated loading rates. This study has shown that current design loading rates for SSFs in NS are conservative, providing an inherent safety factor

The treatment performance of most water quality parameters (BOD_5, TSS, *E. coli*, TN) remained consistent as the SSF systems aged. However, a progressive reduction in phosphorus removal was observed in all filters, regardless of sand type or slope. Results from this study indicated that conventional sand based disposal fields become saturated with phosphorus within 3- 5 years. The incorporation of alternative materials for phosphorus adsorption within passive filters should be examined in future studies.

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APPENDIX A: PHOTOGRAPHS

Photograph of LFSFs located on the 5 % slope showing piezometers and sampling wells.

Photograph of the plywood containment boxes that the LFSFs were constructed within.

Photograph of liner installation and placement of the filter sand.

Photograph of sampling hut showing tipping buckets and autosamplers.

Photograph showing the construction of the 5.5 m LFSF systems and installation of piezometers.