Innovative Onsite Wastewater Treatment Systems for Nitrogen Removal: A Recirculating Gravel Filter with a Preanoxic Zone and a Recirculating Gravel Filter with a Postanoxic Woodchip Bed

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Abstract

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Nitrate released from septic system effluents can percolate through the soil, potentially contaminating ground water and exacerbating surface water eutrophication. Alternatives to conventional septic-drainfield systems can remove nitrogen from this waste-stream, thereby protecting water quality. This study compares the nitrogen removal efficiency of two onsite treatment systems designed to maximize nitrogen removal via sequential nitrification-denitrification. The key requirements for denitrification (including oxic conditions for nitrification and anoxic conditions for denitrification and bioavailable carbon), were provided in both systems, however several key design features differed. The first system was a vegetated recirculating gravel filter (Vegetated RGF) and was designed as a single step system, incorporating nitrification and denitrification conditions in tandem and utilizing the septic tank effluent as the carbon source. The second system separated the nitrification and denitrification steps, using an RGF for nitrification and a vegetated woodchip bed for denitrification. Both systems were fed residential wastewater influent for one year. The two-stage Woodchip bed system provided far greater nitrogen and fecal coliform removal than the single-stage system, however, the two stage system was highly sensitive to temperature and removed less nitrogen during cold months. The Vegetated RGF average effluent total nitrogen (TN) was 15.1 ± 1.9

mg/L, which equates to an average of 69% TN removal. The Woodchip bed system produced an average effluent of 1.7 ± 1.0 and 6.4 ± 4.2 mg-TN/L, during warm and cold months, respectively, resulting in an average TN removal of 92%. BOD, TSS and TP removal were similar in both systems. The Woodchip bed system exhibited exemplary nitrogen and fecal coliform removal and therefore has the potential to vastly improve residential wastewater treatment.

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INTRODUCTION

Nitrate is a very soluble and mobile form of nitrogen that is a pollutant of concern. Septic system effluents are common source of nitrate pollution, which can percolate through the soil and contaminate drinking water wells and surface waters. Septic system effluents often have nitrate levels in excess of the EPA drinking water maximum contaminant goal limit (MCGL) of 10 mg-N/L[1,2]. According to the EPA, over 25% of the United States population uses septic systems to treat their residential wastewater[3]. Unfortunately, conventional septic systems do not provide favorable conditions for denitrifying wastewater, i.e., converting nitrate to harmless nitrogen gas. Therefore, septic system effluents require additional treatment for denitrification.

Onsite Wastewater Treatment Technologies for Nitrogen Removal

There are many options for secondary treatment of septic effluents, however, most have limitations due to either cost, maintenance, space, or energy requirements. Oakley et. al.[4] compared the nitrogen removal performance of 20 different types of onsite wastewater treatment systems and found that only one system was able to produce effluents containing less that 10 mg/L total nitrogen. This system was a single pass sand filter followed by a denitrifying woodchip bed[4]. Sand filters have a limited range of applications, however, and are not ideal for locations where the strength or quantity of wastewater varies widely. Sand filters are also vulnerable to surface clogging due to biofilm accumulation[5]. Gravel filters are similar to sand filters in that both are attached-growth systems, however, the gravel provides higher hydraulic conductivity and is therefore applicable to wider variations in flow strength and volume and is less prone to clogging. Adding a recirculating option to either sand or gravel filters can improve nitrification, due to both increased oxygen concentrations and contact time with the microorganisms living on the media. Recirculating gravel filters (RGFs) are ideal because they

require a smaller land area (i.e., footprint) and can treat higher strength wastewater than intermittent sand filters[6].

Recirculating Gravel Filter for Nitrification

RGFs typically consist of a lined bed filled with 2-4 feet of gravel media. Residential wastewater is pretreated in a septic tank, where organic forms of nitrogen are converted to ammonia, and then fed to the RGF. The septic tank effluent is evenly distributed across the top layer of gravel through a series of pressurized pipes. The effluent trickles downward and is then collected and sent to a recirculation basin where a pump returns the effluent to the top of the gravel media. The effluent recirculates several times before finally being discharged. As the septic tank effluent moves through the gravel, microorganisms attached to the gravel carry out nitrification, converting ammonia to nitrate. Nitrified RGF effluents require further treatment for denitrification. Woodchip beds have been shown to be an effective technology for denitrification, and are discussed in more detail, below.

RGF systems can also be designed to perform both nitrification and denitrification in a single bed. Ammonia nitrogen contained in septic tank effluents is converted to nitrate in an upper aerobic zone of the RGF, then converted to nitrogen gas in a lower, saturated anoxic zone. A carbon source is added to the anoxic zone, which provides an electron donor for the denitrification process. Carbon sources vary, but a commonly used, readily available source is the septic tank effluent itself. Sand and gravel recirculating filters typically achieve around 40-50% total nitrogen removal[5].

Woodchip Bed for Denitrification

Woodchip beds have been used extensively to provide denitrification of contaminated groundwater, and more recently, for residential wastewater effluents[7–15]. Woodchips provide the

necessary carbon source, used as an electron donor, for the biologically mediated denitrification process. Other carbon sources such as wheat straw, alfalfa, corn stalks, corn cobs and rice husks have been tested, but woodchips appear to supply the most consistent, sustained release of carbon over multi-year periods[16]. More soluble carbon sources release large amounts of carbon initially, promoting high denitrification rates, but the carbon supply is quickly exhausted. For example, corn cobs and rice husks both showed a sharp decline in soluble carbon and associated denitrification rates after just 70 days[17,18]. Three separate woodchip denitrification studies showed that carbon availability declined after the first year, but then remained relatively steady for up to 6-8 years[8,9,16].

The size of the woodchip does not appear to affect the availability of soluble carbon or denitrification performance. Van Driel and Robertson[19] found that coarse and fine woodchips provided similar denitrification performance, and a similar study by Cameron and Schipper[14] tested four different sizes of woodchips, also finding no difference in denitrification rates. Woodchip size does however affect hydraulic conductivity, with smaller particles (e.g. sawdust), providing lower conductivity. Several studies examined hydraulic conductivity within denitrification beds and found that hydraulic conductivity differences attributed to different carbon sources did not impact denitrification performance[14,20].

Leverenz et. al.[15] studied denitrification performance in woodchip beds planted with aquatic plants. Prior to this study, woodchip beds had been shown to be effective at denitrifying agricultural runoff and contaminated groundwater, but had not been used to treat nitrified residential septic effluents. In their study, nitrified septic tank effluent was fed to separate, single-pass gravel or woodchip beds where a constant water level was maintained to encourage anoxic conditions. Cattails (*Typha latifolia*) were planted in some of the beds to test whether the

addition of vegetation affected nitrogen removal. One of two gravel beds was planted with cattails which provided the only potential source of carbon in this bed type. The unplanted gravel bed showed no nitrogen removal regardless of temperature or vegetation, while the planted gravel bed removed an average of 10 mg/L nitrate for a removal rate of 0.74 g-N/m^2d. Planted and unplanted woodchip beds removed 99.7% of the influent nitrate during the first 5 months of the study, where influent nitrate concentrations ranged from 45 to 80 mg/L. Planted and unplanted woodchip bed effluent had nitrate concentrations less than 1 mg-N/L throughout most of the study, but when temperatures dropped below 19 °C, effluent nitrate increased. The planted woodchip bed removed the most nitrate and performed better than the unplanted woodchip bed during cold periods. The nitrate removal rate calculated for both planted and unplanted woodchip beds was 5.9 g-N/m^2d. The study authors hypothesized that reduced nitrogen removal during cold temperatures may be due to plant assimilation or microbial-root interactions[15]. Another study also credited improved woodchip bioreactor performance to a symbiotic relationship between plant roots and microorganisms[21].

Denitrification studies using woodchips in reactive barriers to remediate nitrate groundwater contamination have also observed that woodchip beds remove less nitrogen during cold temperatures. However, a woodchip reactive barrier denitrified groundwater during winter months, when temperatures were as low as 3°C, showing that denitrification is limited, but still possible, at extremely low temperatures[22]. Denitrifying organisms are known to reduce their activity when temperatures are low, but organisms responsible for breaking down the woodchips into bio-available form of carbon also appear to be temperature sensitive[23]. This limitation was likely to extend to future denitrification woodchip bed installations, but it was unknown how a similar system might perform in a colder climate.

Study Objectives

Water quality in Washington State could be improved through implementation of secondary septic treatment, but it was unknown how much the colder temperatures experienced in Washington would reduce woodchip bed denitrification performance. Our study includes the installation of a vegetated woodchip bed similar to the Leverenz et. al.[15] design and observes the changes in nitrogen reduction associated with the northwest Washington climate. For comparison, we also constructed a vegetated RGF, designed to perform both nitrification and denitrification in a single unit. We subjected both systems to a series of stress tests (described under Materials and Methods) in order to determine how the systems are affected by changes in influent loading or system operation. Similar operating conditions allows for a critical comparison between the two systems, particularly between nitrogen removal capabilities.

The overall goal of this project is to evaluate and verify nitrogen removal for three public domain technologies designed to treat domestic wastewater prior to subsurface dispersal, also see Wei[24]. If this testing shows these technologies achieve annual average total nitrogen-N ≤ 20 mg/L, the Department of Health will take the appropriate steps to develop standards for their use in the State of Washington. In addition to nitrogen removal, we were particularly interested in how to optimize the use of the Woodchip bed system. This study had three secondary goals relating to the Woodchip bed system. First, to verify the effectiveness of a Woodchip bed system for onsite wastewater applications. Second, to relate nitrogen removal performance to temperature. Third, to measure effluent soluble carbon in order to better understand how the release of organic matter from the woodchips changed over the course of the year-long study.

MATERIALS AND METHODS

The verification testing to evaluate the performance of three onsite nitrogen reduction systems was conducted at the Snoqualmie Wastewater Treatment Plant (WWTP). This section provides a description of the test site, including the basis for the site selection, the site layout, and wastewater feeding method. Descriptions of the nitrogen reduction systems are provided, including their flow schematics, design components, and nitrogen removal mechanisms. Details of the testing program are described including the sampling schedule, field sampling activities and data collection, analytical methods, and quality assurance/quality control (QAQC) methods.

Test Site Description

Site Selection

The test site was located at the Snoqualmie WWTP, which is 28 miles east of Seattle, at approximately 425-feet (ft) elevation. The WWTP has an average design capacity of 3.0 million gallons per day to serve a population of about 11,000 people. The influent wastewater is primarily domestic, with no significant industrial discharges. Prior to locating the pilot project at the Snoqualmie WWTP one year of influent wastewater data was evaluated and confirmed that the wastewater characteristics met the wastewater characteristics criteria given in the ETV protocol, as shown in Table 1[25]. Total Kjeldhal nitrogen (TKN) concentrations were not measured for the Snoqualmie WWTP and were thus estimated from the measured ammonia-N values using a typical NH_3-N/TKN ratio of 0.60 for domestic wastewater. With this assumption the estimated influent TKN concentrations ranged from 37 to 70 mg/L, which is within the ETV protocol criteria.

On-site Testing Facility

A layout and flow schematic of the pilot study site is shown in Figure 1. Performance of the enhanced recirculating gravel filter is discussed in Wei[24]. Each of the nitrogen reduction systems had its own treatment train with separate feed dosing and septic tanks. Flow from each septic tank was directed to the respective recirculating gravel filter (RGF) for each system. For the Vegetated system, it entered their anoxic zones at the front of the system. For the RGF of the postanoxic Woodchip bed system (referred to as the Intermediate RGF), the septic effluent entered the recirculation tank before being applied to the RGF. The Vegetated RGF recirculation basin received effluent flow from the anoxic zone and had a pump for adding the recirculation flow to the RGF feed distribution systems, and discharged daily overflow to a drain line that directed it back to the WWTP oxidation ditch. A portion of the treated effluent from the Intermediate RGF overflowed to the woodchip bed. The remaining portion of the treated recirculation flow was returned to the recirculation tank that also received the septic tank effluent. Automatic samplers shown in Figure 1 were used to collect 24-hr composite samples from the influent wastewater, the system effluents for the individual treatment systems, and from the effluent of the Intermediate RGF of the Woodchip bed system.

Table 1. ETV Protocol influent wastewater characteristics criteria and the Snoqualmie WWTP average influent data for 2010.

	ETV Protocol Criteria	Snoqualmie WWTP 2010
BOD, mg/L	100 - 450	245 - 315
Total Suspended Solids, mg/L	100 - 500	274 - 351
Total Phosphorus, mg/L	3 - 20	4 - 8
TKN, mg/L	25 - 70	*
NH_3-N, mg/L	-	23 - 44
Alkalinity, mg/L as $CaCO_3$	> 60	*
pH	6 - 9	*
Temperature, °C	10 - 30	*

*These criteria were met during testing program.

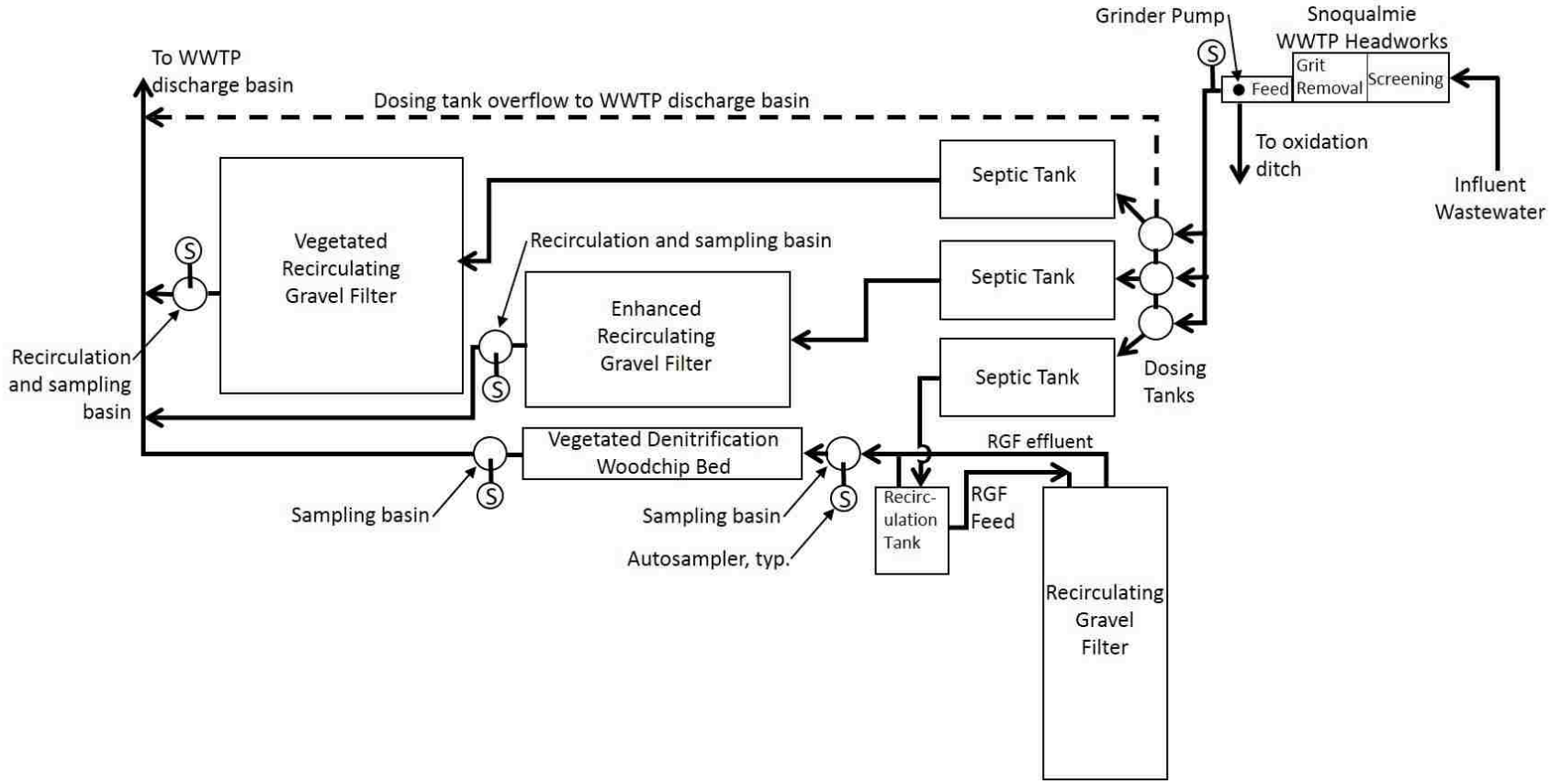

Figure 1. Flow schematic and layout of the onsite treatment test systems.

Wastewater Feed Design

Each system received 480 gallons per day (gpd) of septic tank effluent, as specified by the Washington Department of Health (DOH) for a design daily flow from a 4 bedroom residential home[25]. Feed for the test system was obtained from a wet well after the screening and grit removal of the Snoqualmie WWTP influent. A feed control system consisting of a grinder pump and separate dosing tanks provided equal flow at selected times to each of the systems. A Liberty LSG202M grinder pump transported influent wastewater through a 2-inch (in.) diameter PVC pipe to fill each 18-in diameter dosing tank. The pump was equipped with a programmable logic controller to control the start time and length of each fill. The final liquid level in each dosing tank was controlled with a stand-up pipe for overflow to a waste line. After feeding with dose tank overflow, the feed pump was turned off for 1.5 minutes before an actuated valve at the bottom of the dose tank was opened to discharge wastewater to each respective septic tank. Based on the diameter of the dosing tank and the height of the stand-up pipe, 16 gallons (gal) of wastewater was delivered for each dosing event. With a total of 30 doses per day, 480 gpd of wastewater was delivered to each test system. The dosing frequency was controlled with the programmed logic controller to provide a typical diurnal flow pattern for a single-family home. The dosing schedule for this diurnal flow pattern is shown in Table 2:

Table 2. Dosing schedule to represent a typical diurnal wastewater flow from a single-family home.

Dosing Period	Dosing Time	Number of Doses	Percent of Daily Flow
Morning	6 a.m. – 9 a.m.	10	33
Afternoon	11 a.m. – 2 p.m.	8	27
Evening	5 p.m. – 8 p.m.	12	40
	Total	30	100

Septic Tanks

Individual 1250 gallon two-compartment septic tanks provided pretreatment of the wastewater before entering each of the nitrogen removal systems. During each dosing, wastewater entered through the septic tank inlet and displaced effluent, which then flowed by gravity to the nitrogen removal systems. An effluent filter was attached to the septic tank outlet pipe to remove grease and fibers from the septic tank effluent to help avoid plugging in the media of the nitrogen removal systems.

Automatic Samplers

Teledyne ISCO automatic samplers were used for site sample collection. Each of the automatic samplers contained a peristaltic pump that delivered liquid from the sampling basin to the container sitting inside the automatic sampler. The pump was coupled with a liquid detector allowing accurate and repeatable sample volumes. Sampler model 6712FR was placed at the headworks to draw influent samples prior to the feed system grinder pump. An ISCO 6712 sampler was used for the Vegetated RGF system, located at the system outlet end to draw samples from the effluent overflow pipe in the recirculation chamber. Individual ISCO GLS samplers were used for the RGF effluent of the Woodchip Bed system and for the woodchip bed effluent. These samples were collected from the RGF effluent sampling basin and the woodchip bed effluent overflow pipes, respectively.

Description of Nitrogen Reduction Technology Systems

This section describes in detail the design of the Vegetated RGF and Intermediate RGF/Woodchip Bed systems.

Vegetated Recirculating Gravel Filter (Vegetated RGF)

A schematic of the Vegetated RGF system is shown in Figure 2. The system aerial dimensions are 16 ft by 16 ft for a total top surface area of 256 ft^2. An upper aerobic nitrification zone is above a bottom anoxic zone. The two zones are separated by a 30-mil PVC liner across the entire width and 12 ft length of the system, leaving a 4 ft gap at the septic tank flow inlet end for the nitrified flow to enter the bottom anoxic zone. The septic tank effluent overflow enters at the midpoint of a 15-ft long Hancor ARC 36 flow distribution chamber[26], located along the full bottom width of the Vegetated RGF inlet end. The septic tank effluent flows through a series of slotted openings, or louvers, on the ARC 36 chamber into the anoxic zone. The septic tank effluent and nitrified flow from the aerobic zone flow horizontally through the gravel media anoxic zone to a 4-in. slotted effluent collection pipe located across the bottom width of the Vegetated RGF outlet end.

The effluent from the anoxic zone overflows into a 30-in. diameter by 7.5-ft high recirculation basin (Figure 3). The recirculation basin contains a 0.33 hp centrifugal pump (Gould PE31) that feeds flow to the distribution piping at the top of the aerobic bed. The recirculation pump is activated every 24 min by the programmable controller for a period of 2.3 min to result in 60 uniform doses per day. The pump flow rate is 27.7 gallons per minute (gpm) for a total daily recirculation flow of approximately 3800 gal, which equates to an average recirculation ratio of about 8.0 based on a daily influent flow of 480 gal. An effluent flow that is approximately equal to the influent, subject to losses by evapotranspiration and gains by precipitation, overflows from a 4-in. diameter pipe located at about 4.5 ft above the bottom of the recirculation chamber.

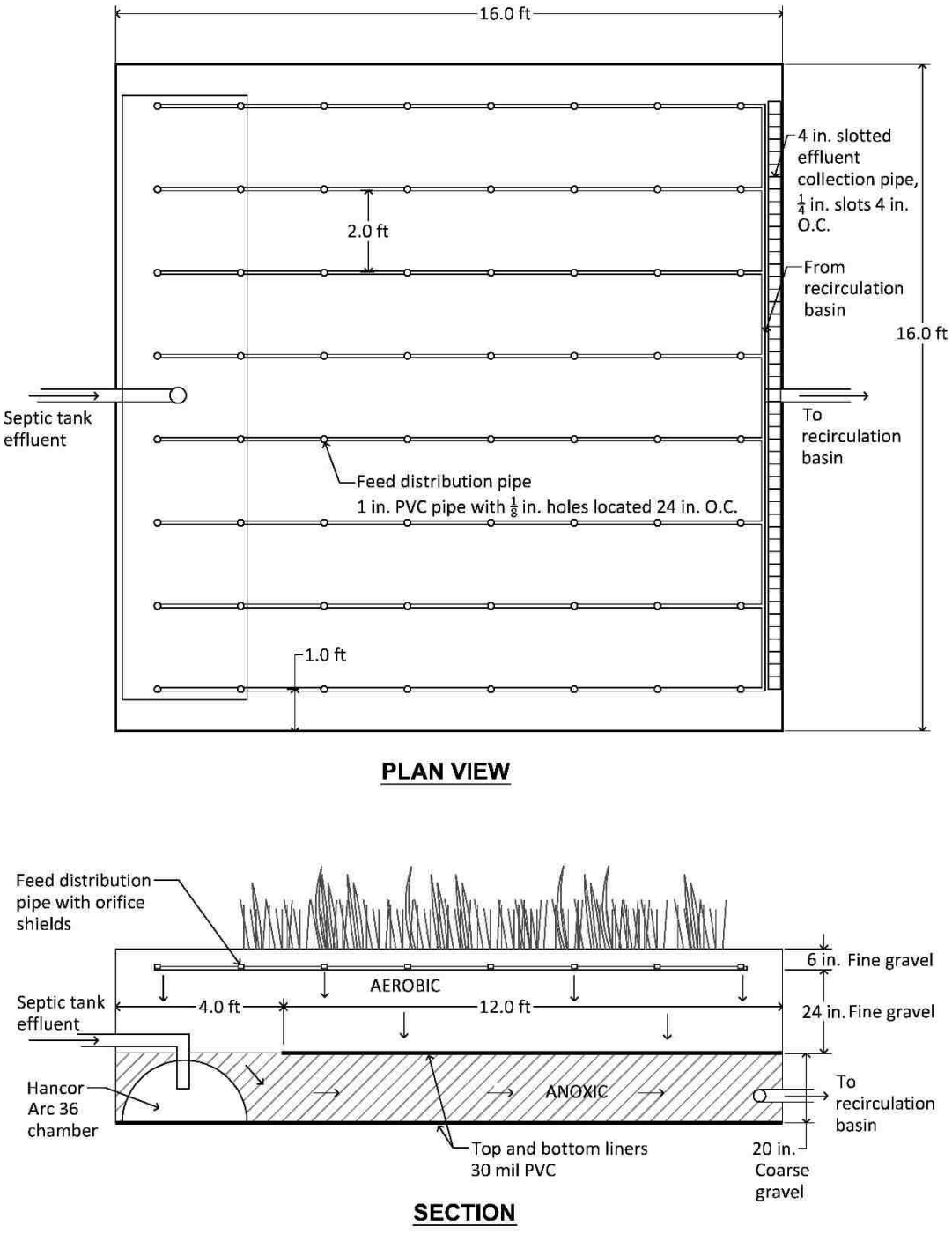

Figure 2. Schematic of the vegetated recirculating gravel filter system.

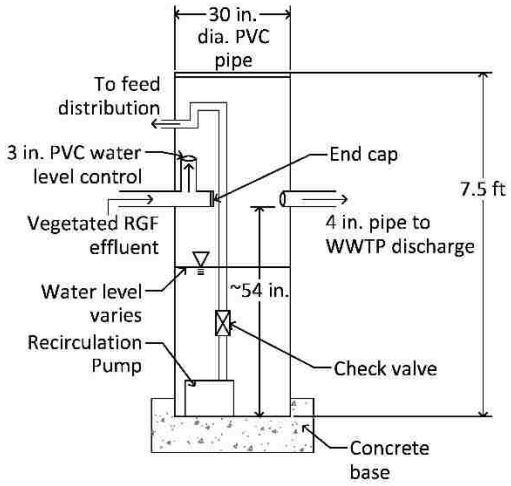

Figure 3. Recirculation basin for the vegetated recirculating gravel filter system

Dosing of flow from the recirculation pump to the top of the aerobic bed is done under pressure through eight 1-in. diameter PVC lateral pipes equally spaced at 2 ft and with the outer pipes at 1 ft from the Vegetated RGF outer wall. The lateral pipes have 1/8-in. diameter holes, placed 24 in. on center and aimed upward at 90 degrees to eject the feed flow against orifice splash shields to help spread the feed flow across the top area. A mixture of perennials, flowers, shrubs, and grasses are planted uniformly across the top of the bed, in between the laterals, to provide a vegetated surface and plant root structure within the aerobic fine gravel zone.

A Teledyne ISCO 6712 automatic sampler is used to collect effluent samples from the Vegetated RGF system. A sample line is placed inside the 3.0-in. anoxic effluent overflow pipe, located in the recirculation basin. The sample line is connected to a peristaltic pump contained in the sampler which feeds samples into a composite sample container inside the sampler housing. The sampler is programmed to draw a 100-200 ml subsample at 15 minutes after every feed dose. With a total of 30 doses a day, 30 equal subsample volumes are collected at the same frequency as the feed doses to make up the 24-hr composite sample.

The process design summary for the Vegetated RGF system is given in Table 3. The total footprint area and depth are 256 ft^2 and 4.2 ft, respectively. At 480 gpd, the nominal hydraulic application rate (HAR) is 1.9 gal/ft^2-d. A fine-gravel media with an effective size of 2-3 mm is used for the upper aerobic bed at a depth of 24 in. The media in the anoxic bed is 0.5-1.0 in. coarse gravel at a depth of 20 in. Assuming uniform horizontal flow through the anoxic bed, the average HAR is 18.0 gal/ft^2-d. Note that the instantaneous HARs are much higher due to the recirculation flow. The average empty bed contact time (EBCT) for the aerobic and anoxic zones based on a daily feed flow of 480 gpd are 8.0 and 6.6 days, respectively. At an estimated porosity of 0.4, the average pore volume contact time is 3.2 and 2.6 days for the aerobic and anoxic zone, respectively.

Table 3. Process design summary of the vegetated recirculating gravel filter system.

Parameter	Unit	Value
Dimensions (length × width × depth)	ft	16 × 16 × 4.2
Top area	ft^2	256
Surface vegetation		A large variety of grasses, flowers, and shrubs
Aerobic bed (fine gravel)		
Effective size	mm	2 - 3
Treatment depth[a]	in	24
Anoxic bed (coarse gravel)		
Size	in	0.5 - 1
Depth	in	20
Recirculation ratio		8.0[b]
Average hydraulic application rate		
Aerobic[c]	gal/ft^2-day	1.9
Anoxic[d]	gal/ft^2-day	18.0
Empty bed contact time		
Aerobic	day	8.0
Anoxic	day	6.6

[a]Measured from below distribution pipe.
[b]Recirculation ratio was 6.0 prior to 7/23/2012.
[c]Based on top total cross-sectional area.
[d]Based on horizontal flow cross-sectional area

Biological nitrogen removal by nitrification in the top aerobic zone and denitrification in the bottom anoxic zone is accomplished in the following manner:

1. Ammonia and organic nitrogen from the septic tank effluent passes through the anoxic zone and is fed to the aerobic zone by flow from the recirculation chamber. Autotrophic bacteria on the media in the aerobic zone oxidize ammonia to nitrite and nitrate. Heterotrophic bacteria in the anoxic and aerobic zones can breakdown organic nitrogen to ammonia. Oxygen needed by the nitrifying bacteria is provided by oxygen contained in the pore spaces in the aerobic zone media after the bed drains in between dosings. Oxygen in the pore spaces of aerobic zone media can also be gained during recirculation, when flow is sprayed into air

by the feed lateral spray nozzles and subsequently trickles down through the aerobic zone media.

2. The nitrite and nitrate contained in the aerobic zone flows are biologically reduced to nitrogen gas by denitrification in the anoxic zone. Due to the lack of aeration in the anoxic zone, heterotrophic bacteria attached to and contained in the gravel media pore spaces use nitrite/nitrate as an electron acceptor for the oxidation of organic substrates. A rich organic substrate is provided to the denitrifying bacteria in the anoxic zone by the BOD contained in the septic tank effluent. Because of the relatively large surface area and biofilm growth in the aerobic and anoxic zones, a large population of nitrifiers and denitrifiers are maintained in the respective zones.

It should be noted that not all of the influent ammonia and organic nitrogen can be removed in the nitrogen reduction system. Some portion of the septic tank effluent nitrogen is in the effluent flow from the recirculation chamber. For example, at an average recirculation ratio of 8.0, which is the ratio of the recirculation flowrate (RQ) to the influent flowrate (Q), the total average flowrate to the anoxic zone is 9Q and thus $1/9^{th}$ of the influent total nitrogen (TN), mostly as NH_3-N, would theoretically be in the effluent overflow of the recirculation chamber. Actual proportions will be different due to differences in the timing of the recirculation flow dosing, the septic tank overflow events, the use of nitrogen for biomass synthesis from BOD removal, and the rate of conversion of organic-N to NH_3-N.

It should also be noted that some biological denitrification can occur in the upper aerobic zone. As the biofilm on the aerobic zone media becomes thicker due to heterotrophic biofilm growth, oxygen is depleted before it can diffuse into the deeper biofilm layers. Nitrite and nitrate produced from nitrification in the outer aerobic zone can diffuse into the anaerobic biofilm depths to provide electron acceptors for biological activity and thus, denitrification.

Recirculating Gravel Filter and Vegetated Denitrifying Woodchip Bed

As was shown in the site plan in Figure 1, a two-stage nitrogen removal system consists of a recirculation gravel filter followed by a vegetated denitrifying woodchip bed. Nitrification occurs in the RGF and postanoxic denitrification occurs in the woodchip bed. A schematic of the nitrifying RGF is shown in Figure 4 and the details of the RGF recirculation basin are shown in its schematic in Figure 5. The RGF areal dimensions are 8 ft by 20 ft, for a footprint surface area of 160 ft^2. The total depth is 3.0 ft. The top contains 6 inches of pea gravel and the flow from the feed lateral distribution pipes travels downward through 24 inches of fine gravel with an effective size of 2-3 mm. The feed distribution system consists of four 1.0-inch PVC pipes with 1/8th-inch holes at 24-inch center. The lateral feed pipes are contained in Hancor ARC 24 flow distribution chambers[26] which helps to distribute the feed flow uniformly in the feed application area. The feed laterals are 2.0 ft apart and the outer pipes are 1.0 ft from the RGF walls. The bottom contains 6 inches of 0.50- to 0.75-inch rock over a 30-mil PVC liner. Three 4-inch slotted effluent collection pipes with 1/4 inch slots at 4-inch centers directs this flow to an effluent pipe that goes to the recirculation basin. The effluent collection pipes are 3.0 ft apart and the outer pipes are 1.0 ft from the RGF walls.

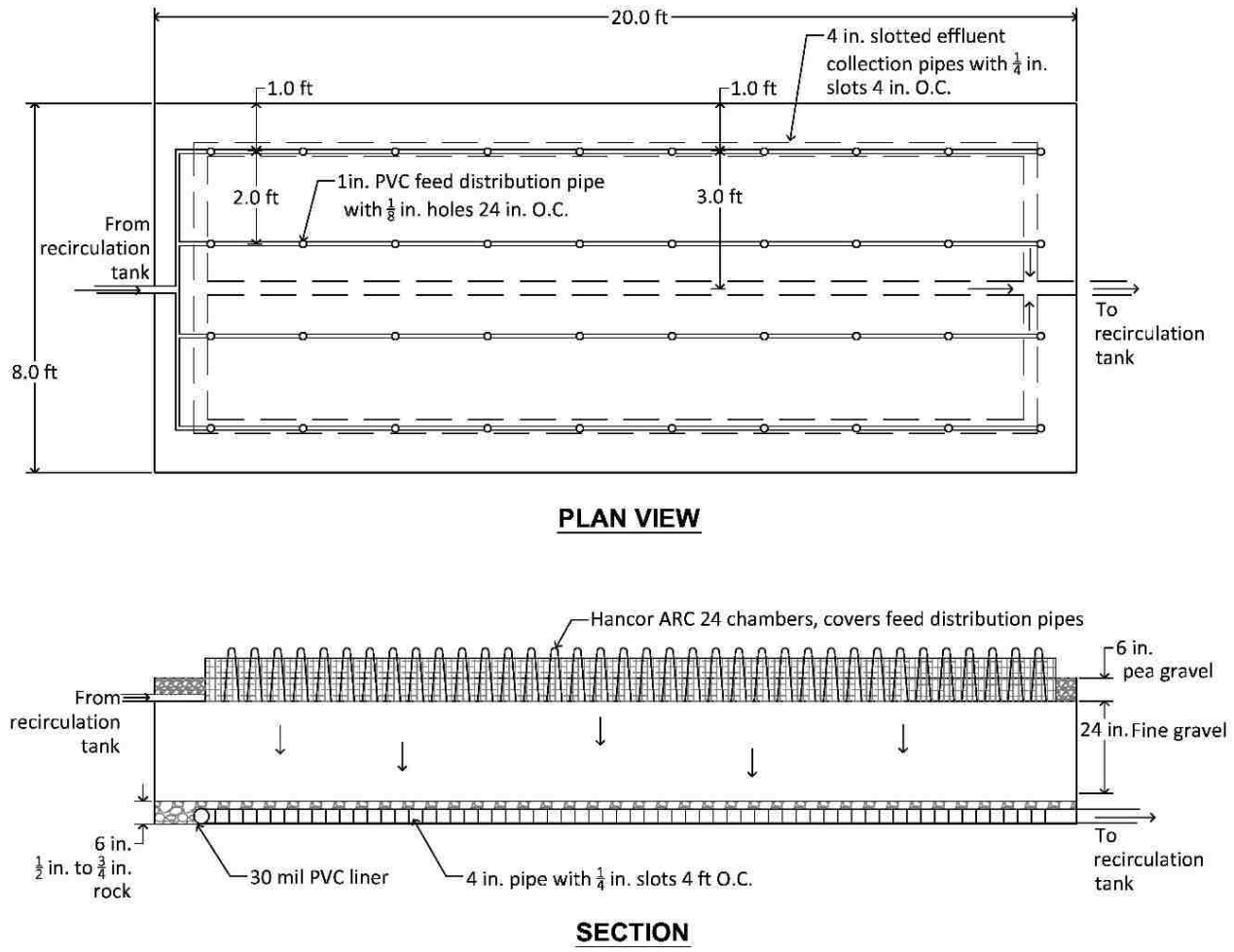

Figure 4. Schematic of the recirculating gravel filter stage.

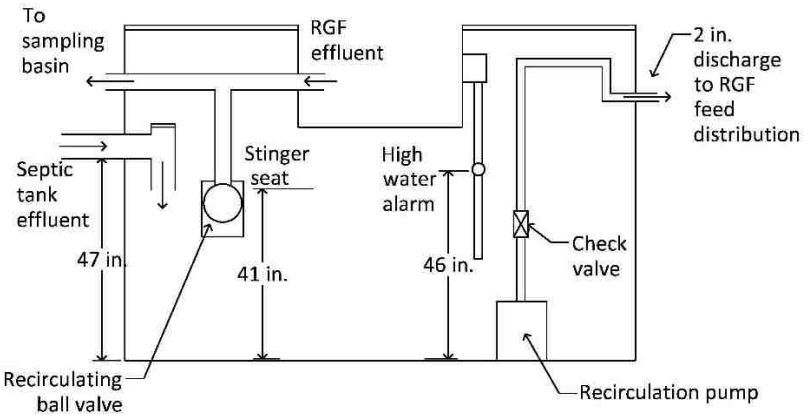

Figure 5. Recirculation basin for the recirculating gravel filter.

Effluent flows from the septic tank into the recirculation basin (Figure 5). When the recirculation liquid level is lowered after the recirculation feed pump is turned on, all of the effluent goes into the recirculation tank. Eventually the water level increases so that the ball valve stops flow to the recirculation tank and the effluent flow goes only to the effluent sampler pipe and to the woodchip bed. The 0.33 hp recirculation pump (Gould PE31) is activated every 20 min by a programmable controller for a period of 2.3 min to result in 72 uniform cycles per day. The pump flow rate is about 17.3 gallons per minute (gpm) for a total daily recirculation flow of about 2800 gal, which equates to an average recirculation ratio of about 6.0 based on a daily influent flow of 480 gal.

The RGF process design summary is given in Table 4. At 480 gal/d, the average hydraulic application rate (HAR) is 3.0 gal/ft^2-d. A 24-in. deep, fine gravel media with an effective size of 2-3 mm is used for the RGF treatment zone. The average empty bed contact time (EBCT) for the RGF based on a daily feed flow of 480 gal is 5.0 days. Assuming a media porosity of 40 percent, the average pore volume contact time is 2.0 days.

Table 4. Process design summary for the RGF in the two-stage RGF and Woodchip bed system.

Design parameter	Unit	Value
Dimensions (length × width × depth)	ft	20.0 × 8.0 × 2.0
Top area	ft^2	160
Aerobic media (gravel)		
Effective Size	mm	2 - 3
Depth[a]	in	24
Recirculation ratio		6.0
Average hydraulic application rate		
Aerobic	gal/ft^2-day	3.0
Empty bed contact time		
Aerobic	day	5.0

[a]Measured from below the feed distribution pipe

A schematic of the woodchip bed is shown in Figure 6. The total length, width, and depth are 19.0 ft., 3.5 ft., and 3.5 ft., respectively for a total surface footprint area of 66.5 ft^2. RGF effluent enters the woodchip bed tank through a 4-in. PVC pipe to a 4-inch wide water chamber preceding three stacked, approximately 14-in. diameter foam filled EZflow bundles[27] to provide uniform flow distribution into the woodchip bed. The treated effluent is collected in vertical 4-in diameter slotted pipe at the end of the woodchip bed which connects to a 4-in. PVC overflow pipe in the overflow control/sampling basin. The 4 in. PVC outlet pipe in the sampling basin was positioned to allow water to overflow at an elevation approximately 6-in below the top surface of the woodchips.

The woodchip media portion of the Woodchip bed system is 17.5 feet long and contains alder woodchips, approximately 0.5 to 3-in long, 0.0625-in thick and greater than 0.375-in wide. Cattails (*Typha latifolia*) are planted at the top of the bed.

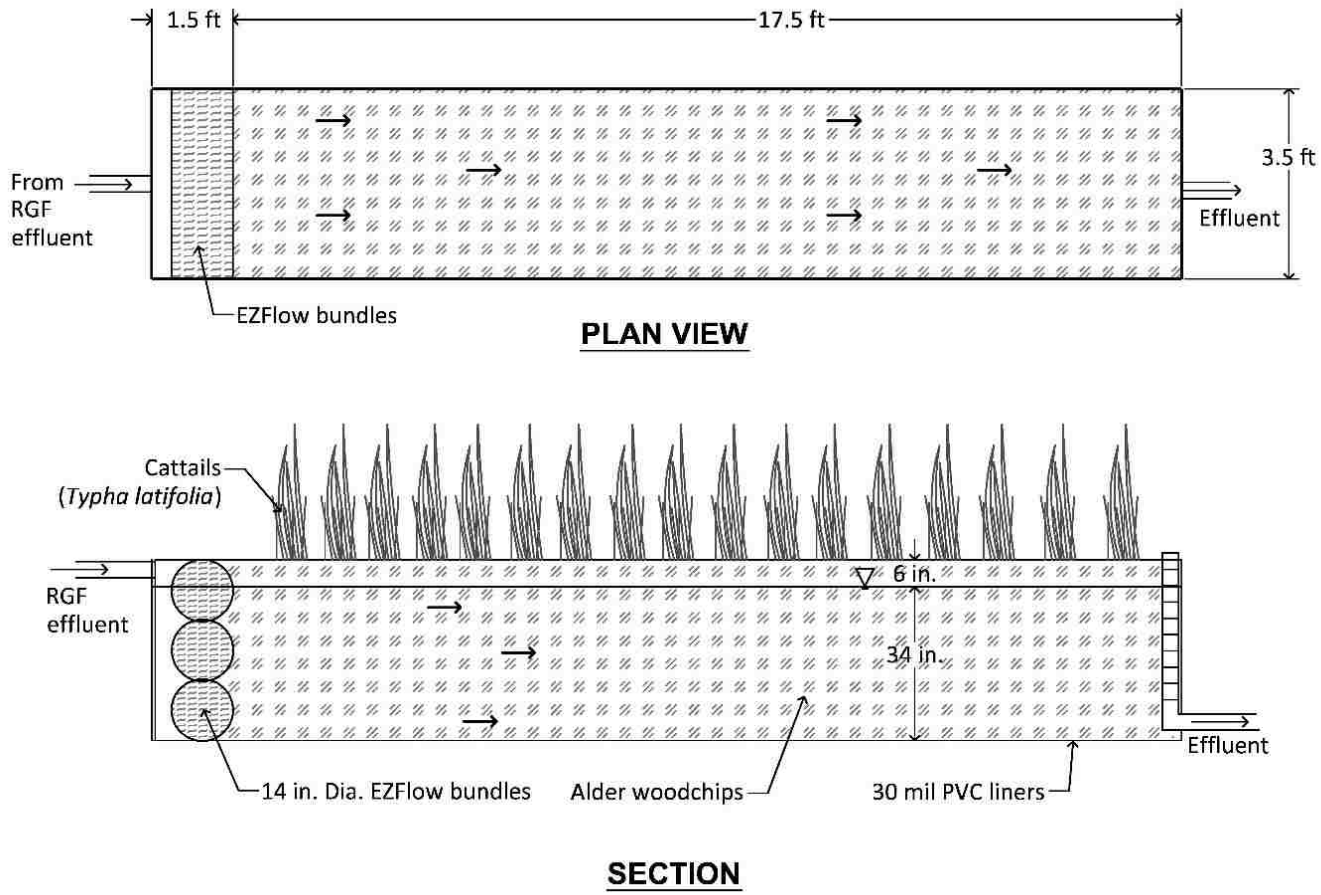

Figure 6. Schematic of the vegetated denitrifying woodchip bed stage.

The woodchip bed process design summary is given in Table 5. At 480 gpd, the average hydraulic application rate (HAR) for the horizontal flow is 48.5 gal/ft^2-d. A 34-in. saturated depth of woodchips is contained in the anoxic volume. The average empty bed contact time (EBCT) for the woodchip bed based on a daily feed flow of 480 gal is 2.9 days. Assuming a media porosity of 40 percent, the average pore volume contact time is 1.2 days.

Table 5. Process design summary for the woodchip bed in the two-stage RGF and Woodchip bed system.

Design parameter	Unit	Value
Dimensions (length × width × depth)	ft	19 × 3.5 × 2.83
Top area	ft^2	66.5
Alder woodchip media		
Size[a]	in	0.5 - 3.0
Depth[b]	in	34
Average hydraulic application rate	gal/ft^2-day	48.5
Empty bed contact time	day	2.9

[a]Woodchip length and width
[b]Saturated depth

Teledyne ISCO GLS automatic samplers were used to collect effluent samples from the RGF and woodchip bed stages. For the RGF stage, the sample line was placed inside the 4.0-in. cross-tee fitting, located in the sampling basin after the recirculation basin. The sample line for the woodchip bed effluent sampler was placed inside the 4.0-in. water level control pipe in the overflow control/sampling basin. The sample line was connected to a peristaltic pump contained in the autosampler and was used to pump subsamples into the composite collection container inside the autosampler. The sampler was programmed to draw a 100-200 ml subsample 15 minutes after each of the 30 feed dose events to provide a 24-hr composite sample.

System Installation and Startup

A private contractor installed the systems in accordance with construction documents created by DOH. Installation of the systems began in March 2012. Construction activities were complete in June 2012 and the project startup period begin immediately thereafter. DOH adjusted and calibrated the 16-gallon dose volume for each dosing tank for feed events. The RGF systems were seeded by UWCEE staff, using 5 gal buckets to transport mixed liquor with nitrifying bacteria by pouring 15 gallons of the Snoqualmie WWTP oxidation ditch mixed liquor evenly across the top of the beds. Effluent ammonium concentrations were monitored regularly by DOH with a probe (YSI ISE, Model #605104) during startup. During the fourth week of startup, samples were collected for three consecutive days and analyzed in the UWCEE laboratory for ammonia-N (NH_3-N) concentrations. The results showed that the effluent NH_3-N concentration was less than 10 mg/L, which was a metric to confirm successful startup as to then proceed with the verification testing program.

Technology Verification Testing Program

Testing and Sampling Schedule

The 12-month technology verification testing program began on August 1, 2012 for the three nitrogen reduction processes. At least once per month the testing program involved sampling the system with additional sampling events associated with so-called stress periods. Five different types of stress tests were applied during the 12-month program to represent different flow conditions considered possible from single home activities, plus a power failure. A complete sampling schedule for the study is shown. The sampling and stress test schedule is summarized in Table 6. For each sample event, 24-hour composite samples were obtained for the influent

wastewater and effluents from the Vegetated RGF and Woodchip bed systems. An intermediate effluent sample was also obtained from the RGF effluent.

Table 6. Verification test program sampling schedule from August 2012 to July 2013. Week 1 of the verification testing period was on July 30, 2012.

Period	Type of Stress Test	Week Start Date (Monday)	Sample Collection
Week 4 and 6		August 20th September 3rd	Tue
Week 7	Wash Day Stress initiated on Monday	September 10th	Tue, Thu, and Sun
Week 8		September 17th	Mon, Tue, Wed, Thu, and Fri
Week 12 and 14		October 15th October 29th	Tue
Week 15	Working Parent Stress initiated on Monday	November 5th	Tue, Thu, Sun, and Mon
Week 16		November 12th	Tue, Wed, Thu, and Fri
Week 21 and 25		December 17th January 14th	Tue
Week 26	Low-loading Stress initiated on Tuesday	January 21st	Wed
Week 27		January 28th	Thu
Week 29		February 11th	Wed, Thu, Fri, Sat, and Sun
Week 30		February 18th	Mon
Week 31		February 25th	Wed*
Week 32		March 4th	Tue* and Wed*
Week 33		March 11th	Wed
Week 36		April 1st	Tue
Week 37	Power/Equipment Failure stress initiated on Monday	April 8th	Sun
Week 38		April 15th	Mon, Tue, Wed, and Thu
Week 42		May 13th	Tue and Wed*
Week 45		June 3rd	Tue
Week 46	Vacation Stress initiated on Tuesday	June 10th	Tue
Week 47		June 17th	Fri, Sat, and Sun
Week 48		June 24th	Mon, Tue, and Wed
Week 52		July 22nd	Tue, Wed, Thu, Fri, and Sat

*Additional sampling days with samples only analyzed for alkalinity, COD, NH_4-N, NO_x-N, and TN.

Stress Testing Procedures

The ETV protocol includes a series of stress tests to determine the system performance under loading variations that are different than the typical 24-hour diurnal flow pattern for a single home. The following lists the stress names and operating conditions for each one and are subsequently described:

- Wash-day Stress
- Working Parent Stress
- Low-loading Stress
- Power/Equipment Failure Stress
- Vacation Stress

The Wash-day Stress simulated multiple laundry loads over a short period of time. This stress consisted of three consecutive wash-days, each separated by a 24-hour period. On each wash-day, the morning and afternoon dosing periods received an additional hydraulic loading of three wash loads equal to 28 gallons of tap water added to the septic tank influent. Laundry detergent and non-chlorine bleach were added with each wash load. During the stress test, the total feed volume was maintained at 480 gpd.

The purpose of the Working Parent Stress was to simulate a household in which the occupants are at work during week days with most of the daily flow then occurring in the evening. The flow pattern was altered over a period of five days. Each day 40 percent of the daily flow was delivered during the morning dosing period and 60 percent of the daily flow was delivered during the evening dosing period. The evening dosing of the day also included one wash load. The total daily flow was 480 gallons.

The Low-loading Stress simulated household conditions where flows were reduced for an extended period. The total daily flow volumes were reduced by 50 percent (240 gpd), for a duration of 21 days. The flow pattern was also modified, with 35 percent of the daily flow

delivered during the morning dosing period, 25 percent during the afternoon dosing period, and 40 percent during the evening dosing period.

The Power/Equipment Failure Stress simulated a situation where power loss or equipment failure prevented the system from receiving and recirculating flow. The stress test began with a typical daily flow pattern until 2 pm on the day when the stress was initiated. Power was then turned off, influent flow and the recirculation pumping in each system was stopped for 48 hours. After the 48-hour period, power was restored and 60 percent of the total daily flow was delivered over a three hour period and included one wash load.

The Vacation Stress simulated the absence of the home occupants for an 8-day period. On the day the stress was initiated, 35 percent of the total daily flow was delivered during the first dosing period and 25 percent during the second dosing period. The influent flow was then stopped for 8 consecutive days, but power was available to maintain the recirculation pump flow in each system. On the ninth day, 60 percent of the normal daily flow was delivered, along with three wash loads.

Site Sampling and Data Collection

The site autosampler locations are shown in Figure 1 and described in the section above, "Automatic Samplers." Influent composite samples were collected using an automated refrigerated sampler. Effluent samples were also collected using automated samplers that were packed with ice prior to the start of the sampling event to maintain temperature at about 4°C. Twenty four-hour composite samples consisted of 30 equal subsample volumes drawn 15 minutes after the dosing tanks delivered wastewater to the septic tanks. The field samples were transported in coolers packed with ice to the University of Washington Civil and Environmental

Engineering (UWCEE) laboratory for analysis. Upon arrival, the temperature of each sample was taken and recorded.

At the project site, grab samples were collected by UWCEE staff within an hour of the time that the 24-hour composite samples were removed. The peristaltic pumps in the autosamplers were manually activated to collect a grab sample of approximately 400 mL into 500 mL Nalgene bottles. In situ grab measurements for pH, dissolved oxygen and temperature using calibrated meters (YSI EcoSens pH100A and YSI ProODO) were done for all the system effluents. Only temperature and pH measurements were taken at the influent sample point.

At the same time and location as the in situ field measurements, separate samples were collected for fecal coliform (FC) analysis. FC samples were drawn using the autosampler and collected into 100 mL bottles (Idexx). FC samples were analyzed by the Snoqualmie WWTP lab personnel, and if unavailable, by Am Test Inc. Laboratories in Kirkland, Washington. Both are certified labs for fecal coliform tests.

Analytical Methods

Standard Methods for the Examination of Water and Wastewater[28] was used as the basis for all laboratory analysis. Any modifications to the Standard Methods will be described in the subsequent sections for each parameter. A list of parameters and tests performed on the composite samples is shown in Table 7. All parameters were measured for all sampling locations with the exception of nitrate+nitrite for the influent and no TP measurement for the Intermediate RGF sample. The acceptance criteria for duplicates or spike recoveries are also listed in Table 7.

Table 7. List of analytical parameters and methods.

Parameter	Facility	Acceptance Criteria for Duplicate (%)	Acceptance Criteria for Spikes (%)	Analytical Method
pH	On-site	90-110	N/A	SM #4500H B
Temperature	On-site	90-110	N/A	SM #2550
Dissolved Oxygen	On-site	80-120	N/A	ASTM D888-09
BOD_5/$CBOD_5$	UWCEE Laboratory	80-120	N/A	SM 5210B
COD	UWCEE Laboratory	80-120	N/A	SM 5220D
TSS	UWCEE Laboratory	80-120	N/A	SM 2540D
VSS	UWCEE Laboratory	80-120	N/A	SM 2540E
Alkalinity	UWCEE Laboratory	80-120	N/A	SM 2320B
Total Nitrogen	UWCEE Laboratory	80-120	60-140	SM 4500 P J + SM 4500 NO3 H
Ammonia	UWCEE Laboratory	80-120	80-120	SM 4500 NH3 G
Nitrate+Nitrite	UWCEE Laboratory	90-110	60-140	SM 4500 NO3 H
Total Phosphorus	UWCEE Laboratory	80-120	60-140	SM 4500 P B + SM 4500 P E
Fecal Coliform	Snoqualmie WWTP Laboratory/Am Test Inc., Kirkland	80-120	N/A	SM #9222D

SM- Standard Methods for the Examination of Water and Wastewater, 2005
ASTM- American Society for Testing and Materials

Five-Day Biological Oxygen Demand (BOD)

The BOD test was done in accordance to Standard Methods #5210B. This method consisted of filling a 300ml bottle with an appropriately diluted sample, sealing it to be airtight and incubating it at 20°C for 5 days. Dissolved oxygen in the bottle was measured before and after incubation. An YSI 5905 DO probe and YSI 58 DO Meter were used for measurements. Standard Methods specified that the BOD bottle DO depletion must be at least 2.0 mg/L and the DO residual must be at least 1.0 mg/L after five days of incubation for the test result to be acceptable. Not knowing the BOD value of the sample, there were occasions where the test

criteria were not met due to the sample dilutions selected. For every batch of BOD tests, two blank bottles were also set up and followed to determine if they met a test depletion criteria requirement between 0.0 and 0.20 mg/L. Three glucose glutamic acid (GGA) standards were done once per month with the acceptance criteria that their average difference in the BOD values from the theoretical value must be less than 30.5 mg/L and their coefficient of variation (CV) must be less than 15 percent. Additionally, Winkler titration was done once every two months to check for proper meter calibration and the need for instrument maintenance. All the effluent samples were inhibited for nitrification by adding allylthiourea ($C_4H_8N_2S$) to each BOD bottle. These BOD results are referred to as CBOD to indicate a carbonaceous BOD only and nitrification inhibition.

Chemical Oxygen Demand (COD)

The COD test was done in accordance with Standard Methods 5220D. This method consisted of adding 2 ml of sample into a commercial vial with premixed reagents manufactured by Hach. The vial with the sample was then digested in a heating block at 150°C for two hours. After digestion, the COD values of the samples were measured using the internal program of a Hach DR/4000U spectrophotometer. The heating block used was a HACH DRB200 digital reactor block. For pipetting of the influent sample, a wide-mouth volumetric pipet was used to pipet from a beaker with well-mix sample. For SCOD, samples were filtered with a 0.45 μm PES membrane Millex-HP syringe driven filter upon addition to the COD vial. For every batch of COD vials that underwent digestion, the COD of a potassium hydrogen phthalate (KHP) standard was measured using the same method as required by Standard Methods. The acceptance criteria for COD measured for the KHP standard is that it must be within 15 percent of the theoretical value. Once every three months, a calibration curve was developed as required using

five KHP standard concentrations to check the accuracy of the internal program of the spectrophotometer. The x-axis of the calibration was the theoretical COD values and the y-axis of the calibration curve was the measured COD values using the internal program of the spectrophotometer. The acceptance criteria is that the slope of the calibration curve must be within 1±10 percent.

Total Suspended Solids and Volatile Suspended Solids

The TSS and VSS were done in accordance with procedures in Standard Methods 2540D and Standard Methods 2540E, respectively. The TSS method consisted of filtering a well-mixed sample through a glass-fiber filter. The filter with the residue collected was then dried at 103 to 105ºC. The weight of the dried residue and the amount of sample volume used for filtering gave a measure of the TSS concentration. For the VSS method, the dried residue on the filter was ignited at 550ºC and cooled in a desiccator. The weight loss due to the ignition and the amount of sample volume used for filtering gave a measure of the VSS concentration. The glass-fiber filter used were Whatman grade 934AH or its equivalents.

Alkalinity

Alkalinity was measured in accordance with Standard Methods 2320B. The procedure consisted of titrating 100 ml of sample with 0.02N sulfuric acid to a 4.6 pH. The alkalinity concentration was determined based on the volume of 0.02N sulfuric acid added to reach the end-point pH. The 0.02N sulfuric acid solution was purchased from Fisher Scientific. Every time a new batch of 0.02N sulfuric acid was transferred out of the packaged container, its normality was checked against a known sodium carbonate primary standard.

Ammonia

Ammonia-nitrogen was measured using Standard Method 4500-NH_3-G and Seal Analytical's Method G-102-93 Rev 7 with a Bran + Luebbe AutoAnalyzer 3 (AA3).

Samples were filtered immediately upon arriving at the UWCEE laboratory using 0.45um Millepore Millex filters. If necessary, samples were diluted using Milli-Q water. Alkaline phenate and dichloroisocyanuric acid were combined with samples to produce a blue color with intensity proportional to their ammonia concentration. The AA3 measured ammonia concentrations by photometric determination at 660 nm wavelength with a 10mm flowcell. Reagent preparation and additional procedure information has been documented in the UWCEE Standard Operating Procedure for Ammonia.

Nitrate + Nitrite

Nitrate + nitrite nitrogen (NOx-N) was measured using Standard Method 4500 NO_3 H and Seal Analytical Method No. G-109-94 Rev 7 with an AA3.

Samples were filtered immediately upon arrival at the UWCEE laboratory, using 0.45um Millepore Millex filters. If necessary, samples were diluted using Milli-Q water. Hydrazine, in an alkaline solution with a copper catalyst reduced nitrate to nitrite in the AA3 flow tubes. Sulfanilamide and N-(1-naphthyl) ethylenediamine dihydrochloride (NEDD) were then added to produce a pink color proportional to the nitrite concentration. The AA3 measured NOx-N concentrations by photometric determination at 550 nm wavelength with a 10mm flowcell. Reagent preparation and additional procedure information has been documented in the UWCEE Standard Operating Procedure for Nitrite and Nitrate.

Total Nitrogen

Total nitrogen was determined using a two-step process; Standard Method 4500 PJ for digestion followed by 4500 NO_3 H with an AA3.

Unfiltered samples were diluted prior to digestion, with the full set of standards digested along with the samples. The digestion process converted nitrogenous wastewater compounds to nitrate. Digested samples were then analyzed for nitrate, resulting in a measurement of total nitrogen. Following digestion, samples were filtered before being analyzed by the AA3 for NOx-N as described in section "Nitrate + Nitrite." Reagent preparation and additional procedure information has been documented in the UWCEE Standard Operating Procedure for Total Nitrogen Digestion and the Standard Operating Procedure for Nitrite and Nitrate.

Total Phosphorus

Total phosphorus was determined using a two-step process; Standard Method 4500 P B for digestion, followed by 4500 P E.

Unfiltered samples were diluted prior to digestion, with the full set of standards digested along with the samples. The digestion process converted all forms of phosphorus to orthophosphate. Orthophosphate is then converted, using acidified ammonium molybdate, to a phosphomolybdate complex. Ascorbic acid and antimony were then added to the phosphomolybdate complex, which produced a blue color with intensity proportional to the orthophosphorus concentration. Orthophosphorus concentrations were measured using a Shimadzu spectrophotometer, Model UV-1601. Reagent preparation and additional procedure information has been documented in the UWCEE Standard Operating Procedure for Total Phosphorus.

Quality Assurance and Quality Control Overview

A number of Quality Assurance and Quality Control (QA/QC) procedures were completed to ensure the accuracy and quality of the data gathered for the project. The QA/QC procedures included performance evaluation, blind samples, and field duplicates.

Performance Evaluation

The purpose of Performance Evaluation (PE) was to evaluate the accuracy of analytical procedures. Performance evaluation was conducted twice during the course of evaluation; in May 2012, and between December 2012 and January 2013. PE samples for pH, alkalinity, BOD_5, $CBOD_5$, COD, TSS, TKN, NH_4-N, NO_x-N, and TP were purchased from Ultra Scientific and ERA. Concentrations of the purchased PE samples were only known to the QA/QC manager for the project. Laboratory personnel performed the analyses of the PE samples and reported the results to the QA/QC manager. The QA/QC manager then compared the results with answers obtained from the PE sample suppliers. The comparison was to assess the accuracy of the testing results obtained by the laboratory personnel. Results from the two PE sample testings shown in Table 8 show very good agreement between the UWCEE laboratory results and the PE samples.

Table 8. Comparison of the UWCEE laboratory analytical results and the supplier values for the performance evaluation events.

	1st PE Testing			2nd PE Testing		
Parameter[a]	Analytical Result	Supplier Value	CV (%)	Analytical Result	Supplier Value	CV (%)
pH	9.2	9.1	1.1	9.3	9.1	1.1
Alkalinity[b]	116.0	117.0	0.6	167.0	168.0	0.4
BOD	65.2	69.0	4.0	155.2	140.0	7.3
CBOD	64.7	59.4	6.0	155.1	120.0	18.0
COD	64.7	59.4	6.0	218.1	226.0	2.5
TSS	110.0	114.0	2.5	79.7	84.1	3.8
TKN	9.1	9.3	1.8	1.1	1.2	3.7
NH_4-N	6.9	6.8	0.4	13.0	13.8	4.1
NO_x-N	12.1	12.5	2.6	7.9	8.0	0.6
TP	2.6	2.5	1.7	5.9	5.2	8.9

[a]Otherwise specified, units are in mg/L
[b]Unit in mg/L as $CaCO_3$

Blind Samples

The purpose of the blind samples was to evaluate the analytical precision of the laboratory work. Blind sample testing was done at a minimum frequency of once every three months and the results are shown in Table 9. For each test, the QA/QC manager selected an effluent from one of the three systems, known only to the QA/QC manager and individual responsible for sampling at the site. The selected sample was split into two; one was labelled in the usual way with the effluent's name and the other was labelled as the blind sample. Laboratory personnel then performed analytical analyses on the blind sample without knowing its identity. Comparison of the blind sample result with its corresponding effluent was used to evaluate analytical precision. The results in Table 9 show excellent duplication of the analytical values for the blind and selected effluent sample.

Table 9. Results of blind samples and the corresponding selected effluents[a].

Sample Date	$CBOD_5$	SCOD	TSS	VSS	Alkalinity[b]	TN	NH_4-N	NO_x-N	TP
9/21/2012									
Blind Sample	11.6	21.7	5.6	5.1	228.7	9.1	6.6	1.6	2.8
Selected Effluent	10.6	21.2	6.1	5.2	228.7	9.3	6.8	1.6	2.9
CV (%)	6.4	1.6	6.0	1.4	0.0	1.2	1.3	1.3	0.7
10/30/2012									
Blind Sample	7.4	28.6	6.2	4.3	159.0	12.5	3.2	7.9	4.0
Selected Effluent	7.2	28.3	6.0	4.7	160.0	11.2	3.5	8.3	4.4
CV (%)	1.9	0.7	2.3	6.3	0.4	7.5	5.1	3.4	6.4
1/23/2013									
Blind Sample	7.7	30.4	4.0	3.1	186.0	6.5	5.6	0.2	2.9
Selected Effluent	7.1	28.8	4.0	3.0	187.0	6.3	5.5	0.2	2.9
CV (%)	5.7	3.8	0.0	2.3	0.4	2.4	1.8	0.0	1.2
4/2/2013									
Blind Sample	10.4	30.3	3.8	3.4	223.0	9.1	7.7	0.2	4.9
Selected Effluent	10.6	31.1	4.0	3.8	222.0	9.2	7.7	0.2	4.6
CV (%)	1.3	1.8	3.6	7.9	0.3	0.8	0.5	0.0	4.0
7/23/2013									
Blind Sample	4.2	21.4	<2.5	-	173.0	14.1	5.4	7.5	4.5
Selected Effluent	4.5	22.8	<2.5	-	174.0	15.0	5.4	7.5	4.5
CV (%)	4.9	4.5	-	-	0.4	4.3	0.0	0.4	0.0

[a]Otherwise specified, units are in mg/L
[b]Unit in mg/L as $CaCO_3$

Field Duplicates

The purpose of the field duplicates was to check for any site sampling deficiencies, such as collection of non-representative samples or contamination of the composite containers. Each of the three testing systems had a sampler to collect its usual effluent sample. For a field duplicate, a second sampler was placed next to the primary sampler and collected a duplicate composite sample from the same sampling point. The field duplicates were analyzed and compared. Field duplicate analysis was done once for each effluent system over the duration of the project and the

results are below in Table 10. Similar results between the field duplicates showed that the composite samples collected were representative and there was no contamination of the composite containers.

Table 10. Results of field duplicate samples and the corresponding effluents[a].

Sample Date	$CBOD_5$	SCOD	TSS	VSS	Alkalinity[b]	TN	NH_4-N	NO_x-N	TP
10/16/2012									
Vegetated RGF	10.9	26.6	5.2	4.2	160.0	17.2	4.5	9.7	3.2
Field Duplicate	10.9	27.8	4.2	3.5	161.0	16.0	4.6	8.8	3.1
CV (%)	0.0	3.1	15.0	12.9	0.4	5.1	2.0	6.9	2.9
11/8/2012									
Woodchip Bed	3.6	28.9	2.0	1.8	135.0	0.98	0.04	0.06	2.2
Field Duplicate	3.7	28.9	2.5	2.3	134.7	0.96	0.04	0.07	1.9
CV (%)	1.9	0.0	15.7	17.2	0.2	1.5	0	10.8	7.6

[a]Otherwise specified, units are in mg/L.
[b]Unit in mg/L as $CaCO_3$.

RESULTS

Introduction

The primary project objective was to assess the nitrogen removal performance of the single-stage vegetated recirculating gravel filter (Vegetated RGF) system and the two-stage vegetated denitrifying woodchip bed (Woodchip bed) system over a testing period of one year. This study also observed system recovery following five stress tests. Additionally, the Woodchip bed system was monitored to observe changes in nitrogen removal and soluble carbon, in relation to temperature. Results from the verification testing provides information for agencies (e.g., DOH) and homeowners regarding expected system performance.

Intermediate samples (Intermediate RGF) were collected for the two-stage system for all analytical parameters tested, except total phosphorus. The Intermediate RGF sample was collected after the recirculating gravel filter and before the woodchip bed. Most results presented are for the final effluents of the Woodchip bed system, and Intermediate RGF stage results are provided when relevant to overall system performance. The two-stage Woodchip bed system produced effluents with lower TN, ammonium, nitrate and fecal coliform concentrations, whereas the single-stage Vegetated RGF system effluents had lower sCOD concentrations. BOD, TSS and TP removal were similar for both systems.

Table 11. Verification testing results from August 2012 to July 2013.

	TN (mg-N/L)	Ammonia (mg-N/L)	NOx (mg-N/L)	TP (mg-P/L)	BOD (mg/L)	sCOD (mg/L)	TSS (mg/L)	Fecal Coliform (CFU/ 100mL)
Influent								
Average	48.9	29.3	-	5.9	314	157	362	$1.1x10^7$
Std Dev	9.45	5.4	-	1.3	98	32	148	$8.9x10^6$
Vegetated RGF								
Average	15.2	4.1	9.5	3.5	5.6	20.7	3.58	$4.2x10^5$
Std Dev	1.8	1.0	2.0	1.1	1.8	7.2	1.60	$4.3x10^5$
Woodchip bed								
Average	4.0	0.5	2.4	3.4	10.2	37.6	2.85	$3.2x10^3$
Std Dev	3.8	0.5	3.7	1.9	13.7	20.7	1.77	$5.8x10^3$

Startup Period

Startup Analytical Results

Per the Quality Assurance Project Plan (QAPP), effluent ammonia concentrations had to be less than 10 mg/L for three consecutive days in order to conclude the startup period and begin verification testing. For samples collected on July 25-27, 2012, influent ammonia concentrations averaged 32.3 ± 1.0 mg-N/L, and effluent ammonia concentrations averaged 3.9 ± 0.5 mg-N/L and 0.5 ± 0.1 mg-N/L, for the Vegetated RGF and Woodchip bed systems, respectively. Therefore, verification testing was initiated on July 30, 2012. Additional parameters were intermittently monitored during the startup period (Table 12).

Table 12. Startup period analytical results.

Date	Temp. °C	TN (mg-N/L)	Ammonia (mg-N/L)	NOx (mg-N/L)	BOD (mg/L)	TSS (mg/L)	COD/sCOD* (mg/L)	Alkalinity (mg/L)
Influent								
17-Jul-12	-	67.9	48.9	-	304	284	662	220
25-Jul-12	21.9	48.4	32.0	-	500	634	868	230
26-Jul-12	-	-	31.4	-	-	-	-	-
27-Jul-12	20.2	-	33.3	-	-	-	-	-
Vegetated RGF System								
17-Jul-12	21.4	18.6	13.0	8.8	16.8	7.0	45.7	205
25-Jul-12	23.6	20.4	4.4	13.4	7.8	4.4	39.4	197
26-Jul-12	-	-	3.8	-	-	-	-	-
27-Jul-12	22.0	-	3.6	-	-	-	-	-
Woodchip Bed System								
17-Jul-12	21.4	3.2	0.1	1.5	13.0	3.7	51.5	177
25-Jul-12	22.4	4.2	0.5	0.3	-	3.4	68.7	213
26-Jul-12	-	-	0.5	-	-	-	-	-
27-Jul-12	22.1	-	0.7	-	-	-	-	-

*Effluent

Verification Testing Period

During the course of verification testing, sampler malfunctions occasionally resulted in missing samples. For this reason, Intermediate RGF samples were not available for September 11 or November 13, 2012. Woodchip bed samples were not collected on November 6 and 11, 2012. The intermediate RGF and Woodchip bed did not include a complete 24-hour composite for April 14, 15 or 16, 2013. Normal plant operations at the Snoqualmie WWTP also occasionally impacted verification testing. On November 8, 2012, construction activities resulted in a loss of power to the influent sampler, so this sample was not collected. Snoqualmie WWTP emptied their mixed liquor tanks for several days in early January. As a result, influent BOD_5, COD and TSS concentrations were unusually high for the January 15, 2013 sample.

BOD_5, $CBOD_5$, and sCOD

BOD_5 was measured for the influent and $CBOD_5$ was measured for the effluents. The average influent BOD_5 was 314 ± 98 mg/L. The Vegetated RGF system achieved 98.2% BOD removal, with the effluent $CBOD_5$ concentration averaging 5.6 ± 1.8 mg/L. The Intermediate RGF step accomplished all of the $CBOD_5$ removal in the dual Woodchip bed system, with Intermediate RGF effluent values averaging 4.7 ± 2.6 mg/L. After flowing through the Woodchip bed, effluent $CBOD_5$ actually increased to 10.2 ± 13.7 mg/L, for an overall removal of 96.8% for the two-stage system.

Influent COD and sCOD averaged 715 ± 223 mg/L and 157 ± 32.4 mg/L, respectively. The average sCOD for the Vegetated RGF system was 20.7 ± 7.18 mg/L, indicating 86.8% removal. As seen with BOD, the two stage system showed the greatest COD removal after the Intermediate RGF stage with an average sCOD of 21.6 ± 5.5 mg/L, and an increase to 37.6 ± 20.7 mg/L for the Woodchip bed stage. This gave an overall sCOD removal for the two stage system of 76.1%.

Table 13. The Vegetated RGF system provides similar removal of $CBOD_5$ and greater removal of sCOD than the Woodchip bed system.

	[a]Influent	[b]Vegetated RGF	Percent Removal	[b]Woodchip bed	Percent Removal
$BOD_5/CBOD_5$, mg/L					
Average	314	5.6	98.2%	10.2	96.8%
Std. Dev.	98	1.8		13.7	
95th Percentile	514	9.1		27.6	
sCOD, mg/L					
Average	157	20.7	86.8%	37.6	76.1%
Std. Dev.	32	7.2		20.7	
95th Percentile	214	30.3		71.4	

[a]BOD_5 measured for influent

[b]$CBOD_5$ measured for effluents

Suspended Solids, TSS and VSS

The average influent total suspended solids (TSS) concentration was 363 ± 148 mg/L. Effluent TSS averaged <4.0 mg/L for the Vegetated RGF, <10.0 mg/L for the Intermediate RGF, and was reduced further to <3.0 mg/L after the Woodchip bed stage. Both the Vegetated RGF and Woodchip bed systems achieved 99% removal. Volatile suspended solids (VSS) removal was similar, with an average influent VSS concentration of 324 ± 131 mg/L, which was reduced to 3.7 ± 1.54 and 1.4 ± 2.87 mg/L, respectively, by the Vegetated RGF and Woodchip bed systems (i.e. 98.9% and 99.6% removal, respectively). The Intermediate RGF stage alone reduced VSS by 98.3%.

Table 14. Both the Vegetated RGF and Woodchip bed systems removed high concentrations of suspended solids.

	Influent	Vegetated RGF	Percent Removal	Woodchip bed	Percent Removal
[a]TSS, mg/L					
Average	362	3.6	99.0%	2.9	99.4%
Std. Dev.	148	1.6		2.0	
95th Percentile	662	7.1		8.3	
VSS, mg/L					
Average	324	3.7	98.9%	0.9	99.7%
Std. Dev.	131	1.5		2.3	
95th Percentile	578	7.0		8.1	

[a]TSS concentrations below detection limit were assumed to be half of the detection limit

Fecal Coliform

The average influent fecal coliform (FC) concentration was $1.1 \times 10^7 \pm 8.8 \times 10^6$ colony forming units (CFU) per 100 mL sample. The Woodchip bed system reduced FC to an average concentration of $3.2 \times 10^3 \pm 5.8 \times 10^3$ CFU's. The Vegetated RGF did not reduce FC as much, with an average concentration of $4.0 \times 10^5 \pm 4.2 \times 10^5$ CFU's. The Woodchip bed and Vegetated RGF systems provided >99.9% and 96.4% removal, respectively.

Total Nitrogen

Influent total nitrogen (TN) concentrations averaged 48.9 ± 9.5 mg-N/L, but varied throughout the year. Higher TN values were observed during the summer and fall, lower values in the winter, and especially low values in March and April 2013. The Vegetated RGF had quite consistent effluent TN concentrations throughout the year, and usually much higher values than the Woodchip bed system. The Vegetated RGF effluent TN concentrations averaged 15.1 ± 1.9 mg-N/L, which corresponds to 69.1 ± 4.0% removal.

The yearly average effluent total nitrogen concentration for the Woodchip bed system was 4.0 ± 3.8 mg-N/L, for an average of 91.8 ± 7.8% removal. However, the performance of the

Woodchip bed system was very temperature dependent, so we also considered these data for warm and cold periods. During the warm months (i.e., August through October 2012, and May through July 2013) effluent temperatures averaged 21.6 ± 3.0°C, and during the cold months (i.e., November 2012 through April 2013) effluent temperatures averaged 10.7 ± 2.1°C. During the warm periods effluent TN concentration averaged 1.7 ± 1.0 mg-N/L, and during the cold periods TN concentrations averaged 6.4 ± 4.2 mg-N/L. Therefore, for the Woodchip bed system warm and cold month TN removal averaged 96.8% and 85.7%, respectively. In comparison, TN removal for the Vegetated RGF system was not temperature dependent with removal averaging 70.1% and 67.4% in the warm and cold sampling periods, respectively.

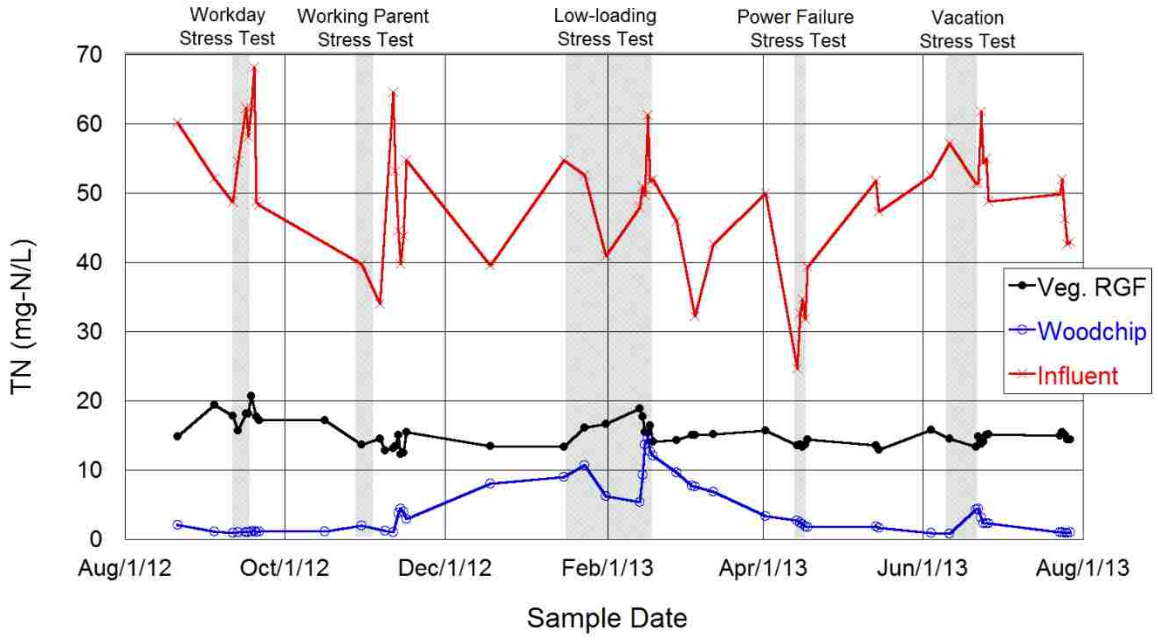

Figure 7. The Woodchip bed effluent TN increases with reduced influent temperatures experienced from November 2012 to April 2013.

Nitrite and Nitrate

The Vegetated RGF system had an average effluent concentration for combined nitrite and nitrate nitrogen (NOx) of 9.4 ± 2.0 mg-N/L. The Intermediate RGF stage of the Woodchip bed system had an average NOx concentration of 20.9 ± 5.5 mg-N/L, while the Woodchip bed effluent had an average NOx concentration of 2.4 ± 3.7 mg-N/L. NOx removal by the Vegetated RGF system was not significantly affected by temperature. The Woodchip bed system exhibited excellent NOx removal during warm months, with an average effluent concentration of only 0.1 ± 0.2 mg-N/L. During cold months, NOx removal was greatly reduced, with an average effluent NOx value of 4.8 ± 4.1 mg-N/L. The relationship between denitrification and temperature is further described in the Discussion.

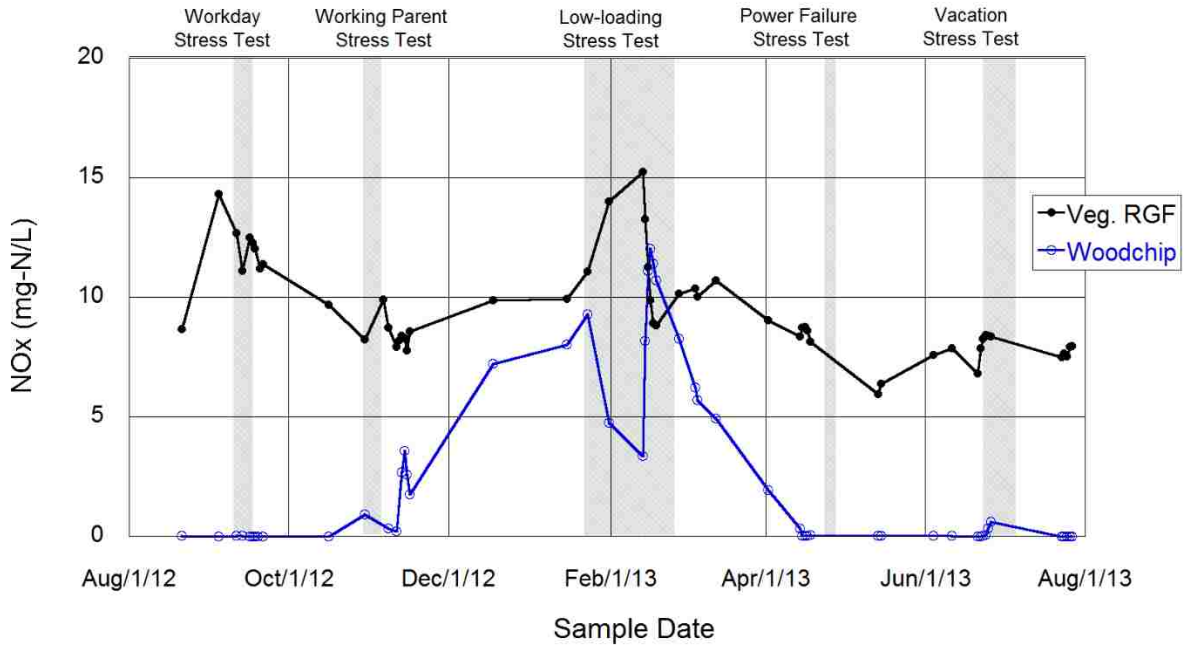

Figure 8. Effluent NOx increased in the Woodchip bed system during cold months, from November through April.

Ammonia

The overall average influent ammonia concentration was 29.3 ± 5.4 mg-N/L. The Vegetated RGF effluent ammonia concentration averaged 4.1 ± 1.0 mg-N/L. The Woodchip bed system ammonia concentration averaged 0.5 ± 0.5 mg-N/L with an average ammonia concentration of 0.7 ± 0.4 mg-N/L at the Intermediate RGF stage. This value, for the Intermediate RGF stage, in combination with its average TN and NOx concentrations of 23.9 ± 5.4 mg-N/L and 20.9 ± 5.5 mg-N/L, indicates that the Intermediate RGF stage was very effective at converting influent ammonia to NOx and that denitrification may also have occurred in this stage.

Organic Nitrogen

Organic nitrogen (organic-N) was not directly measured, however, organic-N concentrations were calculated by subtracting the NOx plus ammonia concentrations from TN. This gave average effluent organic-N concentrations of 1.6 ± 0.9 mg-N/L and 1.1 ± 0.4 mg-N/L for the Vegetated RGF and Woodchip bed systems, respectively.

Total Phosphorus

The average influent total phosphorus (TP) concentration was 5.9 ± 1.3 mg-P/L. Average effluent TP concentrations were similar between systems, i.e., 3.5 ± 1.1 mg-P/L and 3.4 ± 1.9 mg-P/L for the Vegetated RGF and Woodchip bed systems, respectively. These concentrations correspond to about 40-45% TP removal. However, the Woodchip bed tended to have lower TP concentrations, with a median TP concentration of 3.0 versus 3.6 mg-P/L for the Vegetated RGF system. The average TP value for the Woodchip bed system was strongly impacted by a single outlier, i.e., 12.7 mg-P/L.

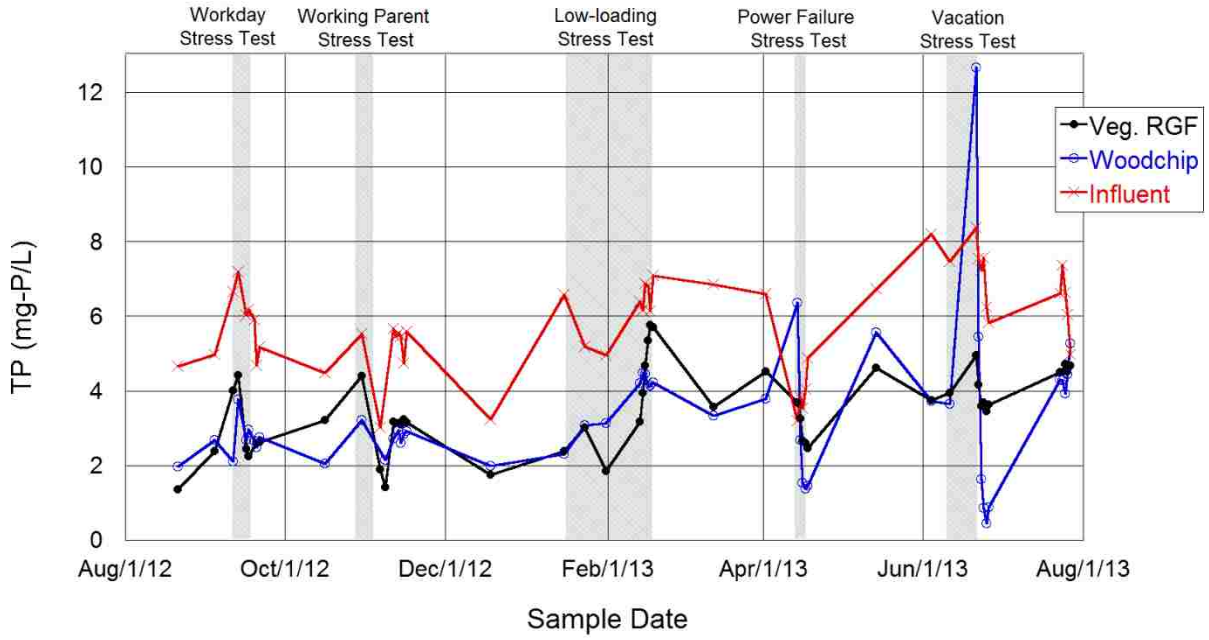

Figure 9. Total phosphorus reductions by the Vegetated RGF and Woodchip bed systems were similar, with Woodchip bed maxima occurring during the Vacation Stress Test

Secondary Water Quality Parameters: Temperature, pH, Alkalinity, Dissolved Oxygen

Temperature

The project site experienced a wide range of temperatures throughout the year, with minimum and maximum influent temperatures of 6.5°C and 25.0°C, respectively, and an average influent temperature of 16.4 ± 4.8°C. Effluent temperatures closely matched the influent temperature with minimum and maximum values for the Vegetated RGF system of 6.8°C and 25.9°C, respectively, and 6.1°C and 25.4°C for the Woodchip bed system.

Alkalinity and pH

The influent pH averaged 7.4 ± 0.3. Both the Vegetated RGF and Woodchip bed produced effluents with lower pH, with averages of 6.8 ± 0.3 and 6.6 ± 0.2, respectively. pH values after the Intermediate RGF stage of the Woodchip bed system averaged 6.8 ± 0.3. Influent alkalinity,

measured as $CaCO_3$, averaged 231 ± 36 mg/L. The Vegetated RGF effluent had an average alkalinity of 153 ±23 mg/L, while the Woodchip bed system averaged 154 ± 37 mg/L.

Dissolved Oxygen

Dissolved oxygen (DO) was not measured for the influent, where it should have been zero. Both the Vegetated RGF and Woodchip bed systems had average DO values below 1.0 mg/L. The Vegetated RGF system DO concentration averaged 0.4 ± 0.4 mg/L, while the Woodchip bed system had slightly lower values averaging 0.2 ± 0.2 mg/L.

Stress Tests

Some stress tests caused changes in system performance, while others did not appear to impact the system at all. The average effluent concentrations during warm and cold months were compared to the averages during the respective stress test to determine whether the stress test caused a system upset. Trend analyses and t-tests were used to determine if there was a significant difference between stress and non-stress samples. Stress samples are defined as those taken while the stress is occurring (e.g., power outage) and includes the consecutive sampling days right after the stress, as the system recovered. Non-stress samples are separated from the stress event by at least one week when taken before a stress test and by one week or more when taken after a stress test.

Washday Stress

The Vegetated RGF system exhibited a slight increase in effluent total nitrogen during the Washday Stress Test. The average TN concentrations were 16.3 ± 2.5 mg-N/L during the two sample days before and after the stress and increased slightly to an average of 18.0 ± 1.5 mg-N/L during the stress test.

Working Parent Stress

The Working Parent Stress occurred at the transition between the warm to cold months. The Woodchip bed system displayed an increase in effluent NOx during the stress event, with much higher concentrations in the samples almost one month after the stress event. Woodchip bed average effluent NOx during the stress test was 1.9 ± 1.4 mg-N/L, and increased to an average 7.6 ± 0.6 mg-N/L for the two samples after the stress test. Possible reasons for lower values during the stress event are likely tied to temperature and are addressed in the Discussion.

Low-loading Stress

The Low-loading Stress Test was initiated on January 23, 2013, and lasted 21 days. The Vegetated RGF and Woodchip bed systems both exhibited increased effluent TN during this test when compared to the two sample events before and after the stress event. The Vegetated RGF average effluent TN was 14.1 ± 0.8 and 16.4 ± 1.5 mg-N/L before/after and during the stress, respectively, while the Woodchip bed average effluent was 8.6 ± 0.8 and 10.7 ± 3.4 mg-N/L before/after and during the stress, respectively. The Woodchip bed effluent NOx concentrations were elevated during the stress, when compared to the two sample events before and after the stress event. The Woodchip bed effluent NOx averaged 8.9 ± 3.2 mg-N/L during the stress event and 7.4 ± 0.9 mg-N/L before/after the stress event.

Power Failure Stress

$CBOD_5$, sCOD and TSS concentrations were elevated for the Woodchip bed system during the Power Failure Stress test. For these three parameters, the increase was especially apparent at the beginning of the stress test, with concentrations tapering off towards the end of the week. The Woodchip bed effluent $CBOD_5$ concentrations averaged 12.1 ± 6.1 and 6.3 ± 9.2 mg-N/L during stress and non-stress samples, respectively. The sCOD concentrations averaged 42.3 ± 17.7 mg/L

during the stress and 36.6 ± 11.4 mg/L during non-stress samples before and after the stress test. The Woodchip bed TSS concentrations were 3.6 ± 3.3 and 1.3 ± 0.0 mg/L during stress and non-stress samples, respectively.

Vacation Stress

$CBOD_5$ and sCOD concentrations were elevated for the Woodchip bed system during the Vacation Stress test. TSS and VSS concentrations noticeably increased in both the Vegetated RGF and Woodchip bed systems. Similar to the Power Failure Stress test, this increase was especially apparent at the beginning of the stress test, with concentrations tapering off towards the end of the experiments. The Vacation Stress test was also associated with a marked increase in the Woodchip bed effluent ammonia, with averages of 1.43 ± 0.77 and 0.17 ± 0.26 during stress and non-stress samples, respectively. The Vacation Stress Test was further associated with the Woodchip bed system's maximum effluent TP value, i.e., 12.7 mg-P/L.

DISCUSSION

The Woodchip bed system displayed exceptional nitrogen reduction over the course of one year, especially during periods of warm temperatures. The Vegetated RGF system removed markedly less nitrogen than the Woodchip bed system, however, its performance was more consistent and not temperature dependent. Design differences between the two systems are responsible for the disparity in nitrogen reduction performance and are discussed in further detail, below. Fecal coliform removal was better in the Woodchip bed system, however the Vegetated RGF system achieved better sCOD reductions. BOD, TSS and TP removal were similar for both systems.

Nitrogen Reduction Performance

Separating the nitrification and denitrification steps into two stages resulted in better overall nitrogen reduction in the Woodchip bed system. The top 24 in. of the gravel media in the Vegetated RGF system was aerobic to encourage nitrification, and the bottom 20 in. of gravel was saturated to encourage denitrification. Due to the system configuration, we could not collect samples from the Vegetated RGF between the upper nitrification and lower denitrification stages. The Intermediate RGF stage of the Woodchip bed system provided aerobic conditions for nitrification, although some denitrification may have occurred, while anoxic conditions to encourage denitrification were provided in the Woodchip bed stage. Nitrification and denitrification performance are addressed individually, below.

Nitrification

Nitrification, i.e., the conversion of septic tank effluent ammonia to nitrate, was the initial nitrogen conversion process that took place in both systems. The Intermediate RGF stage effluent had much higher nitrate and much lower ammonia than the Vegetated RGF system,

Figure 10, indicating that the Intermediate RGF stage achieved more complete nitrification. Ammonia composed nearly 40% of the effluent total nitrogen for the Vegetated RGF system, indicating that inadequate nitrification conditions existed for this system.

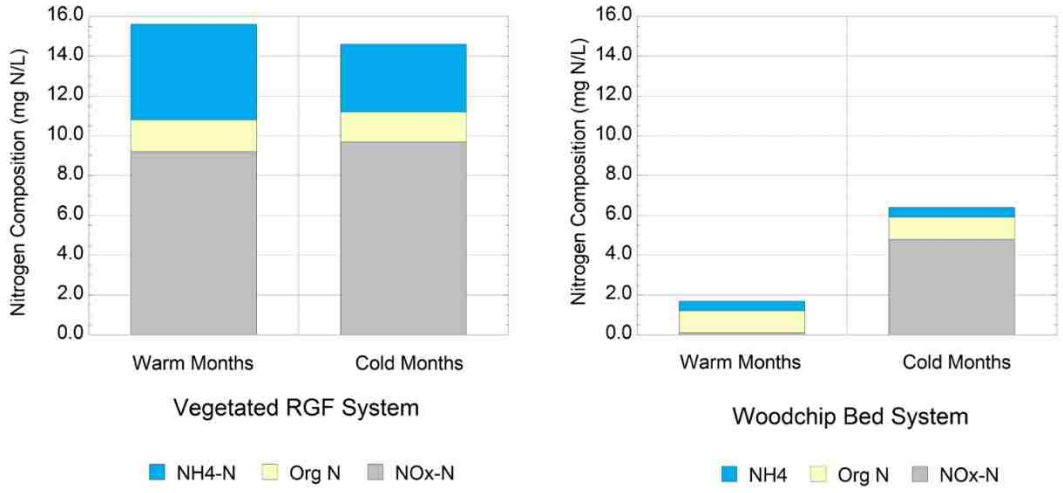

Figure 10. Effluent nitrogen speciation.

Dissolved oxygen, temperature and pH are all important environmental variables that influence nitrification. Dissolved oxygen must be greater than 1 mg/L for nitrification to occur[5]. The Intermediate RGF stage average effluent dissolved oxygen was 5.7 ± 1.9 mg/L, confirming that aerobic conditions existed. The Vegetated RGF system dissolved oxygen measurements were taken after the denitrification zone, therefore it is unknown whether this system had adequate oxygen in the upper nitrification zone. A pressure test performed on the Vegetated RGF system after the verification testing was complete showed that 20 of the 64 distribution orifices were clogged. This may have constricted the effluent path through the gravel media, reducing the gravel media surface area available for nitrification. The clogged orifices were likely caused by roots from the surface vegetation in the Vegetated RGF system. In contrast, the Intermediate

RGF stage had no surface vegetation and had only one clogged orifice at the time of pressure testing.

Microorganisms responsible for nitrification are sensitive to temperature, with cold temperatures associated with reduced nitrification rates[5]. The Intermediate RGF stage nitrate production was only slightly lower in the cold months than in the warm months, indicating that temperatures did not fall low enough to inhibit nitrification. The Vegetated RGF system showed similar nitrate conversion in the cold and warm months, with the presence of surface vegetation roots possibly supporting a more diverse microbial community and therefore buffering nitrification activities during colder temperatures[15,21]. The results for both systems indicate nitrification was not inhibited by low temperatures even during the winter months when effluent temperatures averaged 11.0 ± 1.9 °C and 10.7 ± 2.1 °C for the Vegetated RGF and Woodchip bed system, respectively.

Nitrification activities consume influent alkalinity, as demonstrated by the decrease in alkalinity and pH for both systems. Crites and Tchobanoglous cite the optimum pH for nitrification being 7.2 to 9.0, however the Vegetated RGF system and Intermediate RGF stage effluents both had average pH of just 6.8 ± 0.3[5]. The Intermediate RGF stage ammonia values were consistently less than 1.0 mg-N/L, therefore it appears that alkalinity for the source water in these systems did not limit nitrification. The Vegetated RGF system may have also benefitted from the addition of alkalinity produced during denitrification, which was distributed to the nitrification zone during recirculation. However, any benefit from this additional alkalinity was not reflected in lower effluent ammonia. The un-nitrified septic tank effluent added to the anoxic zone of the Vegetated RGF was likely not well-mixed with the effluent from the aerobic zone, and was therefore the source of the elevated Vegetated RGF effluent ammonia.

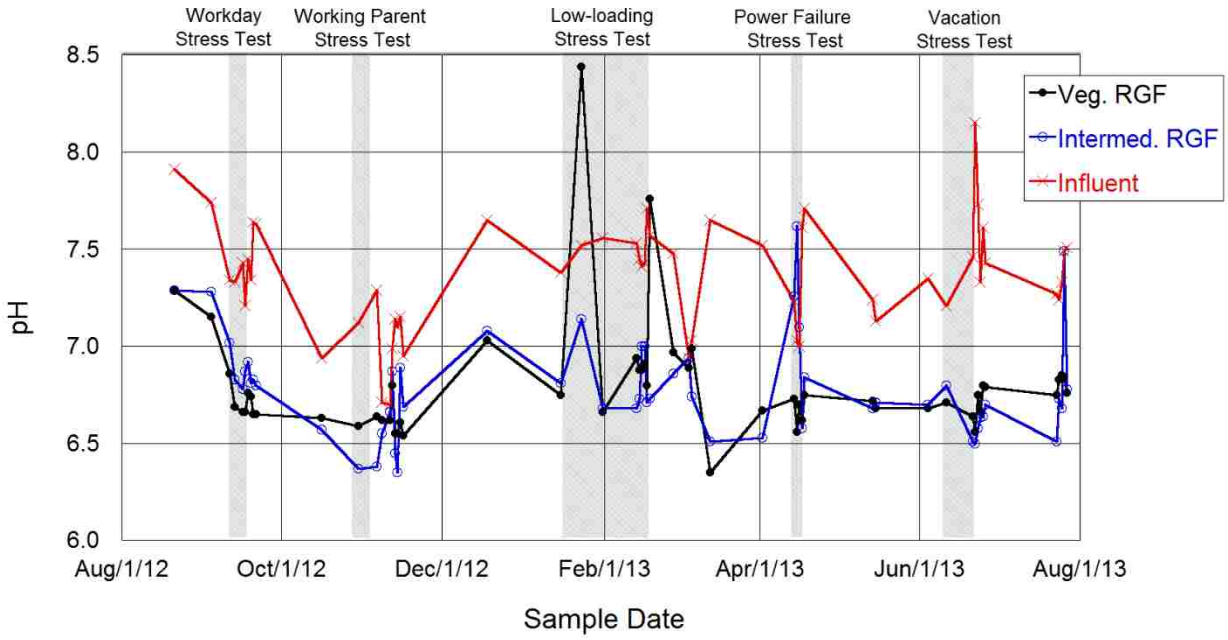

Figure 11. Influent and effluent pH values, with the Intermediate RGF effluent just slightly lower than the Vegetated RGF.

Stress tests performed throughout the verification testing appeared to have a limited impact on nitrification. The Intermediate RGF stage rarely had ammonia values above 1 mg-N/L, however the effluent ammonia was above this value for the six sample days following the three-day Washday Stress Test. This test was performed early in the verification testing schedule, therefore the higher ammonia concentrations are more likely due to a poorly developed nitrifying microbial community rather than the stress test itself. The Vacation Stress Test appears to have reduced nitrification in the Intermediate RGF stage, as high effluent ammonia concentrations were observed during the first two days after wastewater flow was turned back on.

Denitrification

Overall denitrification performance was considerably better in the Woodchip bed system than in the Vegetated RGF system. The environmental variables important to nitrification (dissolved

oxygen, pH and temperature) are also important to denitrification, however, the additional carbon source required for denitrification ultimately controlled the effluent total nitrogen concentration of each system. Septic tank effluent used as a carbon source in the Vegetated RGF system may not have provided enough sCOD, or was not adequately mixed with nitrified effluent, for complete denitrification. Woodchips used in the Woodchip bed system provided adequate sCOD during warm months, but limited denitrification during cold months, possibly due to the temperature sensitivity of the microbial community responsible for breaking down the woodchips[11,15,23].

Both systems provided anoxic conditions to encourage denitrification, with effluent dissolved oxygen concentrations regularly below 1 mg/L. The average effluent pH was similar for the two systems, with slightly lower pH values during warm months. The effluent temperature of both systems was also comparable, however, the Woodchip bed system effluent sCOD concentrations declined noticeably during the colder months. Warm temperatures increased the Woodchip bed effluent sCOD (>40 mg/L) and resulted in remarkable denitrification performance (NOx <0.1 mg/L). During cold months, the Woodchip bed system average effluent sCOD concentration decreased (28.0 ± 10.8 mg/L) and average effluent NOx increased (4.8 ± 4.1 mg-N/L). Reductions in the Woodchip bed system denitrification were most dramatic when effluent temperatures were less than 10°C. Similar temperature sensitivity was noted in Leverenz et. al. with reduced denitrification observed between 11°C and 19°C, where 11°C was the lowest recorded temperature during their study[15]. For the Vegetated RGF system, temperature did not appear to affect dentrification performance. A reduction in average Vegetated RGF effluent sCOD was observed during cold months, however effluent NOx concentrations were similar between warm and cold months.

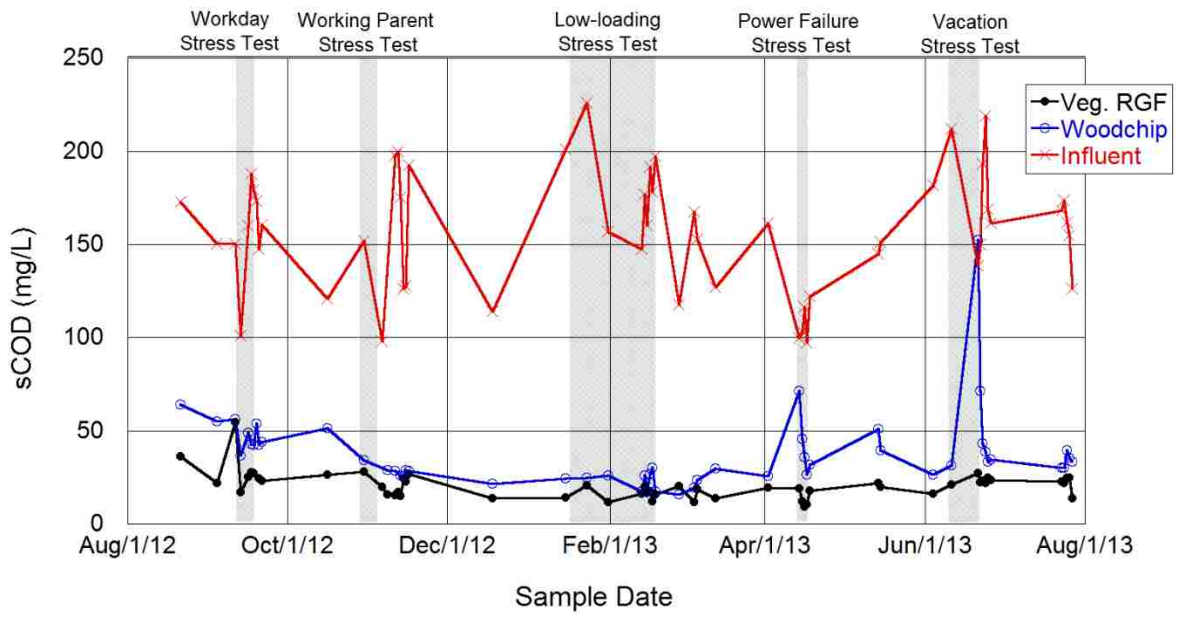

Figure 12. The Woodchip bed effluent soluble carbon concentrations were higher and more variable than the soluble carbon concentrations in the Vegetated RGF effluents.

The Woodchip bed effluent sCOD concentrations were highest in the first two months of verification testing, due to the warm temperatures in August and September and to leaching, often observed with new woodchips[15,21,29]. The length of time that the woodchips will continue to release adequate amounts of soluble carbon is unknown. Previous studies that operated similar systems observed a small, but steady decline in sCOD over their 2-year study[15]. One laboratory scale study observed that 7-year old woodchips still provided adequate sCOD for denitrification, and that the initial rapid loss of sCOD appears to be confined to the first year[29]. The Woodchip bed system displayed a gradual decline in effluent sCOD concentrations over the year, and reflects a common trend seen among other woodchip systems[15,29].

The Low-loading Stress Test was the only stress test that appeared to reduce denitrification in both systems. The Intermediate RGF stage effluent NOx concentrations reached their maximum value during this test. This is noteworthy because the Intermediate RGF effluent NOx maxima

was connected to an operational parameter (low-loading) and not connected to the temperature minima. The denitrifying microbial population likely died back due to the 21-day reduction in wastewater dosing. Once the wastewater feed returned to the normal dosing, the denitrifying microbial population recovered, and after about one week NOx values decreased.

It should be noted that both systems have the potential for denitrification in their respective nitrification zones. Once biofilm growth becomes well established on the gravel media, it is possible for anoxic conditions to develop in the inner most layers of the biofilm, promoting denitrification. The Vegetated RGF system and Intermediate RGF stage did not appear to experience denitrification in the aerobic zone because their respective nitrogen removal did not increase over the course of the year.

BOD_5/$CBOD_5$, Suspended Solids and Fecal Coliform Removal

The Woodchip bed system had a slightly higher average effluent BOD concentrations than the Vegetated RGF system, however BOD removal was similar, 96.8% and 98.2%, respectively. Effluent BOD from the Woodchip bed system was elevated during the first two months of verification testing, which also aligns with the increase in sCOD caused by initial woodchip leaching. Additionally, the Woodchip bed average effluent BOD concentration was heavily influenced by one outlier, the annual maximum value of 90.1 mg/L, which occurred during the Vacation Stress Test. The lack of wastewater provided during this test may have caused substantial biomass decay, increasing the BOD the day wastewater was turned back on and flushed through the system. The Woodchip bed system also had higher effluent BOD during the Power Failure Test than the Vegetated RGF system, but recovered quickly, returning to low BOD values by the end of the sampling week.

The Woodchip bed system removed a greater amount of fecal coliform than the Vegetated RGF system. In fact, the Woodchip bed system fecal coliform removal was two orders of magnitude greater than the Vegetated RGF system. This is probably due to the difference in system configurations. Because the Woodchip bed system has two stages, the first stage removes most of the suspended solids and fecal coliform, leaving the second stage with a large surface area to remove the small remainder. This is similar to how batch reactors operate, where two batch reactors in series typically achieve greater removal than a single batch reactor. The second reactor receives an influent containing far less contaminants than the first reactor did, and therefore has the advantage of treating a much less concentrated influent.

CONCLUSIONS

The goal of this study was to characterize the nitrogen removal performance for two distinctly different systems. One year of verification testing showed that a woodchip based system was capable of removing a higher proportion of total nitrogen than the Vegetated RGF system. Water quality parameters, in addition to nitrogen, were also monitored and shown to vary by system. The principal results of this study are summarized as follows:

- The Woodchip bed system achieved exceptional nitrogen reduction, with an average effluent total nitrogen concentration around 4 mg-N/L, i.e., a 92 ± 8% removal.
- The Vegetated RGF system removed significantly less nitrogen than the Woodchip system, with an average effluent total nitrogen around 15 mg-N/L, i.e., 69 ± 4% removal.
- The Woodchip bed system provided extremely high fecal coliform removal, with an average effluent concentration of 3.2×10^3 CFU/100 mL. The Vegetated RGF system had lower fecal coliform removal, with an average effluent concentration of 4.0×10^5 CFU/100mL.
- The Vegetated RGF system produced an average effluent lower in sCOD. BOD, TSS and TP removal were similar in both systems.
- The Vegetated RGF system produced effluent with a consistent total nitrogen concentration regardless of temperature, while nitrogen removal in the Woodchip bed system varied strongly in relation to temperature.
- Woodchips provided an adequate carbon source for denitrification in the Woodchip bed system. However, the Woodchip bed system had initially elevated effluent sCOD

concentrations, the carbon availability was temperature dependent, and the longevity of woodchip media is unknown.

- Both systems exhibited reduced effluent quality during one or more of the stress tests, however, they generally recovered in less than one week. Fast recovery following stress events shows that these systems are resilient and capable of high nitrogen removal even when they experience variable operation.

Future Work

Funding resources for this project mandated the use of the ETV protocol, which determined the data collection objectives for these systems. Future studies on similar systems would benefit from more data collection, during normal operating conditions. It was also difficult to thoroughly assess the impact of the stress events with only a few adjacent non-stress samples for comparison. Suggested modifications to the ETV protocol include eliminating the Washday, Working Parent and Low-loading stress tests, lengthening the Power/Equipment failure stress test and more frequent non-stress monitoring.

Temperature was shown to be an important variable in denitrification performance of the Woodchip bed system. Future work should explore strategies for elevating the temperature during cold months, or perhaps insulating the denitrifying woodchip bed to retain heat. Successful temperature regulation of the Woodchip bed system has the potential to produce a year-round, high quality effluent. In addition to experimenting with temperature, future studies should consider how long the woodchips in the Woodchip bed system are able to provide sufficient carbon for denitrification of residential wastewater.

And finally, future studies should be done with the Woodchip bed system installed and monitored in residential applications. This would provide valuable information about how the

system performs under actual residential use, rather than the simulated conditions mandated by the ETV protocol. It is possible that influent characteristics or flow patterns vary considerably from those used in this study, possibly revealing design strengths or weaknesses not yet apparent.

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