Comparison of Biological Aerated Filter (BAF) performance using two granular sunken media at low organic and hydraulic loadings

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Abstract

Biological treatment forms an integral part of wastewater treatment. Biological aerated filters (BAFs) are submerged attached growth bioreactors which provide biological treatment as well as filtration in a single unit. The packing media used in BAFs plays an important role in the system performance and determines the ability of the system to meet treatment objectives. The performance of upflow BAFs was compared using North American clay media and Severn Trent monomedia at low organic and hydraulic loads (0.18 kg tCOD/m^3d – 0.6 kg tCOD/m^3d and 0.1 m/hr – 0.38 m/hr, respectively). Two identical, two stage, bench scale, upflow BAFs were constructed using PVC pipes with an internal diameter of 0.11 m. The system was operated at the Peppers Ferry Wastewater Treatment facility for two months and was fed with effluent from the primary clarifier. Grab samples of influent and effluent from the BAFs were collected thrice a week to evaluate carbon oxidation, solids removal and nitrification. In order to evaluate system recovery when BAFs are operated intermittently, a drying cycle of eleven days was introduced. Both media performed satisfactorily with respect to carbon oxidation and nitrification. On average, total COD and total suspended solids (TSS) removal rates were, respectively greater than 80% and 55%. Conversion of ammonia to nitrate was greater than 90% throughout the study. It was concluded that additional factors like media properties and economic factors need to be considered in selection of the media.

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Chapter 1

Introduction

Biological processes are a vital part of wastewater treatment. The activated sludge process is one of the most widely implemented biological processes. Although suspended growth systems like activated sludge are efficient, the need for compact systems has led to a renewed interest in attached growth systems. The Biological Aerated Filter (BAF) is a submerged attached growth system consisting of three phases: 1. the media supporting the biofilm growth acts as the solid phase, 2. the influent settled sewage acts as the liquid phase, and 3. the gas phase is the air supplied to the system (Pujol et al. 1992, Mendoza-Espinosa and Stephenson 1999). The settled sewage flows through the system either in an upflow or downflow manner. Treatment of wastewater occurs due to the simultaneous physical and biological processes that take place as the sewage comes in contact with the biofilm coated media (Pujol et al. 1992).

This study was conducted for the Western Virginia Water Authority (WVWA), an advanced wastewater treatment facility in Roanoke, Virginia. During heavy precipitation events, the influent to the wastewater treatment plant (WWTP) is characterized by high volumetric flow rates and low organic loading. Conventional Activated Sludge systems would require large reactor volumes to handle the high flow rates. In addition, the low organic loading caused by dilution leads to lower removal efficiencies and could also cause bulking and foaming issues in the secondary clarifiers (Farabegoli et al. 2009). The need to handle high flows during wet weather events, prompted the WVWA to consider use of BAFs. The expanded clay BAF media and a novel media called Severn Trent monomedia used in this study were provided by the WVWA.

Research Objectives

The main objectives of this research were:

1. Evaluate the performance of BAF at low organic loading rates
2. Evaluate system recovery after drying / fasting conditions
3. Compare the performance of BAF with North American clay media and Severn Trent monomedia

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In order to realize these research objectives, two identical, two-stage, upflow BAF systems were built using PVC pipes (two pipes in series per system) with a diameter of 0.11 m. The BAF reactor containing the expanded clay media was initially set up in the lab, but was later shifted to the Peppers Ferry Wastewater Treatment Facility (PFWTF; Radford, Virginia). The BAF reactor containing the Severn Trent monomedia media was operated at the PFWTF for the entire duration of the study. The reactors were operated in an upflow configuration and fed with effluent from the primary clarifier. The reactors were backwashed every 48 hours.

The reactors were operated and monitored for a period of two months at the PFWTF. COD, suspended solids, ammonia-nitrogen, nitrite, nitrate, total Kjeldahl nitrogen (TKN), total phosphorus, pH, temperature and dissolved oxygen were monitored to evaluate system performance. The reactors were operated under two organic loading rates (0.18 kg tCOD/m^{3}d and 0.6 kg tCOD/m^{3}d). Grab samples from reactors were analyzed for total and soluble chemical oxygen demand (COD), total suspended solids (TSS), volatile suspended solids (VSS), ammonia–nitrogen, total Kjeldahl nitrogen (TKN), nitrite and nitrates. Backwash samples were also analyzed for TSS and VSS.

A drying cycle of eleven days was introduced at the end of the first experimental phase. During the drying cycle, the reactors were drained, and influent water and air supply were shut off. The reactors were returned to normal operation after the drying cycle. System performance was evaluated to understand the effect of drying/fasting conditions on BAFs.

Information presented in this thesis is organized into four chapters. The introduction presents the research objectives and provides a brief overview of the study. This is followed by the literature review, where existing literature regarding BAF has been explored to gain understanding regarding the operation of BAFs as well as the various factors affecting its performance. The manuscript gives a detailed description of the experimental set up, analytical methods used, presents the results obtained from this study and the conclusions drawn from it. In the final chapter, conclusions drawn are used to provide recommendations and suggestions.

Chapter 2

Literature Review

Introduction

The Western Virginia Water Authority (WVWA) is a public organization that provides water and wastewater services to the City of Roanoke, Roanoke County, Franklin County and Botetourt County. The Roanoke Regional Water Pollution Control Plant (RRWPCP), managed by the WVWA, provides wastewater services to all the jurisdictions in the Roanoke Valley. The plant has an average influent flow of 37 MGD. However, during wet weather events flows greater than 120 MGD have been reported. In order to provide sufficient treatment during such events, WVWA has decided to start operating Biological Aerated Filters (BAFs). During wet weather events, the excess influent would be stored in the equalization basin before it is pumped to the BAFs. At the RRWPCP, the BAFs are designed as a two-stage treatment unit, with six units in each stage. During wet weather events, these two stages will be operated in parallel, thus allowing the BAFs to handle a flow of 30 MGD. The design hydraulic and organic loading for the BAFs are 3 - 12 m/hr and 2 - 8 kg BOD_5/m^3d. Backwashing is carried out every 24 hours, using filtered water and scour air. Selection of suitable packing media plays an important role in the operation and performance of BAFs. The purpose of this study was to compare the performance of upflow BAFs using North American clay media and Severn Trent monomedia. As the BAFs were to be operated intermittently, a drying cycle was introduced during the study in order to understand the time required for system recovery.

Biological Aerated Filters (BAFs)

In the 1970s, the need for compact and efficient biological treatment processes led to numerous research projects, which resulted in the development of Biological Aerated Filters (Blanc and Maulaz 1975, Bebin et al. 1975, Grasmick et al. 1979, Leglise et al. 1980, Pujol et al. 1992, Mendoza-Espinosa et al. 1998). BAFs are submerged, attached growth bioreactors which can be used for the secondary and tertiary biological treatment of wastewater (Stensel and Reiber, 1983). BAFs consist of submerged media with a provision for supplying air to support biomass growth.

Depending upon the configuration, settled sewage flows either in an upflow or downflow manner through the media.

BAFs have been generally used for carbon oxidation, nitrification and suspended solids removal (Stensel and Rakness 1988, Mendoza-Espinosa and Stephenson 1999). In addition, denitrification and phosphorus removal have also been achieved by varying the operating conditions (Aesoy and Hamon 1997,Clark et al. 1997,Mendoza-Espinosa and Stephenson 1999). Pollutant removal occurs when the wastewater comes in contact with the biofilm, leading to biological transformation and physical filtration (Pujol et al. 1992). The main advantage of attached growth processes like BAFs is their small footprint when compared to other secondary treatment processes (Moore et al. 1999). According to Stensel and Reiber (1983), the land usage by BAFs is approximately a fifth of that required by plastic media trickling filters and a tenth of that required by activated sludge process. The major factors responsible for this are the higher concentration of biomass maintained per unit volume and the combination of biological treatment and filtration in a single unit.

Depending on the treatment objectives to be achieved, BAFs can be operated in an aerobic or anoxic mode. A variety of materials have been used as media in the BAFs. Over a period of time, the accumulation of solids clogs the pores and backwashing has to be performed. Backwashing is usually carried out every 24–48 hours (Bacquet et al. 1991). The reported, typical removal rates for carbonaceous BOD, ammonia and nitrates are 4.1 kg/m^3-d, 1.27 kg/m^3-d and 5 kg/m^3-d, respectively (Mendoza-Espinosa and Stephenson 1999).

Factors affecting performance of BAFs

The factors that play a major role in the performance of BAFs are flow characteristics, packing media used, aeration and oxygen utilization and backwashing.

Flow characteristics: The major factors affecting flow characteristics in BAFs are liquid and air flow rates, as well as the media (LeCloirec et al. 1984). Flow characteristics influence the formation and distribution of biofilm in the system. BAFs usually operate as plug flow reactors, although there is some channeling and back-mixing (Boller et al. 1994,Mann et al. 1995,Fdz-Polanco et al.1996, Mendoza-Espinosa and Stephenson, 1999). BAFs can be operated in an upflow or downflow mode. While operating in the downflow mode, settled sewage is supplied at the top of the reactor. The counter-current flow of wastewater and air in the downflow mode is particularly advantageous when combined carbon oxidation and nitrification are being carried out in a single unit. As the wastewater travels towards the lower region of the reactor, the reduced total organic loading and the abundant oxygen creates conditions which are conducive to the growth of nitrifiers (Gonzalez-Martinez and Wilderer, 1991, Grady et al. 2011). However, upflow configurations with co-current wastewater and air flow are claimed to be better at handling higher flow rates. Also, in the upflow mode, odor issues are minimized, as only treated effluent comes in contact with the atmospheric air.

Media: A variety of materials have been used as packing media in BAFs (Stephenson, 1997). Table 2.1 lists the different media used in pilot and full scale BAFs. The packing media used has significant effects on the biological and physical processes responsible for pollutant removal. In general, the packing media should be resistant to attrition, chemically stable, and possess a high surface area and low specific weight (Valentis and Lesavre 1989, Kent et al. 1996). The media depth in full scale BAFs is usually between 2 and 4 meters (Pujol et al. 1994). Based on density relative to that of water, media can be classified as floating or sunken media. Denser media would require higher air and water flow rates during backwashing, thereby increasing the energy consumption during operation (Stensel and Rakness ,1988, Pujol et al. 1994). Packing media of different sizes have been used to meet different treatment objectives. Media size effects the surface area available for biofilm growth, as well as the physical filtration process (Smith and Marsh, 1995). When BAFs are used as roughing filters, the packing media is usually greater than 6 mm. For secondary and tertiary treatment media sizes used are 3-6 mm and less than 3 mm, respectively (Quickenden et al. 1992). Large media reduces nutrient and solids removal due to the high void spaces and reduced surface area for biofilm growth, while smaller media provides increased nutrient and solids removal, as well as higher biomass concentration (Stensel and Rakness, 1988, Robinson et al. 1994). However, smaller media requires more frequent backwashing than larger media. According to Sagberg and Berg (1996), the variation in void spaces and the possible break up of air bubbles may be the reason for improved BAF performance while using irregular media as compared to spherical media. Natural mineral media, such as expanded clay, has been reported to achieve superior substrate removal as compared to sand, glass or plastic media of similar dimensions (Farabegoli et al. 2003).

Table 2.1 Different packing media used in Biological Aerated Filters[1]

Media	Media type	Media size (mm)	Reactor configuration	Reference
Sunken	Expanded clay	~ 1.3	Upflow	Sagberg and Berg, 1992
		~1.9		Smith and Hardy, 1992
		~3.5		Verdy et al., 1994
		6 - 8		Furhen et al., 1994
		4 - 8	Downflow	Farabagoli et al., 2004
	Anthracite	3	Downflow	Terayama et al., 1997
	Vitrified clay	3 - 4	Downflow	Clapp et al., 1994
	Expanded shale	3 – 6 (Nit)	Downflow	Dillion and Thomas, 1990
		2 – 5 (Carb.)		Dillion and Thomas, 1990
		3 - 6		Bacquet et al., 1991
		2 – 6		Robinson et al., 1994
		2.5 – 3.5		Tschui et al.,1994
	Porous stone	20 -35	Upflow	Costa Ries and Sant'Anna, 1985
	Slag	~40	Downflow	Dee et al., 1994
	Granular	~2.8	Upflow	Jimenez et al., 1987
Floating	Polystyrene	3 - 6	Downflow	Pujol et al., 1994
		2.5 – 3.5	Upflow	Pujol et al., 1994
		3 – 3.5	Upflow	Tschui et al., 1994
			Upflow	Toettrup et al., 1994
		3.5		Verdy et al., 1994
		3.5		Andersen et al., 1995
		2 - 3.5		Visvanathan and Nhien, 1995
	Polypropylene	2.3 – 2.7	Upflow	Mann and Stephenson, 1996
	Recycled plastic	5	Upflow	Zeghal et al., 1995

[1] Adapted from (Mendoza-Espinosa and Stephenson 1999)

Aeration and Oxygen Utilization: Aeration is one of the factors which dictates the level of treatment achieved in BAFs (Vedry et al. 1994). Pollutant load, endogenous respiration rate of biomass, and oxygen transfer efficiency determine the aeration rate to be provided (Robinson et al. 1994). When the aeration rate is too low, anoxic zones may be formed, leading to inadequate substrate removal; whereas, when the aeration rate is too high, scouring of the biofilm occurs, resulting is poor solids removal (Pearce et al. 1996). According to Stensel (1988), a longer detention time of the air bubbles within the void spaces may increase oxygen utilization efficiency in BAFs. It has been reported by Reiber and Stensel (1985) that even though the oxygen utilization rate increased as the pollutant load increased in BAFs, the bulk liquid oxygen concentration did not show any major changes.

Backwashing: Regular backwashing needs to be carried out in BAFs, in order to remove the captured solids and excess biomass (Faup et al. 1982, Park and Ganczarczyk, 1994). Backwashing is performed using an air scour to dislodge the captured solids and excess biomass, and high rate liquid flow for flushing the dislodged particles (Canler and Perret, 1994). The direction of flow during backwashing depends on the reactor configuration and type of media used. Downflow BAFs are usually backwashed in the upflow direction (Jimenez et al. 1987, Rogalla and Sibony, 1992), whereas upflow BAFs may be backwashed either in the downflow (Andersen et al. 1995, Visvanathan and Nhien, 1995) or in the upflow direction (Mendoza-Espinosa et al. 1997). Backwash must be optimized so as to maintain the system performance and to reduce energy consumption. Under-washing of the system can cause premature headloss, solids break-through, and frequent backwashing (Robinson et al. 1994). Whereas, over-washing can cause reduction in the biomass concentration, which affects the effluent clarity due to decreased biological filtration (Robinson et al. 1994). The characteristics of the packing media, such as size, shape, and porosity, as well as that of the wastewater to be treated determine the frequency of backwashing (Robinson et al. 1994). When BAFs are used for secondary treatment, the frequency of backwashing is usually 24 – 48 hours, but when used for tertiary treatment, backwashing is usually carried out on a weekly basis (Dillon and Thomas, 1990, Bacquet et al. 1991, Smith et al. 1992).

Parameters for evaluating BAF performance

The most common application of BAFs has been for combined carbon oxidation and solids removal. Table 2.2 lists the pilot scale and full scale applications of BAFs for carbon oxidation. The mechanisms responsible for carbon removal are: filtration, absorption and oxidation (Stensel and Rakness, 1988). BAFs are reported to accomplish higher carbon removal per unit volume than other secondary treatment processes, like the activated sludge process and trickling filters (Smith et al. 1992, Pujol et al. 1994). Carbon removal of up to 4.1 kg BOD removed $m^{-3}day^{-1}$ have normally been reported for BAFs used for combined carbon oxidation and nitrification (Mendoza-Espinosa and Stephenson, 1999). However, due to the plug flow nature of BAFs, organic breakthrough may occur during peak flows (Ruffer and Rosenwinkel, 1984). According to Koutsakos et al. (1992), BAFs are more stable at variable temperatures than trickling filters and rotating biological contractors; however, at temperatures below 5˚C, solids and carbon removal decreases. Visvanathan and Nhien (1994) reported that the maximum substrate removal occurred at 38˚C, but the removal efficiency decreased with further increases in temperature.

Table 2.2 Carbon oxidation in BAFs[1]

Reactor Configuration	Reactor volume (m^3)	Influent concentration COD (mg/L)	Organic loading rate (kg COD/m^3d)	Removal (%)	HRT (h)	Reference
Upflow	0.0085	3000 - 3500	3.3 - 15.4	33 – 82	4.5 - 23	Costa Reis and Sant'Anna, 1985
Downflow	0.3	424 (average)	< 9.2	>90	0.4 – 0.76	Dillon and Thomas, 1990
Downflow	0.14	<200	10.5	~55	0.5	Rogalla et al., 1990
Downflow	0.2 – 0.3	324 (average)	< 15	86	0.4 -0.6	Rogalla and Bourbigot, 1990
Downflow	0.02	350	8 - 10	90	--	Bacquet et al., 1991
Downflow	22	13.6 $sCOD_{Mn}$		12	--	Sakuma et al.,1993
	0.1			20	--	
	0.7	$9sCOD_{Cr}$	$2.3COD_{Cr}$	30	--	

Upflow and downflow	Full scale plants 31.5 – 90.3	35 - 607	0.5 - 6.3	55 - 85	--	Pujol et al., 1992
Downflow	Full scale 4 cells 143 m^3 each	131	1.5	93	1.3	Wheale and Cooper – Smith, 1995
Upflow	Full scale, two units 151.2 m^3 each	25 - 43	~2.4 (per unit)	48 - 70	21	Peng et al., 1995
Upflow	Full scale, 8 cells 219 m^3 each	109 – 250 (BOD)	4 (BOD)	>93	--	Brewer, 1996
Upflow	Lab scale, two stage 0.0092 m^3 each	257 (BOD_5)	2.4 (BOD_5)	> 90	3.88	Aseidu, 2001
Downflow	Pilot scale, 0.03m^3	251	3.7 – 8	35 (sCOD)	-	Farabegoli et al., 2009

[1] Adapted from (Mendoza-Espinosa and Stephenson, 1999)

BAFs are reported to have high suspended solids removal efficiencies (Pujol et al. 1992). Removal of solids occurs primarily due to filtration, which occurs as the wastewater passes through the packing media (Stensel and Rakness, 1988, Ryhiner et al. 1994). The support media used, the biofilm structure, and the hydraulics of the reactor are the major factors which affect solids removal in BAFs (Arvin and Harremoes, 1989).

Partial nitrification is achieved when BAFs are used as part of secondary treatment for simultaneous removal of organic matter, suspended solids, and ammonia. BAFs, when used for tertiary treatment, mainly remove ammonia and suspended solids. Biological nitrification is a two-step process. In the first step, ammonia oxidizers convert ammonia to nitrite, and in the second step nitrite oxidizers convert nitrite to nitrate (Grady et al. 2011). The influent organic and solids loads, as well as the hydraulic residence time, are the major factors affecting nitrification in BAFs (Akunna et al. 1994, Böller et al. 1997). At higher organic loading, the rapid growth of heterotrophic organisms restricts the growth of autotrophic bacteria leading to a decrease in nitrification (Akunna et al. 1994). Higher solids in the influent can also inhibit nitrification. Solids get adsorbed to the biofilm, leading to thicker biofilms which promote the growth of heterotrophic organisms. As a result, nitrification decreases (Böller et al. 1997). Nitrification is also affected by the dissolved oxygen (DO) present in the system. It has been recommended that in order to prevent inhibition of nitrification, the bulk DO concentration of 4 -5 mg/l should be maintained in BAFs (Chen and Cheng, 1994). Nitrification is affected by temperature variations, as well. According to McHarness et al., (1975), the decrease in nitrification at lower temperature can be overcome by increasing the hydraulic residence time. Table 2.3 lists various full scale and pilot scale applications of BAFs for nitrification.

Table 2.3 Nitrification in Biological Aerated Filters[1]

Reactor Configuration	Reactor volume (m^3)	Influent concentration NH_3-N(mg/L)	Ammonia loading rate (kg/m^3d)	Ammonia Removal (%)	HRT (h)	Reference
Upflow	0.55	22.7 – 37.5	0.11 mg NH_4-N VM d^{-1} (nitrification rate)	62 - 84	6 -12.9	Faup et al., 1982
Upflow (intermittent aeration)	4.18	17.8	0.03 – 0.05	88.4	7 - 8	Iida and Teranishi, 1984
Downflow	1	13 – 20.9	0.39 – 0.84 (NH_4-N)	90 - 99	0.5 – 0.9	Rogalla and Payraudeau, 1988
Upflow	Full scale	--	<0.46	--	--	Carrand et al., 1990
Downflow	0.3	40.7	< 0.58	65 - 100	0.32 – 0.83	Dillon and Thomas, 1990
Downflow	0.14	< 20	< 0.6	--	1	Rogalla et al., 1990
Downflow	0.2 – 0.3	40 (TKN)	1(NH_4-N)	> 95	1	Rogalla and Bourbigot, 1990
Downflow	22	11	0.9 (NH_4-N; 1.2 removal rates)	57	--	Sakuma et al., 1993
	0.1	23.4		78	--	
Upflow	Full scale, 333	~22	~1.87 (NH_4-N)	89	--	Verdy et al., 1994
Upflow	0.81 – 1.16	--	3 (NH_4-N)	80	--	Peladan et al., 1996

Upflow	Full scale, 18 cells 292 m^3 each	13 - 28	0.15	92 -96	--	Brewer, 1996
Upflow	Pilot plant, two stage, Reactor volume: 1st (1.1 m^3); 2nd (1.04 m^3)	10.3 ± 0.6 NH_3-N	< 0.6	>90	--	Gilmore et al., 1999
Downflow	Pilot scale, 1 stage: 0.03m^3	35 ± 5	0.78 ± 0.12	91	--	Farabegoli et al., 2009

[1] Adapted from (Mendoza-Espinosa and Stephenson, 1999)

BAFs have been used for both nitrogen and phosphorus removal. Denitrification is achieved by operating BAFs under anoxic conditions. During denitrification the facultative or strict anaerobic microorganisms reduce the nitrates and nitrites to nitrogen gas (Akunna et al. 1994). In oxygen deficient environments, nitrates and nitrites act as electron acceptors, while the organic matter present in wastewater acts as the electron donor (Akunna et al. 1994). For both post-denitrification, as well as pre- denitrification, an additional carbon source is usually provided. When BAFs are used for post-denitrification, additional carbon in the form of methanol, ethanol hydrolyzed sewage sludge, isopropanol and molasses have been used (Aesoy and Hamon, 1997,Cecen and Gonenc, 1995, Zeghal et al. 1995). In pre-denitrification, BAFs are usually fed with recycled nitrified effluent from the carbon oxidation/nitrifying BAF or settled sewage, in order to meet the additional carbon requirements (Mendoza-Espinosa and Stephenson 1999). Denitrification has also been achieved in upflow BAFs by adjusting the placement of the aerators so as to create anoxic zone in the lower part of the reactor and an aerobic zone above it (Rogalla and Bourbigot 1990). When the influent COD/NO_x-N ratio is 5 (Cecen and Gonenc, 1995, Chui et al. 1996) or greater than 6 (Rogalla and Bourbigot, 1990), high denitrification rates of up to 5 kg NO_3-N m^{-3} day^{-1} have been reported.

Phosphorus removal in BAFs is achieved by chemical precipitation (Rogalla et al. 1990,Goncalves et al.1994, Clark at al. 1997). A major portion of the phosphorus is removed by flocculation and settling, while the rest is removed by biological filtration (Rogalla et al. 1990). It has been reported by Clark et al.(1997) that with the use of chemical precipitation, 85% phosphorus removal has been attained on average for different chemical dosing ratios. Pujol et al.(1994) reported a phosphorus removal efficiency of 70% during the testing stage of a tertiary treatment BAF in Germany.

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Chapter 3

Manuscript 1

Title:

Comparison of Biological Aerated Filter (BAF) performance using two granular sunken media under low organic and hydraulic loadings

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Abstract

Biological Aerated Filters (BAFs) are submerged attached growth bioreactors which provide biological treatment as well as filtration in a single unit. The packing media used in BAFs plays an important role in the system performance and determines the ability of the system to meet treatment objectives. The performance of upflow BAFs was compared using North American clay media and Severn Trent monomedia at low organic and hydraulic loads (0.18 kg tCOD/m^{3}d – 0.6 kg tCOD/m^{3}d and 0.1 m/hr – 0.38 m/hr, respectively). Two identical, two stage, bench scale, upflow BAFs were constructed using PVC pipes with an internal diameter of 0.11 m. The system was operated at the Peppers Ferry Wastewater Treatment facility for two months and was fed with effluent from the primary clarifier. Grab samples of influent and effluent from the BAFs were collected thrice a week to evaluate carbon oxidation, solids removal and nitrification. A drying cycle of eleven days was introduced in order to evaluate system recovery. Both media performed satisfactorily with respect to carbon oxidation and nitrification. On average total COD and total suspended solids (TSS) removal rates were, respectively greater than 80% and 55%. Conversion of ammonia to nitrate was greater than 90% throughout the study.

Keywords: Biological Aerated Filters (BAFs), granular media, carbon oxidation, nitrification

Introduction

Suspended as well as attached growth biological systems have been used for wastewater treatment. Biological Aerated Filters (BAFs) is one such attached growth bioreactor, combining biological treatment and filtration in a single unit. BAFs can be used as secondary or tertiary treatment units. It is sometimes referred to as Submerged Aerated Filters. It is essentially a submerged bioreactor in which packing media possessing high surface area is used to maintain biomass growth. Settled wastewater flows either in an upflow or downflow manner through the packing media. Air is supplied by means of diffusers. The high biomass concentration per unit volume makes BAFs a compact and flexible reactor as compared to other wastewater treatment options (Canler and Perret 1994, Pujol et al. 1994). Pollutant removal occurs due to the simultaneous filtration and biological transformation that occurs as wastewater passes through the packing media. Thus, selection of suitable packing media plays a major role in the design, operation and treatment objectives achieved (Moore et al. 2001).

A variety of media having different composition, size, shape and density have been used as packing media in BAFs. Examples of packing media used in pilot scale BAFs includes sunken media like expanded clay, anthracite, vitrified clay, expanded shale, porous stone, slag and granular media as well as floating media like polypropylene and recycled plastic (Mendoza-Espinosa and Stephenson 1999). It is recommended that packing media used in BAFs should be resistant to attrition, chemically stable, possess high surface area and low specific weight (Valentis and Lesavre, 1989, Kent et al. 1996). Carbonaceous BOD, ammonia and nitrate removal rates of up to 4.1 kg BOD/m^{3}d, 1.27 kg NH_3-N/m^{3}d and 5 kg NO_3-N/m^{3}d respectively have normally been reported for BAFs (Mendoza-Espinosa and Stephenson, 1999).

Mann et al. (1995) compared the performance of pilot scale upflow BAFs using sunken and floating media at flow rates ranging from 0.2 L/min to 0.5 L/min. The organic loading ranged from 0.56 – 1.4 kg sCOD/m^{3}d. It was observed that the increase in flowrate caused unsteady state conditions in the reactors. However, with the passage of time, steady state was attainted at all flow rates. Although, at higher flowrates, the reactors took longer to reach steady state. Results from this study indicated that the treatment efficiencies dropped gradually, rather than immediately at each flowrate. It was also reported that hydraulic shock loads had much adverse impact than organic shock loads on the performance of BAFs. The results indicated that floating media performed better at higher flow rates and under shock loads.

Performance of pilot scale downflow BAFs using two particle size ranges (1.5 – 2.5 mm and 3.5 – 4.5 mm) of foamed clay media Starlight C was evaluated by Moore et al. (1999). The larger media had a sunken density of 1650 kg/m^3 compared to 1500 kg/m^3 of the smaller media. The reactors were operated at flowrates ranging from 0.3 L/min – 0.6 L/min and at organic loading from 4.9 to 12.2 kg tCOD/ m^3d. The reactors were reported to achieve steady state solids removal after three days of start-up and the effluent suspended solids was below 20 mg/L on most days. Both sizes of media achieved efficient COD and solids removal but poor nitrification was observed. Farabegoli (2009) evaluated the performance of pilot scale downflow BAF using expanded clay media Filtralite® at hydraulic loading rate of 0.76 m/hr. At average organic and ammonia loading rates of 1.6 ± 0.2 kg sCOD/m^3d and 0.78 ± 0.12 kg NH_4^+-N/d respectively, average effluent concentrations of 68 mg/L tCOD, 37 mg/L TSS, 3.3 mg/L ammonia–nitrogen and 21.1 mg/L nitrate–nitrogen were reported.

All the studies on BAFs, until now, have evaluated the performance of BAFs at high organic and hydraulic loading rates. However, it is necessary to understand the system behavior at lower loading rates as well as system recovery when operated under intermittent loading conditions. The purpose of this research was to compare the performance of upflow BAFs using North American clay media and Severn Trent monomedia at low organic and hydraulic loading. Carbon oxidation, solids removal and nitrification were the parameters used to evaluate the system performance. In this study, to achieve better understanding of the performance of BAFs under intermittent loading conditions, a drying/fasting cycle of 11 days was introduced. System recovery after the drying cycle was also evaluated.

BAF Setup and Operation

The upflow, bench-scale BAF system, as shown in Figures 3.1 and 3.2, consisted of two identical, two-stage reactors built from 4 inch id (0.11 m), polyvinylchloride (PVC) pipes. One set of BAF columns contained the North American clay media (Figure 3.3), while the other set contained the Severn Trent monomedia (Figure 3.4). In order, to achieve the overall media depth of 2.7 m, the columns were staged. The overall depth of each column reactor was 1.8 m, with 0.2 m provided between the bottom of the media and the influent and a freeboard of 0.25 m between the top of the media and effluent port. A medium depth of 1.35 m was provided in each column. Both media particles possessed similar size but the density of the Severn Trent monomedia was almost 1.6 times more than the North American clay media. The properties of the media are summarized in table 3.1.

The columns were joined at mid-height using 4 inch (0.11 m) diameter PVC couplings and provided with a PVC end cap at the bottom. Two additional ports were provided at a height of 0.7 m and 1.1 m from the bottom in each column in order to facilitate air injection during backwashing. About 0.2 m of 5 mm sized aggregate was provided at the bottom of each reactor in order to disperse the influent air and wastewater. Multiple perforations of 0.1 mm diameter, were made along the circumference of a single high temperature resistant thick walled plastic tube of 0.25 inch (0.6 cm) diameter in order to provide coarse air bubbles in each column. A 1.0 hp, piston air compressor (GAST brand, Benton Harbor, Michigan) was used to supply air at 4.7 cfm (0.133 m^3/min) and 20 psi (137.9kPa). In order to prevent backflow of liquid from the columns to the compressor during backwashing or when air supply was halted, the tubes were furnished with check valves. Settled effluent from the primary clarifiers were pumped into the columns using variable speed peristaltic pumps (Cole Parmer, Vernon Hills, Illinois) at the flowrates of 14 mL/min and 50 mL/min during phases I and II, respectively.

As the system was operated as a two stage BAF, effluent from the first column was collected in a 5 gallons (18 liters) bucket and pumped as influent to the second column. A system of 0.25 inch (0.6 cm) diameter PVC tubes was used to transport the influent and effluent from the columns. Backwashing was carried out every 48 hours. Backwashing was performed by draining the columns to remove the particulate matter and excess biomass. During the draining operation, the air supply was turned off. Following the draining cycle, an air scour was carried out for 2–3 minutes. After this, the treated effluent from the holding tank was pumped into the columns in an upflow manner, at a flowrate of 200 mL/min. Operation of the system resumed after backwashing by ensuring that the air compressor was switched on and influent pump flow rates were set at the pre-determined level.

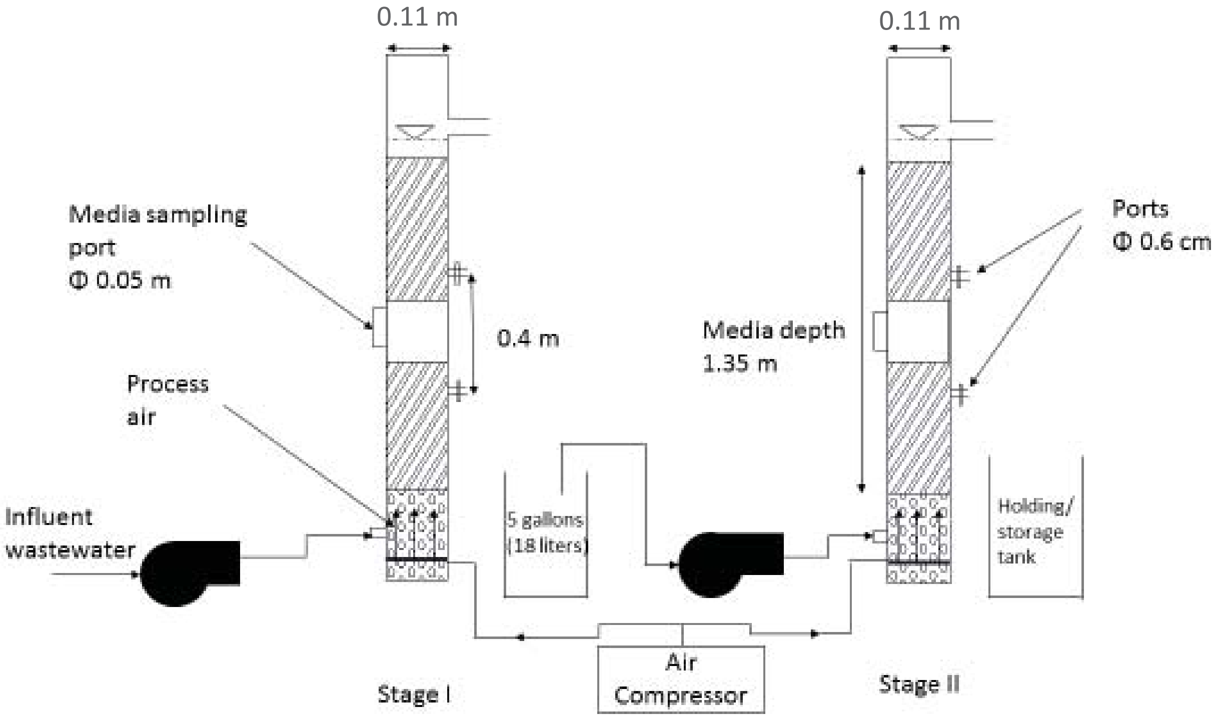


Fig 3.1 Schematic of bench scale set up

Fig 3.2 Photograph of the bench scale set up

The columns were operated in two phases characterized by increasing hydraulic loading from 14 mL /min to 50 mL/min. Initially, the columns containing the clay media were set up in a Virginia Tech laboratory and were fed with settled wastewater obtained from the Christiansburg Wastewater Treatment Plant (Virginia, USA). The wastewater was transported each week in 5 gallon (18 liters) carboys and refrigerated at 4˚C. The wastewater was allowed to reach room temperature before being pumped into the columns. The columns using the Severn Trent monomedia were setup at the Peppers Ferry Wastewater Treatment Plant (PFWTP). Thus, for ease of operation, the columns containing the clay media were also shifted to the PFWTP. The system was operated at the PFWTP for 65 days. During the operation, analytical tests were carried out on influent and effluent from the columns. After 110 and 44 days of operation for clay media and monomedia respectively, a drying/fasting cycle of eleven days was introduced. The purpose behind this was to evaluate the ability of the system to recover after drying, as well as gain insight into operation of BAFs under intermittent loading conditions.

Fig. 3.3 North American Clay Media

Fig. 3.4 Severn Trent Monomedia

Table 3.1 Media Properties

Parameter	Clay Media	Severn Trent Monomedia
Particle size (mm)	4-6	4-6
Porosity	0.44	0.38
Bulk density (g/cc)	0.85	1.58
Particle density (g/cc)	1.53	2.57

Analytical Methods

Grab samples of influent and effluent from the columns were monitored regularly to evaluate system performance. Most of the parameters were evaluated according to Standard Methods for Examination of Water and Wastewater (APHA 2012). The following parameters were monitored to evaluate the performance of the BAF columns (Table 3.2).

Table 3.2. Analytical methods

Parameter	Analytical method	Frequency
Total Suspended and Volatile Suspended Solids (TSS and VSS)	2540 B. Total Solids Dried at 103-105˚C 2540 E. Fixed and Volatile Solids Ignited at 550°C	Thrice a week
Total and Soluble COD (tCOD and sCOD)	Hach Low Range COD kit (3-150 mg/l)	Thrice a week
Total Ammonia Nitrogen (TAN)	Hach High Range Ammonia test and tube kit (0-50 mg/l)	Twice a week
Nitrite and Nitrate – N (NO_2-N and NO_3-N)	4500 NO_2^- C and 4500 NO_3^- C, Ion Chromatography	Twice a week
Total Kjeldahl Nitrogen (TKN)	4500-N_{org} Semi Micro Kjeldahl method	Once a week
Total Phosphorus (TP)	Inductively Coupled Plasma – Mass spectroscopy (ICP-MS)	Thrice during the study

Samples of influent settled sewage, effluent from each stage as well as backwash from each stage were collected in Nalgene sampling bottles (100 mL) and transported by cooler to a Virginia Tech laboratory and analyzed immediately or preserved and stored at 4˚C for later analysis. In addition to the parameters listed in Table 3.2, pH, dissolved oxygen (DO) and temperature were also monitored periodically. DO and temperature were measured using a portable DO meter (Oakton, Vernon hill, Illinois). During the study period, the temperature ranged from 21 ± 3ºC. Measurements of pH were taken with a meter (Oakton, Vernon hill, Illinois).

Statistics

Statistical analysis of data was carried out using the statistical package present in SigmaPlot (Systat Software, San Jose, CA). As comparison between two groups of data was required, a t-test was at first considered. The α value was set at 0.05. However, the raw data for tCOD, TSS, VSS and ammonia failed the normality test (Shapiro – Wilk), and the sCOD data failed the equal variance test (Brown – Forsythe). As a result, the t- test could not be executed. Therefore, the Mann – Whitney rank sum test was conducted. This test compared the median values between the two groups of data, in order to determine whether a significant statistical difference existed between the performances of the two media.

Results and Discussions

Influent Wastewater Characteristics

The influent wastewater characteristics observed during the study are reported in Table 3.3. The characteristics of primary effluent for the three wastewater plants used during this study are reported in Table 3.4. The oxygen demand values from the plants have been reported as BOD_5. Whereas, during this study, oxygen demand was measured as COD values. However, an empirical factor can be used to compare the two. From Tables 3.3 and 3.4, it can be observed that the oxygen demand and ammonia values observed during this study are comparable to the plant data. However, the TSS values obtained during the study appears to be higher than the plant data.

Table 3.3 Influent wastewater characteristics during the study

Parameter	Average	Standard deviation
tCOD (mg/L)	184	79
sCOD (mg/L)	56	10
TSS (mg/L)	142	96
VSS (mg/L)	102	73
Ammonia (mg NH_3-N/L)	23	10

Table 3.4 Influent wastewater characteristics at nearby wastewater treatment plants[1]

Parameter	Roanoke w/w treatment plant	Christiansburg w/w treatment plant	Peppers Ferry w/w treatment plant
Average primary effluent BOD_5 (mg/l)	75	168	71
Average primary effluent TSS (mg/L)	36	89	59
Influent ammonia (mg NH_3-N/L)	na	27	17
Primary effluent TKN (mg NH_3-N/L)	15	na	na

[1] Personal communication with management at the respective plants, August 2015

na – not available

COD Removal

Both total COD (tCOD) and soluble COD (sCOD) were measured thrice a week. Figures 3.5(a, b) and 3.6(a, b), show the COD removal trends in the two sets of BAFs. The influent tCOD and sCOD values respectively ranged from 78 – 340 mg/l and 21 – 78 mg/l throughout the study. The lower ranges of COD values were observed mostly during the initial experimental phase when the BAF columns containing the clay media were being operated in the laboratory. During this phase, settled wastewater was collected on a weekly basis from the Christiansburg Wastewater Treatment Plant (Virginia, USA) and refrigerated at 4˚C, until use. The degradation of the wastewater over the storage time led to lower influent COD. The various phases of operation for both sets of BAFs are shown in Figures 3.5(a, b) and 3.6(a, b). Although, the influent COD values varied, efficient tCOD and sCOD removals were observed, once the system attained steady state.

From Figures 3.5(a, b) and 3.6(a, b), shows the COD removal trends for both the clay as well as the monomedia. Steady state condition was considered to be attained, when effluent values remained fairly constant for four consecutive readings. In order to facilitate transport and set up at the PFWTP, the BAF columns using the clay media were drained and allowed to dry for a day, before the move. This could be the possible reason for the unsteady COD removal rates observed in BAFs using the clay media for the first week at PFWTP. An eleven day drying/fasting cycle was introduced for the clay media from 110 – 121 days and for the monomedia from 44 – 55 days, after start up. After the drying/fasting cycle, both the clay media and the monomedia recovered quickly and steady state COD removal was observed within a week.

The overall tCOD percent removal values of 86±10 % and 81±16 % were observed for clay media and monomedia, respectively. Similar tCOD percent removal values were reported by Moore (1999), when using two different media sizes (1.5 – 2.5 mm and 3.5 – 4.5 mm) of StarlightC® clay media. During steady state operation, the effluent sCOD values averaged 21± 5 mg/l and 18± 8 mg/l for the clay media and the monomedia, respectively. The overall steady state sCOD percent removals for the clay and the monomedia were 68± 15% and 61± 18%, respectively. Overall sCOD percent removal values reported by Moore et al. (1999) for the two different sized clay media were 72±12% and 68± 12%. The first stage effluent tCOD concentrations indicate that on average 71% and 79% of the tCOD removal occurred in the first stages for clay and monomedia, respectively. Thus, the second stage acts as polishing unit to further improve effluent quality. Performing a Mann-Whitney rank sum test on the effluents from the systems indicated that there were no significant differences in the tCOD and sCOD values for the two media ($p = 0.059$ and $p = 0.057$, respectively).

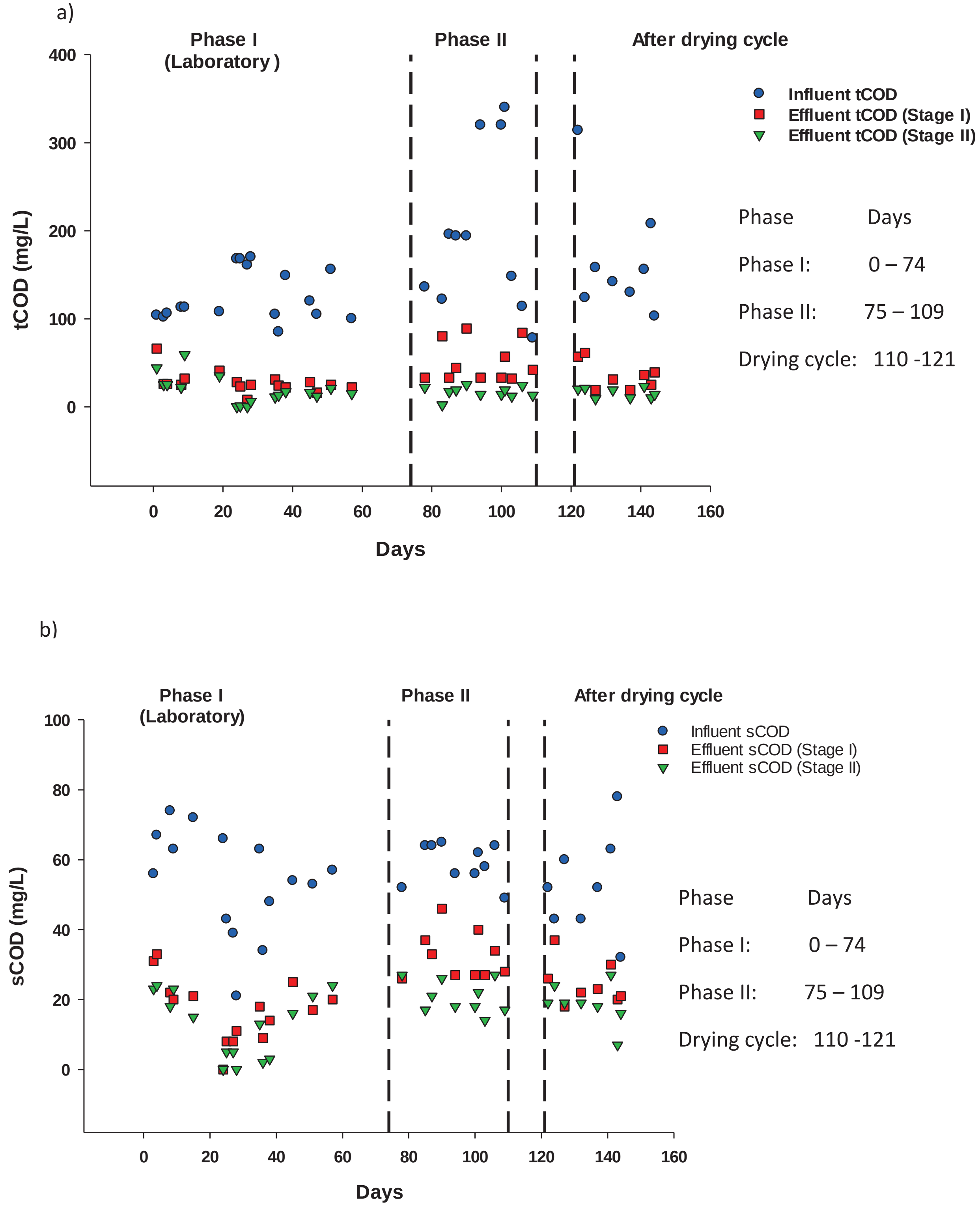


Figure 3.5 a) tCOD and b) sCOD removals in the BAFs using North American clay media

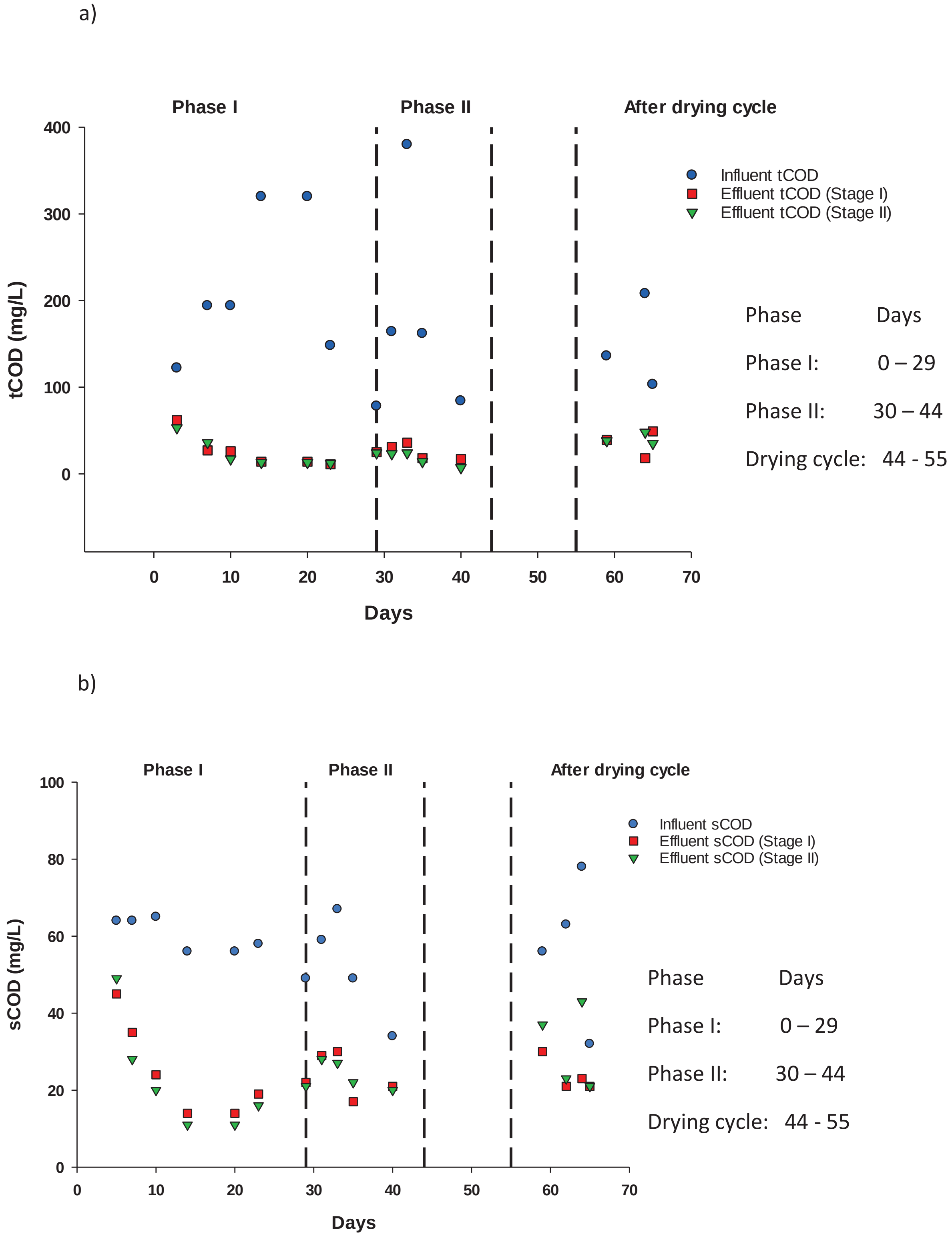


Figure 3.6. a) tCOD and b) sCOD removals in the BAFs using Severn Trent monomedia

Solids Removal

The TSS and VSS removal trends for BAFs using clay media and monomedia are shown in Figures 3.7(a, b) and 3.8 (a, b). The high variability in the effluent TSS and VSS values were observed throughout the study. The influent TSS values varied between 70 – 447 mg/L. Highly variable TSS and VSS values were obtained during Phase I, when the BAFs using the clay media were operated in the laboratory. This was likely due to inefficient mixing of the settled sewage before being pumped to the BAF columns. Many of the solids present in the influent settled out. As a result, grab samples of the influent collected during Phase I for clay media cannot be considered to be representative. Therefore, TSS and VSS values obtained during Phase I for clay media were not used to evaluate the solids removal.

Figure 3.7(a, b) shows that steady state solids removal for clay media was observed during Phase II, after two weeks of operation. From Figure 3.8 (a, b), it can be seen that steady state solids removal for BAF columns using monomedia were attained after three weeks. As the particle size of both media ranged from 4 – 6 mm, the large void spaces present would not have allowed for substantial entrapment of suspended solids. Although physical filtration has been reported to be the major mechanism responsible for suspended solids removal in BAFs (Stensel and Rakness 1988, Ryhiner et al. 1994), it would seem that adsorption of solids onto the biofilm and subsequent biological transformation would play an even more important role in solids removal for larger sized media. The continued poor solids removal observed after the drying cycle for both clay media, as well as the monomedia, further support this hypothesis.

The percent TSS removals of 60 ± 20 % and 57 ± 22 % were observed for clay media and monomedia, respectively. These values are much lower than the percent TSS removals reported by Moore et al.(1999) of 92 ± 7 % and 85 ± 13 % when using two different sizes (1.5 – 2.5 mm and 3.5 – 4.5 mm) of clay media. The average effluent TSS and VSS concentrations for the clay media during Phase II steady state operations were 40 ± 27 mg/L and 17 ± 12 mg/L, respectively. Average TSS and VSS values for steady state operations during Phase I and Phase II for monomedia were 28 ± 9 and 16 ±8 mg/l, respectively. Statistical analysis of the steady state effluent TSS and VSS values using the Mann Whitney rank sum test indicated that there were no significant differences in the TSS and VSS values of the two media (p = 0.71 and 0.928, respectively).

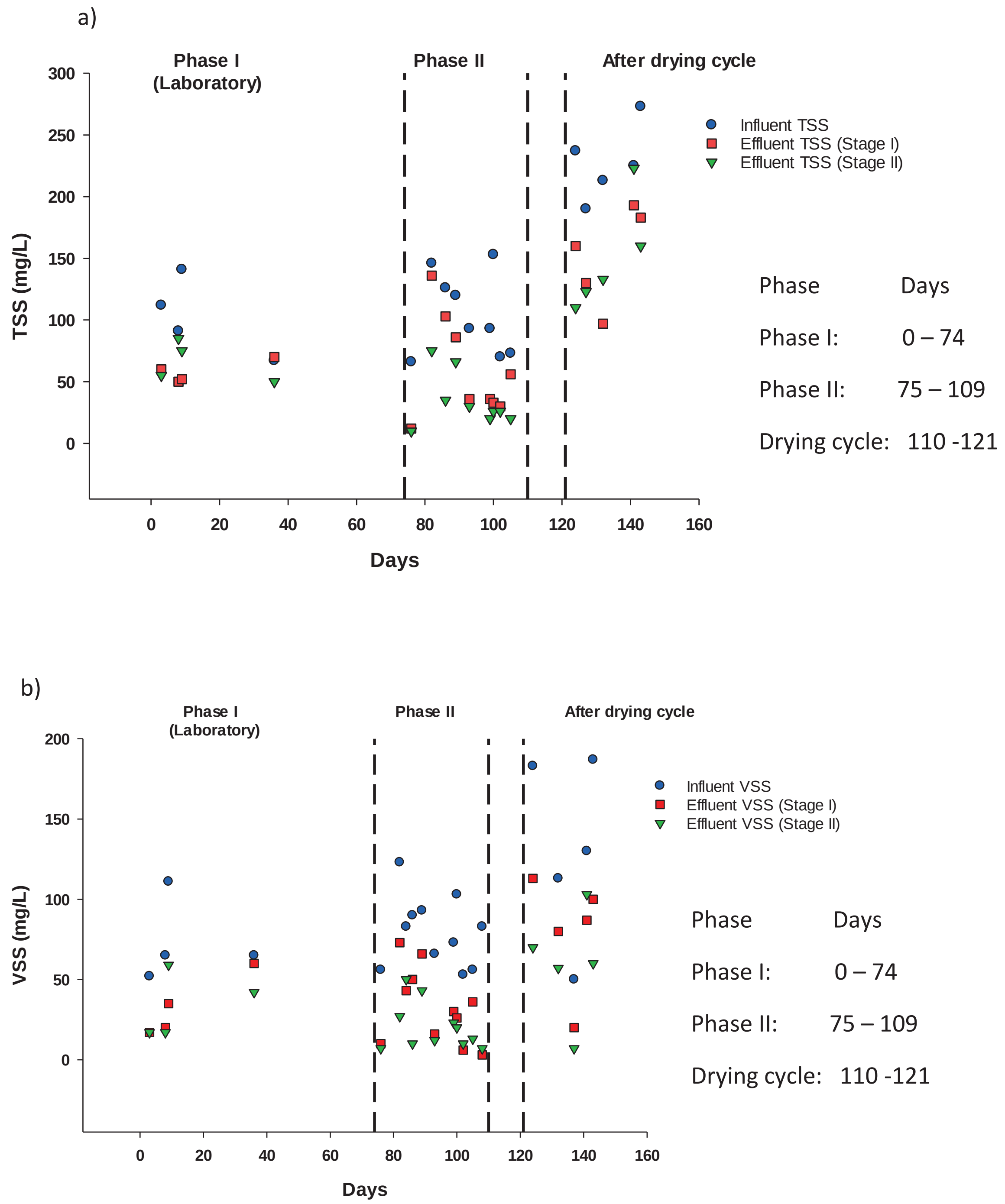


Figure 3.7 a) TSS b) VSS removal in BAFs using North American clay media

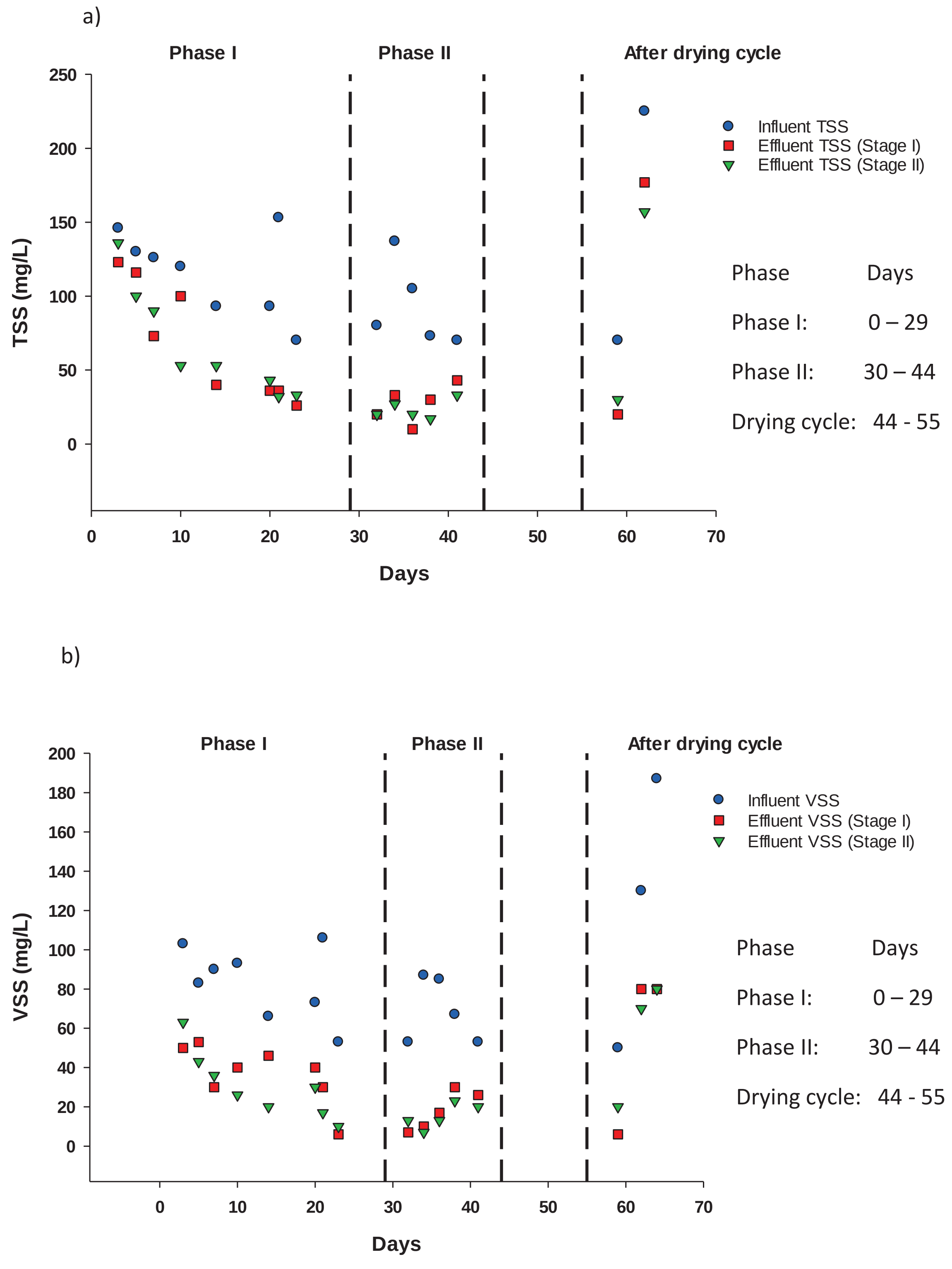


Figure 3.8 a) TSS b) VSS removal in BAFs using Severn Trent monomedia

Ammonia oxidation

BAFs using both the clay media, as well as the monomedia, provided efficient ammonia oxidation throughout the study. Figures 3.9 and 3.10 shows the ammonia oxidation trends for the clay media and the monomedia. The overall percent conversions for ammonia to nitrate were 91 ± 21 % and 92 ± 16 % for the clay and monomedia, respectively. From Figure 3.9, it can be observed that, for the clay media partial nitrification occurred in Stage I while almost complete nitrification occurred in Stage II. While for the monomedia, it can be observed from Figure 3.10 that almost complete nitrification occurred in Stage I itself. The Stage II effluent ammonia concentrations were very close to 0 mg/L with both media. The effluent nitrate concentrations were on an average above 10 mg NO_3-N/L for both media. DO concentrations greater than 6.0 mg O_2/L were measured in the final effluent with both media. In addition to this, low influent carbon loading created favorable condition for nitrification. Efficient nitrification was achieved within a week after the drying cycle with both media. Effluent ammonia concentrations for both media were statistically analyzed using the Mann – Whitney rank sum test and no statistical difference was observed ($p = 0.618$). Thus, it can be concluded that almost complete nitrification can be achieved when operating BAFs at low organic loading rates.

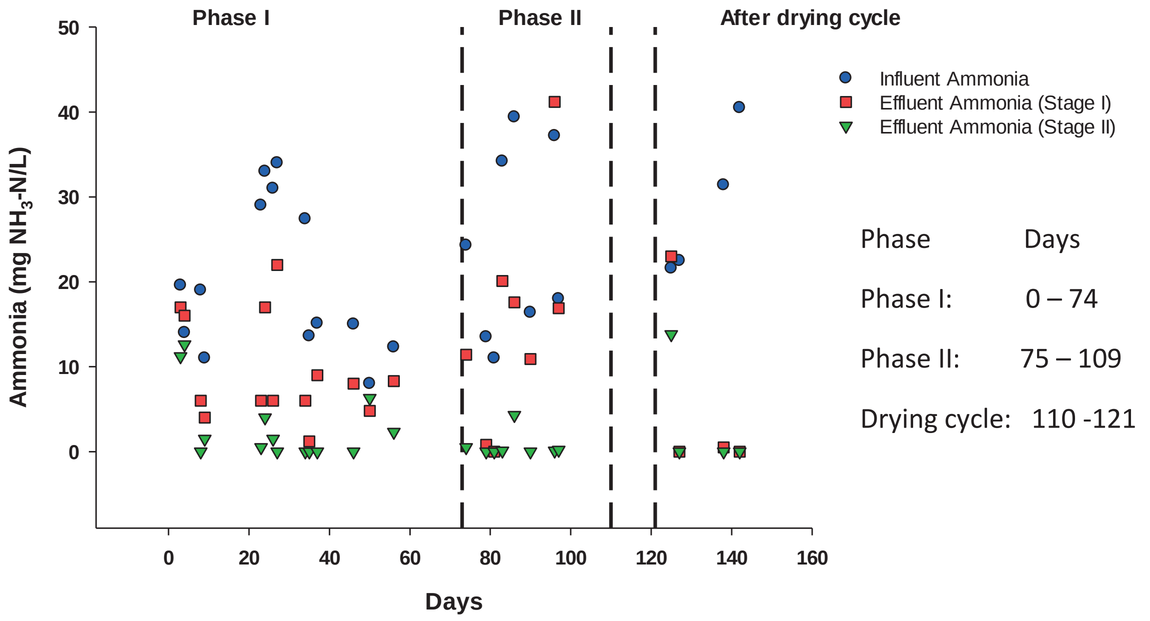


Figure 3.9 Ammonia oxidation in BAFs using the North American clay media

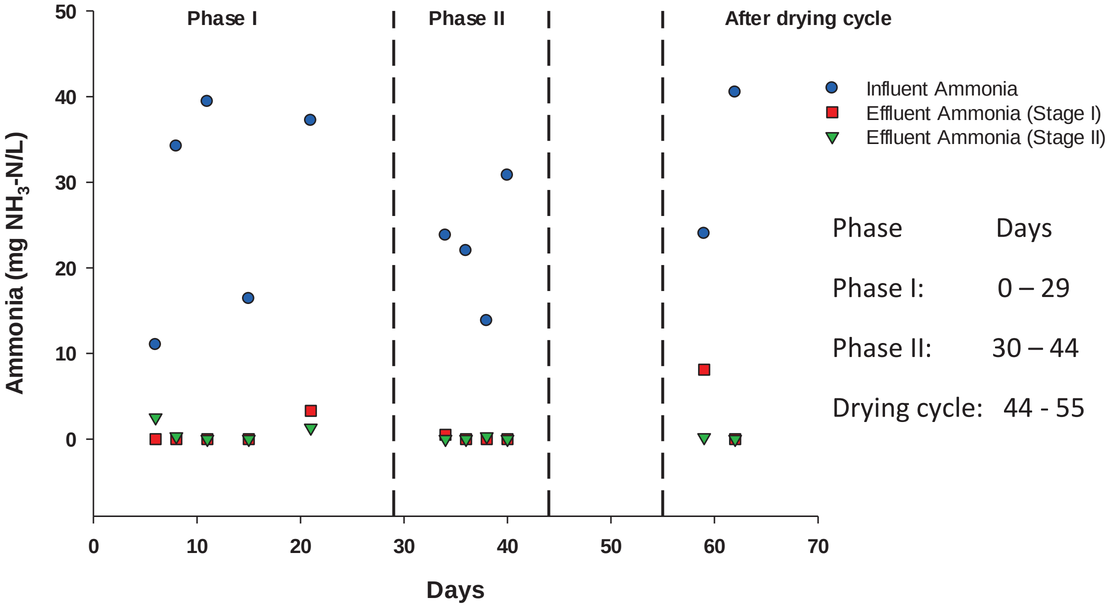


Figure 3.10 Ammonia oxidation in BAFs using Severn Trent monomedia

Phosphorus Removal

Phosphorus concentrations in the influent and effluent were measured thrice during the entire duration of the study using Inductively Coupled Plasma – Mass Spectroscopy (ICP-MS). The results have been tabulated in Table 3.5. No common trend in phosphorus removal was observed. The average influent total phosphorus (TP) at the PFWTP is 3.85 mg P/L (Personal communication with management at PFWTP, July 2015). The average TP value in the primary effluent at the Roanoke wastewater treatment plant is 1.75 mg P/L (Personal communication with management at WVWA, August 2015). These values are comparable to those obtained during the study (Table 3.5). The TP removal observed during the study range from 12 to 70 %.

Table 3.5 Phosphorus measurements

Date	Influent Total Phosphorus (mg P/L)	North American clay media		Severn Trent monomedia	
		Effluent (Stage I) (mg P/L)	Effluent (Stage II) (mg P/L)	Effluent (Stage I) (mg P/L)	Effluent (Stage II) (mg P/L)
5/14/2015	1.78	1.19	1.55	na	na
6/29/2015	2.15	0.68	0.63	1.34	1.32
8/11/2015	1.82	2.58	2.9	1.8	2.74

na – not available

Biomass growth

In Figure 3.11, the biomass growth on both the clay media and monomedia can be observed. The media samples were collected from the media sampling ports, located at mid height of each column. Biomass concentrations appeared to be greater in Stage I than in Stage II for both the media. As the organic content of the wastewater was higher in Stage I, more food was available for the microbes during the first stage of treatment. Stage II received the effluent from Stage I, which had on an average 45% lower sCOD content compared to Stage I influent.

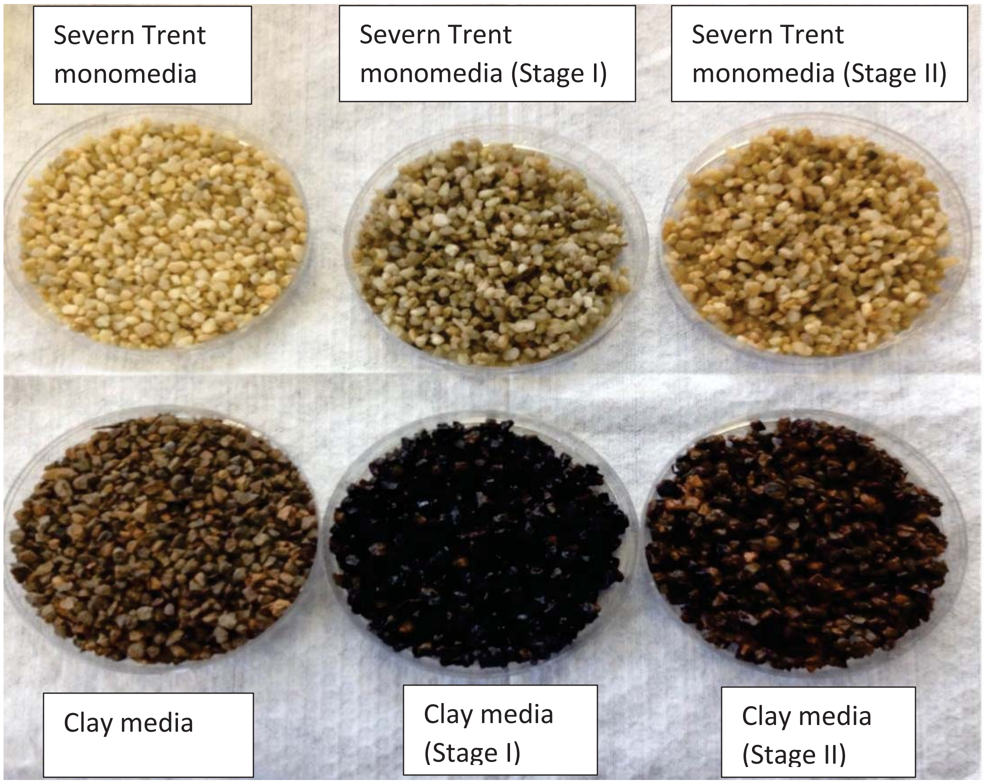


Figure 3.11 Biomass growth on BAF media observed after one month of operation at the PFWTP

Backwash test and results

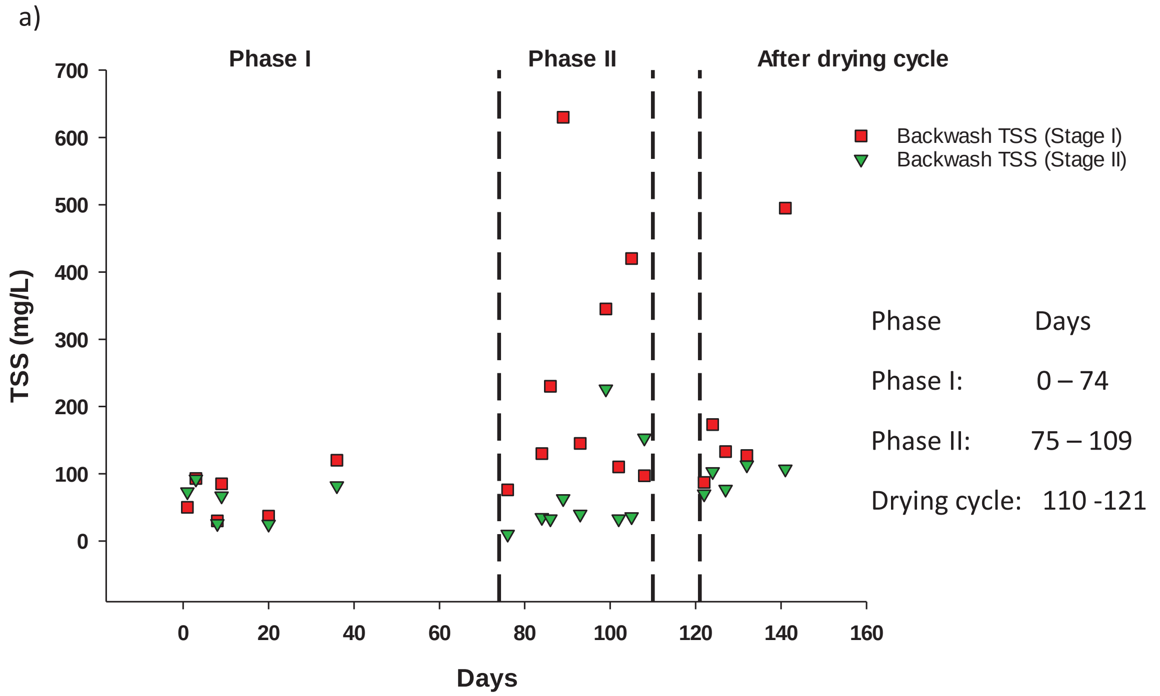
Backwashing was carried out every 48 hours, and Figures 3.12 (a, b) and 3.13 (a, b) shows solids present in backwash for both the clay and the monomedia, respectively. From Figures 3.12 (a, b) and 3.13 (a, b), it can be observed that the solids present in the backwash from Stage I, was higher than that present in Stage II for both the clay and the monomedia. This indicates that most of the solids were captured in Stage I.

In order, to compare the suspended solids removal efficiencies a mass balance of the solids was conducted for the clay and the monomedia. The suspended solids in the effluent and the backwash streams were used for performing the mass balance. The average mass of solids, generated by the two media during the different phases of operation are shown in Table 3.6. From Table 3.6, it can be observed that the clay media produced greater mass of solids per day than the monomedia during all three phases. During the study, it was observed that the clay media could be easily pulverized as compared to the monomedia. The greater solids generated with the clay media could be due to pulverization. During Phase I, the clay media produced on an average 28% more solids per day as compared to the monomedia. While during Phase II, this value rose to 67 %. However, high standard deviation of the data for the clay media was observed during Phase II.

Table 3.6 Average mass of solids generated daily

	North American clay media (g/d) (N)	Severn Trent monomedia (g/d) (N)
Phase I	3.5 ± 2 (2)	2.5 ± 1.7 (5)
Phase II	21.7 ± 16 (11)	7 ± 2 (5)
After dry cycle	23.5 ± 5 (4)	22.8*

*Only one data point



b)

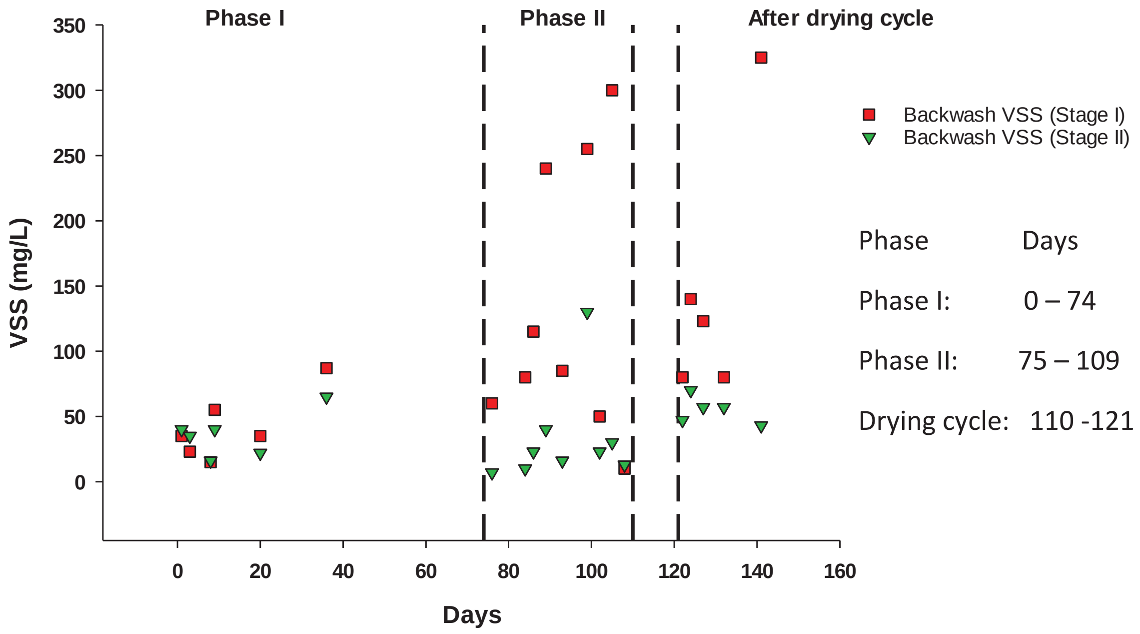
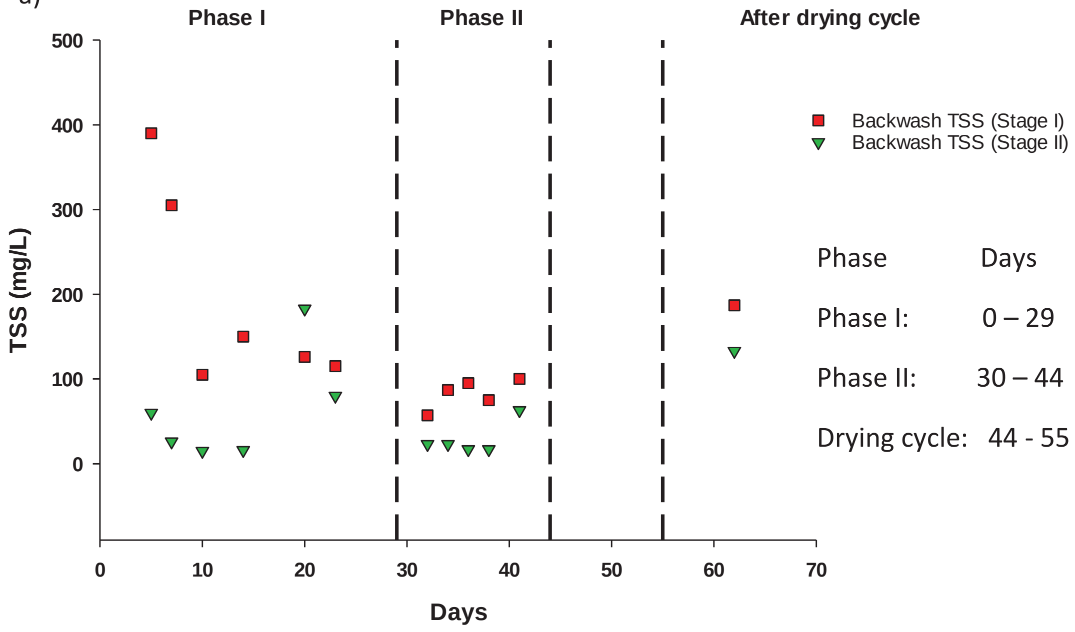


Figure 3.12 a) TSS and b) VSS in backwash for BAFs using North American clay media

a)



b)

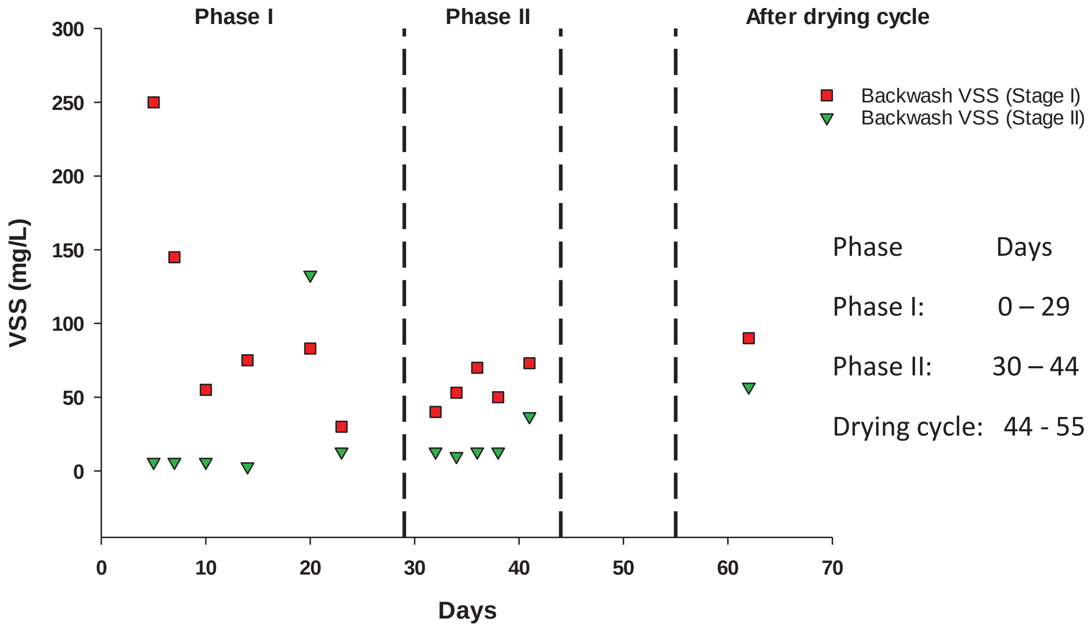


Figure 3.13 a) TSS and b) VSS in backwash for BAFs using Severn Trent monomedia

Comparison of BAF performance before and after drying cycle

In order to understand the effect of the drying cycle on BAF performance, the average tCOD/TSS and tCOD/VSS ratios were determined for waters associated with each media (Table 3.7). The COD mass equivalents for biomass are 1.42 g COD/g VSS and 1.2 g COD/g TSS (Grady et al. 2011). Both tCOD/TSS and tCOD/VSS ratios were much smaller (<1, in most cases) after the drying cycle. The tCOD values of effluent samples for both media showed little variation before and after the drying cycle. The decrease in the tCOD/TSS and tCOD/VSS ratios were due to increased suspended solids observed after the drying cycle. The efficient COD removal in contrast to the poor solids removal observed after the drying cycle could be explained as follows. The conditions maintained in the system during the drying/fasting cycle led to loss/death of most of the biofilm supported by the packing media. As a result, when the system was restarted after the drying cycle, the shear force caused by the flow of wastewater through the packing media caused this biofilm to detach and slough out along with the effluent. This is supported by the high VSS values observed after restarting the system. As the VSS content of the clay media and the monomedia are on average, 0.47 % and 1.05% respectively, the increase in the VSS was contributed by the biofilm that sloughed out. However, a thin layer of active biomass would have remained on the packing media and would have developed further within a week of restarting the operation. The efficient COD removal observed within a week after the drying cycle would be due to biological transformation occurring at active sites of the biofilm. However, a longer time period would be required for the growth of thicker biofilm, which would be necessary to decrease the void spaces in the packing media. This would enhance the removal of solids caused by interception and sedimentation. As the time period after the drying cycle was not sufficient for the growth of this thicker biofilm, poor solids removal was observed after the drying cycle. This is further supported by the longer duration needed to observe steady state solids removal during Phases I and II.

Table 3.7 Comparison of COD and suspended solids before and after drying

Media	Phases	tCOD/TSS			tCOD/VSS		
		Influent	Stage I	Stage II	Influent	Stage I	Stage II
North American clay media	Before drying	1.54	0.89	0.59	2.14	1.68	1.19
	After drying	0.75	0.36	0.20	1.13	0.50	0.39
Severn Trent monomedia	Before drying	1.99	0.73	0.59	2.68	1.25	1.19
	After drying	0.91	0.60	0.42	1.33	1.82	0.69

Impact of media density

Porosity , bulk density and particle density were calculated according to the procedure described in Laboratory manual for soil sciences (Thein and Graveel, 2003). These values are shown in Table 3.1. From Table 3.1, it can be observed that the average particle density for the clay media is 1.53 g/cc while that for the monomedia is 2.57 g/cc. The size and density of the packing media used plays an important role in determining the flowrates required for backwashing. In BAFs, periodic backwashing needs to be carried out. Backwashing in upflow BAFs, is usually carried out by fluidizing the packing media, to scour excess biomass and trapped solids. This is followed by an air scour. Because the density of the monomedia is on average 1.6 times that of the clay media, much higher water flowrates would be required to fluidized it as compared to the clay media. The theoretical minimum fluidization velocities were calculated for the two media using the Carmen – Kozeny equation (considering a particle size of 4 mm for both media). The minimum fluidization velocity required by the clay media was 86 m/hr, while for the monomedia, it was determined to be 195 m/hr. The monomedia would therefore require much higher energy during backwashing.

Conclusion

The results showed that both the North American clay media and the Severn Trent monomedia performed satisfactorily as packing media for BAFs at low organic loading rates (0.18kg tCOD/m^{3}d – 0.6 kg tCOD/m^{3}d). However, additional factors like media properties and economic factors need to be considered in selection of the media. The conclusions from this study are:

1. On average, tCOD, TSS and ammonia removals were, respectively, greater than 80%, 55% and 90% for both media.
2. The average solids produced daily by the clay media were greater than the amount produced by the monomedia. It was apparent that the clay media was at times being pulverized and lost during backwashing.
3. The monomedia was about 1.6 times denser than the clay media. As a result, the monomedia would require higher water flowrates for backwashing, leading to an increase in energy costs. The theoretical minimum fluidization velocities calculated for the clay and the monomedia were 86 m/hr and 165 m/hr, respectively. However, it is recommended that the minimum fluidization velocity be determined experimentally before making any decision.
4. Both media recovered to steady state conditions (carbon oxidation and nitrification) within the first week, after the drying cycle. However, the time needed to recover to steady state may vary, depending on the hydraulic and organic loading rates used.

Chapter 4

Conclusions and Recommendations

This study was designed to compare the performance of upflow BAFs using two granular sunken media, North American clay media and Severn Trent monomedia, at low organic loading rates of 0.18 kg tCOD/m^3-d – 0.6 kg tCOD/m^3-d, as well as to evaluate system recovery after drying/fasting conditions. The results obtained during the study indicated that both media could attain efficient carbon oxidation and complete nitrification when operated at low organic loads. For both media, it was observed that a longer duration of time was required to attain steady state solids removal as compared to carbon oxidation and nitrification.

On average, tCOD, TSS and ammonia removals were, respectively, greater than 80%, 55% and 90% for both media. However, in design, consideration should also be given to the characteristics of media, like density and resistance to attrition, as these would affect the operation of BAFs. The density of monomedia is on average 1.6 times greater than that of the clay media. This would imply that the monomedia would require higher flow rates during backwashing, leading to higher energy consumption. The theoretical minimum fluidization velocity calculated for the monomedia and the clay media are 165 m/hr and 86 m/hr, respectively. The higher daily solids production with the clay media suggests that it can be easily pulverized and washed out of the system. During the study, it was apparent that the clay media would occasionally wash out along with the effluent. It is recommended that a careful cost benefit analysis be carried out before selecting the media.

Both media reached steady state carbon oxidation and nitrification within a week after the drying cycle. Poor solids removal was observed after the drying cycle for both media. Therefore, it is recommended that the media should be wetted occasionally during the drying cycle to enable faster system recovery. However, the time needed to recover to steady state may vary, depending on the hydraulic and organic loading rates used.

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Appendix A

Ammonia and nitrates data

Table A.1 Ammonia and nitrates for clay media

Clay media					
INFLUENT AMMONIA	DAYS	EFFLUENT AMMONIA (I)	EFFLUENT NITRATE (I)	EFFLUENT AMMONIA (II)	EFFLUENT NITRATE (II)
29	23	6	11.7	0.5	19.5
24.3	74	11.4	4	0.5	7.3
13.5	79	3.8	18.8	0	28.3
11	81	0	31.97	0	25.36
34.2	83	20.1	0.96	0	17.45
39.4	87	17	0	4.3	13.6
16.4	91	10.9	2.3	0	14.5
18	98	16.9	0.05	0.2	17.6
23.8	102				
22	104				
30.8	108				
22.5	125	0	22.4	0	26.5
20.5	141	0.1	18.4	0.1	19.9
15	142	0	0.7	0	7.7

Table A.2 Ammonia and nitrates data for Severn Trent monomedia

Severn Trent monomedia					
INFLUENT AMMONIA	DAYS	EFFLUENT AMMONIA (I)	EFFLUENT NITRATE (I)	EFFLUENT AMMONIA (II)	EFFLUENT NITRATE (II)
13.5	4	24.2	0.97	14.08	0.06
11	6	0	0.38	2.5	0.48
34.2	8	0	6.2	0.3	3.62
39.4	11	0	21	0	20.8
16.4	15	0	21.4	0	22.6
18	22	27.9	0	10	8.1
23.8	35	0.5	16.5	0	17.4
22	37	0	14.3	0	17.5
30.8	41	0	18.5	0	18.8
22.5	51				
20.5	64	0	19.2	0.7	20
15	65	6	2.6	0.3	14.17

Table A.3 Ammonia for both media

AMMONIA expressed as mg NH3-N/l						
SR.NO	DATE	INFLUENT	Clay Stage I	Clay Stage II	Monomedia Stage I	Monomedia Stage II
1	20-Mar	19.6	17	11.2		
2	21-Mar	14	16	12.6		
3	25-Mar	19	6	0		
4	26-Mar	11	4	1.5		
5	9-Apr	29	6	0.5		
6	10-Apr	33	17	4		
7	13-Apr	31	6	1.5		
8	14-Apr	34	22	0		
9	22-Apr	27.4	6	0		
10	23-Apr	13.6	1.2	0		
11	25-Apr	15.1	9	0		
12	3-May	15	8	0		
13	7-May	8	4.8	6.3		
14	13-May	12.3	8.3	2.3		
15	4-Jun	24.3	11.4	0.5		
16	9-Jun	13.5	3.8	0	24.2	14.8
17	11-Jun	11	0	0	0	2.5
18	13-Jun	34.2	20.1	0.1	0	0.3
19	16-Jun	39.4	17.6	4.3	0	0
20	20-Jun	16.4	10.9	0	0	0
21	25-Jun	20.2	18.2	13.9	18.1	15.5
22	26-Jun	37.2	41.2	0.1	3.3	1.3
23	27-Jun	18	16.9	0.2	27.9	10
24	29-Jun	23.6				
25	9-Jul	23.8			0.5	0
26	11-Jul	22			0	0
27	13-Jul	13.8			0	0.3
28	15-Jul	30.8			0	0
29	22-Jul	21.6	23	13.8		
30	25-Jul	22.5	0	0		
31	4-Aug	31.4	0.5	0		
32	5-Aug	24			8.1	0.2
33	8-Aug	40.5	0	0	0	0

Appendix B

COD data

Table B.1 tCOD for Severn Trent monomedia

Severn Trent Monomedia	tCOD (mg/l)					
	DAY	INFLUENT	EFFLUENT (I)	EFFLUENT (II)	PERCENT REMOVAL (I)	PERCENT REMOVAL (II)
Phase I	3	122	62	53	49.18032787	56.55737705
	5	196	47	120	76.02040816	38.7755102
	7	194	27	36	86.08247423	81.44329897
	10	194	26	17	86.59793814	91.2371134
	14	320	14	13	95.625	95.9375
	20	320	14	13	95.625	95.9375
	21	340	153	26	55	92.35294118
	23	148	11	12	92.56756757	91.89189189
	29	78	25	24	67.94871795	69.23076923
Phase II	31	164	31	23	81.09756098	85.97560976
	33	380	36	24	90.52631579	93.68421053
	35	162	18	14	88.88888889	91.35802469
	40	84	17	7	79.76190476	91.66666667
After drying phase	59	136	39	38	71.32352941	72.05882353
	62	156	18	8	88.46153846	94.87179487
	64	208	18	48	91.34615385	76.92307692
	65	103	49	35	52.42718447	66.01941748

Table B.2 sCOD for Severn Trent monomedia

Severn Trent Monomedia	sCOD (mg/l)					
	DAY	INFLUENT	EFFLUENT (I)	EFFLUENT (II)	PERCENT REMOVAL (I)	PERCENT REMOVAL (II)
Phase I	3	44	54	36		18.18181818
	5	64	45	49	29.6875	23.4375
	7	64	35	28	45.3125	56.25
	10	65	24	20	63.07692308	69.23076923
	14	56	14	11	75	80.35714286
	20	56	14	11	75	80.35714286
	21	62	113	31		50
	23	58	19	16	67.24137931	72.4137931
	29	49	22	21	55.10204082	57.14285714
Phase II	31	59	29	28	50.84745763	52.54237288
	33	67	30	27	55.2238806	59.70149254
	35	49	17	22	65.30612245	55.10204082
	40	34	21	20	38.23529412	41.17647059
After drying phase	59	56	30	37	46.42857143	33.92857143
	62	63	21	23	66.66666667	63.49206349
	64	78	23	43	70.51282051	44.87179487
	65	32	21	21	34.375	34.375

Table B.3 tCOD for Clay media

Clay media		tCOD (mg/l)				
	DAY	INFLUENT	EFFLUENT (I)	EFFLUENT (II)	PERCENT REMOVAL (I)	PERCENT REMOVAL (II)
Laboratory phase	1	104	66	44	36.53846154	57.69230769
	3	102	26	25	74.50980392	75.49019608
	4	106	26	25	75.47169811	76.41509434
	8	113	25	22	77.87610619	80.53097345
	9	113	32	59	71.68141593	47.78761062
	19	108	41	35	62.03703704	67.59259259
	24	168	28	0	83.33333333	100
	25	168	23	1	86.30952381	99.4047619
	27	161	8	0	95.0310559	100
	28	170	25	6	85.29411765	96.47058824
	35	105	31	11	70.47619048	89.52380952
	36	85	24	13	71.76470588	84.70588235
	38	149	22	17	85.23489933	88.59060403
	45	120	28	16	76.66666667	86.66666667
	47	105	16	12	84.76190476	88.57142857
	51	156	25	21	83.97435897	86.53846154
	57	100	22	15	78	85
At Peppers Ferry W/W plant	78	136	33	22	75.73529412	83.82352941
	83	122	80	2	34.42622951	98.36065574
	85	196	33	17	83.16326531	91.32653061
	87	194	44	19	77.31958763	90.20618557

	90	194	89	25	54.12371134	87.11340206
	94	320	33	14	89.6875	95.625
	100	320	33	14	89.6875	95.625
	101	340	57	19	83.23529412	94.41176471
	103	148	32	12	78.37837838	91.89189189
	106	114	84	24	26.31578947	78.94736842
	109	78	42	13	46.15384615	83.33333333
After drying cycle	122	314	57	20	81.84713376	93.63057325
	124	124	61	21	50.80645161	83.06451613
	127	158	19	9	87.97468354	94.30379747
	132	142	31	19	78.16901408	86.61971831
	137	130	19	10	85.38461538	92.30769231
	141	156	36	23	76.92307692	85.25641026
	143	208	25	10	87.98076923	95.19230769
	144	103	39	14	62.13592233	86.40776699

Table B.4 sCOD for Clay media

Clay media		sCOD (mg/l)				
	DAY	INFLUENT	EFFLUENT (I)	EFFLUENT (II)	PERCENT REMOVAL (I)	PERCENT REMOVAL (II)
Laboratory phase	1	58	59	37	-1.724137931	36.20689655
	3	56	31	23	44.64285714	58.92857143
	4	67	33	24	50.74626866	64.17910448
	8	74	22	18	70.27027027	75.67567568
	9	63	20	23	68.25396825	63.49206349
	15	72	21	15	70.83333333	79.16666667
	24	66	0	0	100	100
	25	43	8	5	81.39534884	88.37209302
	27	39	8	5	79.48717949	87.17948718
	28	21	11	0	47.61904762	100
	35	63	18	13	71.42857143	79.36507937
	36	34	9	2	73.52941176	94.11764706
	38	48	14	3	70.83333333	93.75
	45	54	25	16	53.7037037	70.37037037
	51	53	17	21	67.9245283	60.37735849
	57	57	20	24	64.9122807	57.89473684
	78	52	26	27	50	48.07692308
	83	44	59	26	-34.09090909	40.90909091
At Peppers Ferry W/W plant	85	64	37	17	42.1875	73.4375
	87	64	33	21	48.4375	67.1875
	90	65	46	26	29.23076923	60
	94	56	27	18	51.78571429	67.85714286
	100	56	27	18	51.78571429	67.85714286
	101	62	40	22	35.48387097	64.51612903
	103	58	27	14	53.44827586	75.86206897
	106	64	34	27	46.875	57.8125
	109	49	28	17	42.85714286	65.30612245
	122	52	26	19	50	63.46153846
	124	43	37	24	13.95348837	44.18604651
After drying cycle	127	60	18	19	70	68.33333333
	132	43	22	19	48.8372093	55.81395349
	137	52	23	18	55.76923077	65.38461538
	141	63	30	27	52.38095238	57.14285714
	143	78	20	7	74.35897436	91.02564103
	144	32	21	16	34.375	50

Appendix C

Solids data

Table C.1 TSS and VSS for Clay media

TSS and VSS expressed in mg/l							
Sr.no	Date	Description	INFLUENT	Clay Stage I	Clay Stage II	Clay Backwash (I)	Clay backwash (II)
1	17-Mar	TSS	150	110	120	50	73
		VSS	72	50	36	35	40
2	20-Mar	TSS	112	60	55	93	92
		VSS	52	17	17	23	35
3	25-Mar	TSS	91	50	35	30	26
		VSS	65	20	17	15	16
4	26-Mar	TSS	141	52	75	85	67
		VSS	111	35	59	55	40
5	31-Mar	TSS	550	85	92	85	130
		VSS	445	77	64	50	85
6	9-Apr	TSS	223	45	37	37	25
		VSS	200	42	27	35	22
7	15-Apr	TSS	560	47	34	55	40
		VSS	540	27	28	45	27
8	25-Apr	TSS	67	70	50	120	82
		VSS	65	60	42	87	65
9	3-May	TSS	87	52	196		
		VSS	77	37	140		
10	4-Jun	TSS	66	12	10	76	10
		VSS	56	10	7	60	7
11	9-Jun	TSS	146	136	75		
		VSS	103	73	27		
12	11-Jun	TSS	130	93	110	130	35
		VSS	83	43	50	80	10
13	13-Jun	TSS	126	103	35	230	33
		VSS	90	50	10	115	23
14	16-Jun	TSS	120	86	66	630	63
		VSS	93	66	43	240	40
15	20-Jun	TSS	93	36	30	145	40
		VSS	66	16	12	85	16
16	25-Jun	TSS	355	36	22		
		VSS	150	23	15		
17		TSS	93	36	20	345	226

	26-Jun	VSS	73	30	22.5	255	130
18	27-Jun	TSS	153	33	26		
		VSS	106	26	20		
19	29-Jun	TSS	70	30	26	110	33
		VSS	53	6	10	50	23
20	3-Jul	TSS	73	56	20	420	36
		VSS	56	36	13	300	30
21	6-Jul	TSS	200	97	97	97	153
		VSS	83	3	7	10	13
22	9-Jul	TSS	80				
		VSS	53				
23	11-Jul	TSS	137				
		VSS	87				
24	13-Jul	TSS	105				
		VSS	85				
25	15-Jul	TSS	73				
		VSS	67				
26	18-Jul	TSS	70				
		VSS	53				
27	20-Jul	TSS	450	73	60	87	80
		VSS	410	60	47	70	47
28	22-Jul	TSS	237	160	110	173	103
		VSS	183	113	70	140	70
29	25-Jul	TSS	190	133	123	133	77
		VSS	13	87	80	123	57
30	30-Jul	TSS	213	97	133	127	113
		VSS	113	80	57	80	57
31	4-Aug	TSS	83	27	16		
		VSS	50	20	7		
32	5-Aug	TSS	70				
		VSS	50				
33	8-Aug	TSS	225	193	223	495	107
		VSS	130	87	103	325	43
34	10-Aug	TSS	273	183	160		
		VSS	187	100	60		
35	11-Aug	TSS	447	210	153		
		VSS	353	140	100		

Table C.2 TSS and VSS for Severn Trent monomedia

TSS and VSS expressed in mg/l						
Date	Description	INFLUENT	Monomedia (I)	Momomedia (II)	Monomedia backwash (I)	Monomedia backwash (II)
9-Jun	TSS	146	123	136		
	VSS	103	50	63		
11-Jun	TSS	130	116	100	390	60
	VSS	83	53	43	250	6
13-Jun	TSS	126	73	90	305	26
	VSS	90	30	36	145	6
16-Jun	TSS	120	100	53	105	16
	VSS	93	40	26	55	6
20-Jun	TSS	93	46	53	150	16
	VSS	66	16	20	75	3
25-Jun	TSS	355	36	96		
	VSS	150	26	26		
26-Jun	TSS	93	36	43	126	183
	VSS	73	40	30	83	133
27-Jun	TSS	153	36	32		
	VSS	106	30	17		
29-Jun	TSS	70	26	33	115	30
	VSS	53	6	10	80	13
3-Jul	TSS	73				
	VSS	56				
6-Jul	TSS	200				
	VSS	83				
9-Jul	TSS	80	20	20	57	23
	VSS	53	7	13	40	13
11-Jul	TSS	137	33	27	87	23
	VSS	87	10	7	53	10
13-Jul	TSS	105	10	20	95	17
	VSS	85	17	13	70	13
15-Jul	TSS	73	30	17	75	17
	VSS	67	30	23	50	13
18-Jul	TSS	70	43	33	73	37
	VSS	53	26	20	100	63
20-Jul	TSS	450				
	VSS	410				
	TSS	237				

22-Jul	VSS	183				
25-Jul	TSS	190				
	VSS	13				
30-Jul	TSS	213				
	VSS	113				
4-Aug	TSS	83				
	VSS	50				
5-Aug	TSS	70	20	30		
	VSS	50	6	20		
8-Aug	TSS	225	177	157	187	133
	VSS	130	80	70	90	57
10-Aug	TSS	273	163	183		
	VSS	187	80	80		
11-Aug	TSS	447	207	307		
	VSS	353	157	217		

Appendix D

Statistical analysis

Statistical test results for tCOD

t-test

Normality Test (Shapiro-Wilk): Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Col 2	18	1	24.000	13.000	37.000
Col 1	37	1	16.500	11.250	22.000

Mann-Whitney U Statistic= 206.500

T = 558.500 n(small)= 17 n(big)= 36 (P = 0.059)

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.059)

Statistical test results for sCOD

t-test

Normality Test (Shapiro-Wilk): Passed (P = 0.098)

Equal Variance Test (Brown-Forsythe): Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Col 1	30	1	19.000	17.000	24.000
Col 2	18	1	23.000	20.000	33.500

Mann-Whitney U Statistic= 162.500

T = 483.500 n(small)= 17 n(big)= 29 (P = 0.057)

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.057)

Statistical test results for TSS
t-test

Normality Test (Shapiro-Wilk): Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Col 1	26	1	66.000	28.000	115.000
Col 2	18	1	43.000	28.500	118.000

Mann-Whitney U Statistic= 197.500

T = 350.500 n(small)= 17 n(big)= 25 (P = 0.710)

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.710)

Statistical test result for VSS
t-test
Normality Test (Shapiro-Wilk): Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test

Group	**N**	**Missing**	**Median**	**25%**	**75%**
Col 1	26	1	27.000	12.500	58.000
Col 2	18	1	23.000	15.000	53.000

Mann-Whitney U Statistic= 208.500

T = 361.500 n(small)= 17 n(big)= 25 (P = 0.928)

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.928)

Statistical test results for Ammonia
t-test

Normality Test (Shapiro-Wilk): Failed (P < 0.050)

Test execution ended by user request, Rank Sum Test begun

Mann-Whitney Rank Sum Test

Group	N	Missing	Median	25%	75%
Col 1	27	1	0.1000	0.000	2.725
Col 2	13	1	0.1000	0.000	1.050

Mann-Whitney U Statistic= 140.500

T = 218.500 n(small)= 12 n(big)= 26 (P = 0.618)

The difference in the median values between the two groups is not great enough to exclude the possibility that the difference is due to random sampling variability; there is not a statistically significant difference (P = 0.618)