Final

Evaluation of On-Site Sewage System Nitrogen Removal Technologies

Enhanced Recirculating Gravel Filter

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The University of Washington
Civil and Environmental Engineering Department

and

Washington State Department of Health
Office of Shellfish and Water Protection

Executive Summary

Introduction

Conventional on-site wastewater treatment systems (OWTS), consisting of a septic tank, followed by a drainfield for further treatment and subsurface dispersal, have limited ability for nitrogen removal. Depending on the location, OWTS discharges can cause or contribute to water quality issues related to nitrogen, including unacceptable nitrate levels in drinking water sources and contributing to the acceleration of eutrophication in surface waters. Eutrophication can cause low dissolved oxygen (DO) concentration to levels that are detrimental to fish survival. Many regions of Puget Sound have chronically low DO, and suffer from periodic fish kills. Although marine circulation is the primary source of nitrogen to these sub-basins, the chronically low DO concentrations suggest all prudent measures should be taken to minimize nitrogen inputs. Residential on-site sewage systems have been identified as a significant source of nitrogen in some near shore developments of Puget Sound. Such conditions clearly indicate a need for OWTS that go beyond the traditional septic tank-drainage field practice and can be more effective for nitrogen removal.

Cost effective nitrogen removal in OWTS requires engineered treatment processes that employ biological methods for nitrogen removal. Biological nitrogen removal consists of a combination of an aerobic biological nitrification step in which ammonia is oxidized to nitrate plus nitrite (NOx) by autotrophic bacteria, and an anaerobic biological denitrification step in which NOx is reduced to nitrogen gas by heterotrophic bacteria as they use NOx to oxidize organic carbon in the absence of oxygen. Denitrification is commonly referred to as an *anoxic* reaction to distinguish the fact that the biological reactions are supported by NOx reduction. There are a number of system designs that have been advanced for nitrogen removal in OWTS, but many have had issues of reliability, high maintenance, operational attention, the need for chemical addition, and costs. With consideration to the application for single or multiple residences, OWTS for nitrogen removal that are simple, have minimal mechanical equipment, and do not require daily chemical addition are desired.

A collaborative effort between the Washington State Department of Health (Health) and the University of Washington Civil and Environmental Engineering Department (UWCEE) was undertaken in this project to design and evaluate cost effective, reliable, and low maintenance public domain treatment technologies that have high nitrogen removal efficiencies. In addition to meeting low effluent biochemical oxygen demand (BOD) and low total and volatile suspended solids (TSS and VSS) concentrations and bacteriological reduction, a major treatment objective was to produce an effluent TN concentration below 20 mg/L. A TN concentration of less than 20 mg/L is the Washington State technology-based standard for on-site nitrogen removal. Three passive nitrogen removal systems, with all including a recirculating gravel filter (RGF) for nitrification, were installed and operated for over 13-months at the City of Snoqualmie, WA Water Reclamation Facility (WRF). This report addresses the testing and performance of one of these processes; a septic tank followed by the Enhanced Recirculating Gravel Filter (ERGF) system. This type of system has also been referred to as a recirculating vertical-flow constructed wetland.

Methods

The ERGF system was designed to treat a daily flow of 480 gallons for a 4-bedroom home, based on design guidelines by Health. A 1250-gal, two-compartment septic tank with OSI 4" Biotube® filter in the effluent pipe provided preliminary treatment before the ERGF. The ERGF was 18 ft by 10 ft with an upper recirculating gravel filter aerobic zone and a bottom anoxic zone. The upper aerobic bed had an 18-in. depth of 2-3 mm fine gravel with a 6-in. depth of oyster shell placed directly on top of the fine gravel media and eight 1-in. diameter PVC lateral pipes equally spaced for feed flow distribution. The aerobic and anoxic zones were separated by a 30-mil PVC liner across the entire area of the aerobic bed. The anoxic zone had a 26-in. depth of 0.5-0.75 in. washed gravel. An underdrain system located on the bottom of the aerobic zone collected the nitrified water and direct it to a contact chamber, which also received the septic tank effluent. The contact chamber consisted of a 24-in. diameter PVC pipe that was placed laterally across the bottom of the inlet width of the anoxic zone. The combined flow exited the contact chamber through three 4-in. diameter perforated upflow distribution pipes that were connected at the bottom of the chamber and at the middle and each end of the chamber. The pipes extended along the bottom of the anoxic zone. The liquid from the feed distribution pipes flowed upward to two slotted collection pipes that were located 18 in. above the bottom of anoxic zone. Flow from the collection pipes discharged into the recirculation basin. An effluent sample line was located in the anoxic zone discharge pipe.

A 0.33 hp centrifugal pump (Gould PE31) in the recirculation basin provided 60 uniform doses per day feed to the aerobic zone. Before November 1st, 2012, the volume per dose was 64 gallons for a recirculation ratio of 8.0, and after that it was reduced to 40 gallons per dose for a recirculation ratio of 5.0. The recirculation ratio is the total daily flow pumped from the recirculation basin divided by the influent total daily flow of 480 gallons. An overflow pipe in the recirculation basin was connected to a drain line to direct the ERGF system effluent flow to the Snoqualmie WRF oxidation ditch.

The total footprint area and depth for the ERGF was 180 ft^2 and 4.2 ft, respectively. The aerobic zone media covered 160 ft^2 of the total footprint area. At 480 gpd, the nominal hydraulic application rate (HAR) was 3.0 gal/ft^2-d. The average empty bed contact time (EBCT) for the aerobic and anoxic zones based on a daily feed flow of 480 gpd were 5.0 and 4.2 days, respectively. At an estimated porosity of 0.4, the average pore volume contact time was 2.0 and 1.7 days for the aerobic and anoxic zone, respectively.

Feed for the test system was obtained from a wet well after screening and grit removal of the Snoqualmie WRF influent. The feed system, consisting of a programmable logic controller, a Liberty LSG202M grinder pump, and dosing tank, provided 30 doses per day at 16 gallons each to the septic tank. The dosing frequency was controlled with the programmed logic controller to provide a typical diurnal flow pattern for a single-family home as shown in Table E-1.

Table E-1. Dosing schedule used to represent a typical diurnal wastewater flow pattern from a single-family 4 bedroom home and total daily flow of 480 gal/day.

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

A sampling event consisted of automatic samplers grabbing equal sample volumes of the wastewater influent and ERGF effluent just after each of the 30 dose events to provide flow proportioned 24-hr composite samples. The influent sampler was refrigerated and the effluent sampler contained ice for sample preservation.

After a 1-month start-up period, a 12-month performance testing program was started on July 30, 2012 to evaluate the performance and operation of the ERGF system. The performance testing followed a protocol that was established between NSF international and the United States Environmental Protection Agency (EPA) for the evaluation of on-site systems under the Environmental Technology Verification (ETV) program. Before the testing program began, the ETV protocol was incorporated into a quality assurance project plan (QAPP) that was reviewed and approved by the Washington Department of Ecology. The QAPP outlined the test program operating conditions, testing requirements, data collection methods, sampling schedule, performance constituents to be monitored, and quality control procedures. Standard operating procedures (SOPs) were outlined in detail in a separate document for all of the analytical methods. Data collection spreadsheets with quality acceptance parameters were developed for all the laboratory analyses, and procedures on field sampling, sample delivery and chain of custody were also documented.

The operation and sampling program followed the ETV protocol. A total of 55 sampling events occurred during the 12-month performance testing with a minimum of one sample event for each month. The protocol called for five stress tests that involved changing feed flow conditions and additional sampling days during the stress test period. The stress test conditions and occurrence are summarized in Table E-2.

The following parameters were measured on influent and effluent composite samples to evaluate the nitrogen removal performance: TN, NOx-N and ammonia-N (NH_3-N) concentrations. The organic-N was calculated by subtracting the NOx-N and NH_3-N concentrations from the TN concentration. Other common wastewater treatment parameters were also measured for the influent and effluent composite samples; BOD, chemical oxygen demand (COD), total phosphorus (TP), and alkalinity. A 5-day incubation time was used for all of the BOD measurements. For effluent samples an inhibitor was added to the BOD bottles to prevent nitrification, and thus the resultant BOD is referred to as a carbonaceous BOD (CBOD). Nitrification does not normally occur for raw wastewater BOD as the sample lacks a high enough level of nitrifying bacteria. For effluent COD, the effluent sample was filtered with a 0.45 um membrane filter and is thus a soluble COD (SCOD) measurement. At each sample event influent and effluent grab samples were taken in presterilized bottles for fecal coliform analyses. Grab samples were also obtained for influent and effluent pH and temperature. Effluent flow was measured for dissolved oxygen (DO) in situ.

Table E-2. Stress test condition and schedule during 52 week performance testing. Week 1 of testing period was on July 30, 2012.

Testing Week	Stress Test Name	Simulated Condition	Feed Flow Pattern Change
Week 7	Wash Day	More frequent clothes washing.	Morning and afternoon wash flow (28 gal) with detergent/bleach. Same diurnal flow pattern and total daily flow.
Week 15	Working Parent	No household activity during working hours.	40 percent of flow in morning and 60 percent in evening. Same total daily flow.
Week 26	Low-loading	Extended period of 21 days with less people in home.	Total daily flow at 50 percent; 240 gal. Diurnal pattern at 35, 25, and 40 percent of total for morning, afternoon, and evening periods. Recirculation ratio was 10.0 as the recirculation pumping rate was not changed but the flow was halved.
Week 37	Power/Equipment Failure	Power was off for 48 hrs. No feed and no recirculation pumping.	Power stopped after afternoon flow and sampling. Power resumed during evening period 2 days later and at 60 percent of daily flow instead of 40 percent.
Week 46	Vacation	No feed flow for 8 days. Recirculation pumping continued.	Began after afternoon period. Returned in evening period and with 60 percent of daily flow instead of 40 percent.

Performance Results

For the 12-month performance testing period the average influent TN, BOD, TSS, COD, and TP concentrations were 48.6, 314, 354, 715, and 5.8 mg/L, respectively. The average influent alkalinity concentration was 231 mg/L as $CaCO_3$ and the geometric mean of the influent fecal coliform concentration measurements was $8.4(10^6)$.

The average treatment efficiency over the 12-month testing period is summarized in Table E-3. The average nitrogen removal was 82 percent and the average effluent TN concentration was 8.6 mg/L, which was within the treatment objective of less than 20 mg/L. The average effluent TN concentration consisted of 6.8 mg/L NH_3-N, 0.6 mg/L NOx-N and 1.3 mg/L organic-N. The elevated effluent NH_3-N concentration was due to the fact that a portion of the influent flow was in the effluent overflow from the recirculation basis and that ammonia oxidation did not occur as the influent flow first traveled through the anoxic zone. The effluent NH_3-N concentration was within what would be expected for the 5.0 recirculation ratio to suggest that good nitrification occurred in the aerobic zone of the ERGF system. The ERGF system had high denitrification efficiency as indicated by the low average effluent NOx-N concentration of 0.6 mg/L. The good denitrification efficiency suggests that the septic tank effluent had a high enough influent BOD to nitrogen ratio, an adequate detention time in the anoxic bed, and adequate mixing of the recirculated nitrified flow and the septic tank effluent in the feed contact chamber. The effluent alkalinity and pH averaged 203 mg/L as $CaCO_3$ and 6.9, respectively, to suggest that nitrification performance was not hindered by excessively low pH.

Table E-3. Summary of average percent removal or log reduction for the Enhanced Recirculating Gravel Filter system for the 12-month verification testing period. The fecal coliform reduction is based on the influent and effluent geometric mean concentrations.

Parameter	Percent Removal	Log Reduction
Total N	82	
BOD	97	
TSS	99	
VSS	99	
Total Phosphorus	40	
Fecal Coliform		1.3

With regard to the other wastewater treatment parameters, the BOD and TSS removal across the ERGF system were excellent with average effluent concentrations of 8.6 and 5.3 mg/L and 97 and 99 percent removal, respectively. The total phosphorus removal efficiency averaged 40 percent, which is a little better than expected for typical secondary wastewater treatment systems treating domestic wastewater. A 1.3 log reduction in fecal coliform occurred between the septic tank influent and ERGF effluent. The geometric mean value for the effluent fecal coliform concentrations is 4.6×10^5, which is similar to a typical range of 10^4 and 10^6 given for a filtered effluent following a nitrification activated sludge wastewater treatment system.

Evaluation of the effluent nitrogen over the 12-month performance testing period found that the nitrogen removal performance was impacted by changes in the influent TN concentrations and high headloss across the anoxic zone, and not by temperature or any of the stress tests. Effluent TN concentrations increased with higher influent TN concentration and the effluent TN concentration increased due to an increase in effluent NH_3-N concentration during the last three months of the testing, which had increased headloss across the anoxic zone. The high headloss caused flooding of the lower section of the aerobic zone, which would then limit oxygen availability and nitrification efficiency.

The effluent BOD concentrations were low and showed similar degree of variations on regular sampling days and during stress test sampling days. Minor increases in effluent TSS concentration (2 to 4 mg/L) occurred following the power failure and vacation stress tests, presumably due to biomass sloughing from lack of food. A similar modest increase in effluent TSS was also observed after the washday stress test. The cause of the slight increase in ERGF effluent TSS concentration is not certain but the effect of the detergent addition was a change from the normal feed and is suspect.

The effluent TP concentrations varied widely and tended to follow the patterns in the influent TP concentrations. None of the stress tests seem to have a significant effect on the effluent TP. There was a wide variation in effluent fecal coliform concentrations ranging from 3.0×10^4 to 2.6×10^6 CFU/100ml. For most of the fecal coliform data, the changes in effluent concentrations followed the trends in the influent fecal coliform concentrations. The only exception was an increase in effluent fecal coliform concentration for a number of days after the vacation stress test, which was likely related to an increase in effluent biomass due to sloughing under the starved conditions.

A feature for the ERGF system design was a 6-inch layer of oyster shells at the top of the aerobic zone as a method to provide alkalinity by calcium carbonate leaching from the shells. For the entire 12-month verification testing period, the average alkalinity production by the oyster shells was 10.3 mg/L as $CaCO_3$. While the test results do show that alkalinity can be provided from oyster shells in the treatment process, the amount produced in the ERGF system was relatively small compared to the alkalinity produced from denitrification and was too low to significantly affect the system effluent pH.

Warm and cold temperature ranges occurred in the ERGF system during the 12-month performance testing. The warm period temperatures ranged from 16.7 to 25.1°C during the first 3 months of the testing program and from 18.6 to 24.9°C during the last 3 months. For the cold temperature operating period from November 2012 to March 2013, the temperatures ranged from 7.1 to 11.8°C. In spite of the large range in operating temperatures the removal performance for BOD, TSS, TP, and fecal coliform could not be related to temperature changes. The TN removal efficiency was similar for the first warm period and cold period, but there was a decrease in removal efficiency for the second warm period compared to the preceding cold period; 78 percent versus 86 percent. This was most likely due to the decrease in nitrification efficiency due the headloss increase problem. The minimal sensitivity of performance to temperature is due to the low organic and nitrogen loading for the ERGF system.

Quality Assurance and Quality Control

The Quality Assurance and Quality Control (QA/QC) procedures outlined in the QAPP were completed to ensure the precision, accuracy and quality of the data gathered for the performance testing. The QA/QC procedures included sample replication to measure precision, spike recovery and blind performance evaluation to quantify accuracy, and blind field samples and field duplicates to determine the adequacy of the field sampling, transport and laboratory procedures.

Duplicate analyses were done on all samples for nitrogen measurements and alkalinity and for at least one sample in a sampling event for BOD, COD, TSS and VSS measurements. The laboratory precision was very good, as quantified by the coefficient of variation (CV) shown in Table E-4, and was well below the targeted CV in the QAPP and SOPs. For the small number of samples that did not meet the targeted CV, it was mainly due to having very low effluent values that were close to the detection limits.

Analytical accuracy was determined by a number of methods: (1) frequent spiked recovery samples for nitrogen and phosphorus analyses, (2) frequent known standards for BOD and COD, and (3) two performance evaluation (PE) tests in which pH, alkalinity, BOD, CBOD, COD, TSS, TN, NH_3-N, NO_x-N, and TP were measured on blind commercial standards with the UWCEE lab results compared to the commercial standard answer list provided to the project QA/QC manager.

The accuracy for nitrogen and phosphorus analyses for the test program was very good as indicated by the average percent recovery of the known spike and sample pass frequency as shown in Table E-5.

Table E-4. Summary of QA/QC precision results for all duplicate samples analyses in technology evaluation test program showing the acceptance coefficient of variation (CV) and average CV for all samples.

Analysis	Acceptance CV, %	Average CV, %	Percent of samples passed
TN	20	10.0	99.7
NH_3-N	20	0.9	100.0
NOx-N	10	1.8	99.0
BOD	20	3.1	100.0
COD	20	5.7	100.0
TSS	20	4.9	97.0
VSS	20	6.5	96.0
Alkalinity	20	0.5	100.0
Total P	20	3.7	98.4

Table E-5. Summary of accuracy results for spiked samples for nitrogen and phosphorus analyses.

Analysis	Spiked recovery goal, %	Average spiked recovery, %	Samples passed, %
TN	60-140	102.9	96.4
NH_3-N	80-120	101.4	100.0
NOx-N	60-140	99.7	100.0
Total P	60-140	104.5	100.0

The accuracy goals for BOD and COD analyses were met 100 percent of the time based on testing known standards according to procedures in Standard Methods (APHA, 2005). In the case of BOD, the average recovery for the known standard solution was 105 percent, which was well within the BOD accuracy goal in Standard Methods of ± 15 percent. Similarly for COD the average accuracy relative to the known standard was 104 percent.

The results for the UWCEE lab measurements compared extremely well to the values given for blind samples. For the first PE test the UWCEE measurements were 94 to 104 percent of the values for the above mentioned analytes. For the second PE test the UWCEE measurements were 92 to 113 percent of the values for the above mentioned analytes excluding the BOD sample, which was 129 percent of the stated value for the blind sample and still within the project QA/QC acceptance criteria.

The purpose of the blind samples was to evaluate the analytical precision and accuracy of the laboratory work for all of the sample analyses. Blind sample testing was done at a minimum frequency of once every three months. For each test, the QA/QC manager selected an effluent from one of the three test 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 labeled in the usual way with the effluent’s name and the other was labeled as the blind sample. Laboratory personnel then performed analytical analyses on the blind sample without being informed of its identity. Excellent results were obtained for the blind samples with values ranging from 0.0 to 6.5 percent for all of the measurements.

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 excellent comparative results were obtained to indicate that there was no contamination of the composite containers.

Operations and Maintenance

Qualitative odor observations based on odor strength (intensity) and type (attribute) were made eight times during the verification test. Observations were made during periods of low wind velocity (<10 knots), at a distance of three feet from the treatment system, and recorded at 90° in four directions. There were no discernible odors found during any of the observation periods.

Electrical use was estimated using power consumption information from the pump manufacturer. The estimated average electrical use was 2.53 kilowatts (kW) per day. This estimate appears to be conservative for the one-third horsepower (hp) pump, which operated 2.3 hours/day.

During the test, the system experienced no mechanical problems. The only changes made to the system was to install a Sim/Tech Pressure Filter on October 29, 2012 to address an orifice clogging problem from the growth of filamentous Thiothrix spp. bacteria in anoxic zone effluent. We also adjusted the pump timer to decrease the recirculation ratio from 8.0 to 5.0 on November 1, 2012, to reduce the flow rate to the feed distribution piping in the anoxic zone.

The effluent filter on the outlet from the septic tank required periodic cleaning. During the test, the filter was cleaned after ten months (after one month of start-up and nine months of testing). The orifices in the pressure distribution network were cleaned when the Sim/Tech Pressure Filter was installed. This cleaning was performed to maintain a uniform distribution pattern over the gravel media.

The routine operation and maintenance of the ERGF system was straightforward with the exception of the anoxic zone feed distribution pipe clogging problem described above. The discovery of this clogging problem was based on water level measurements inside the contact chamber. When the problem was identified, the recirculation ratio reduction did not reduce the headloss on a long term basis. While pumping the water out of the anoxic zone was discussed as a method to remove the solids, it was not considered a cost effective maintenance approach nor a long- term solution to the problem at the rate the solids accumulated and moved into the ERGF's feed distribution pipe network.

The treatment system appeared to be of durable design during the test with the exception of the anoxic zone feed distribution pipe network. The piping and construction materials used in the system meet the application needs.

Further ERGF testing and analysis is required to provide treatment performance verification of system design modification needed to address the ERGF's anoxic zone feed distribution pipe clogging problem. Considering this problem occurred early in the test period and could not be corrected during the test without significant system design and construction modifications, Health in consultation with the UWCEE project team determined the development of recommended standards and guidance would not be appropriate for the existing tested system.

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Glossary of Terms

Accuracy - a measure of the closeness of an individual measurement or the average of a number of measurements to the true value and includes random error and systematic error.

Aerobic Process - An aqueous environment where dissolved oxygen is present. Conventional activated sludge treatment uses an aerobic process to support the growth of microorganisms that remove pollutants from untreated wastewater. An aerobic environment is also needed to support the growth of nitrifying bacteria that convert ammonia to nitrite/nitrate in the nitrification process.

Ammonia (NH_3) - The unionized form of the total ammonia nitrogen (TAN). Ammonia exists in equilibrium with ammonia in the gas phase according to Henry's Law and can be removed by stripping it from wastewater at elevated pH. Unionized ammonia is toxic to many organisms at high enough concentrations.

Ammonium (NH_4^+) Ion: The main ammonia species in wastewater under normal pH conditions. At pH 7.5 and lower, more than 99% of the total ammoniacal nitrogen (TAN) is present as ammonium ion.

Ammonia-nitrogen - this refers to the total ammoniacal nitrogen which is the sum of ammonia and ammonium as nitrogen.

Anoxic process - A biological reactor in which no dissolved oxygen exists, but nitrate (NO_3^-) and/or nitrite (NO_2^-) are present to provide electron acceptors for bacteria consumption of carbon with the nitrate/nitrite reduced to nitrogen gas.

Bias -the systematic or persistent distortion of a measurement process that causes errors in one direction.

Chain of Custody (COC) – An unbroken trail of accountability that assures the physical security of samples, data, and records.

Coefficient of Variation - Parameter to describe the variation of analytical test results for two or more samples. It is the ratio of the standard deviation to the mean.

Commissioning – the installation of the nutrient reduction technology and start-up of the technology using test site wastewater.

Comparability – a qualitative term that expresses confidence that two data sets can contribute to a common analysis and interpolation.

Completeness – a qualitative and quantitative term that expresses confidence that all necessary data have been included.

Denitrification - Biological reduction of nitrate or nitrite to nitrogen gas by heterotrophic bacteria when consuming BOD in the absence of oxygen.

Detection limit (limit of detection) – The concentration or amount of an analyte which, on an “a priori” basis, can be determined to a specified level of certainty to be greater than zero.

Duplicates – Two samples collected or measurements made at the same time and location, or two aliquots of the same sample prepared and analyzed in the same batch.

Matrix spike – A QC sample prepared by adding a known amount of the target analyte(s) to an aliquot of a sample to check for bias due to interference or matrix effects.

Nitrification - Biological oxidation of ammonia to nitrite and oxidation of nitrite to nitrate by autotrophic bacteria.

NSF International - An independent agency that develops public health standards, audits and certifications to help protect food, water, and consumer products.

Parameter – A specified characteristic of a population or sample.

Preanoxic process - Application of a denitrification reactor before a nitrification reactor. Nitrate/nitrite is fed to the reactor by a recycle from the nitrification reactor. Influent wastewater or an exogenous carbon source provided BOD for the denitrification reaction.

Precision -a measure of the agreement between replicate measurements of the same property made under similar conditions.

Protocol – a written document that clearly states the objectives, goals, scope and procedures for the study. A protocol shall be used for reference during Vendor participation in the verification testing program.

Organic Nitrogen (organic-N) – A measure of the dissolved and the particulate organic nitrogen in a sample. Organic is calculated by subtracting the ammonia-N concentration and oxidized inorganic nitrogen (NOx) from the TN concentration.

Oxidized inorganic nitrogen (NOx-N) – The sum of nitrate-nitrogen plus nitrite-nitrogen and referred to as NOx-N is this report.

Quality Assurance Project Plan – a written document that describes the implementation of quality assurance and quality control activities during the life cycle of the project.

Representativeness – A measure of the degree to which data accurately and precisely represent a characteristic of a population parameter at a sampling point, a process condition, or environmental condition.

Reproducibility – The precision that measures the variability among the results of measurements of the same sample at different laboratories.

Residuals – The waste streams or solids, excluding final effluent, which are retained by or discharged from the technology.

Standard deviation – A measure of the variation around the mean for two or more data.

Standard Operating Procedure – a written document containing specific procedures and protocols to ensure that quality assurance requirements are maintained.

Technology Panel -a group of individuals established by the Verification Organization with expertise and knowledge in nutrient removal technologies.

Testing Organization – an independent organization qualified to conduct studies and testing of nutrient removal technologies in accordance with protocols and test plans.

Total Ammonia Nitrogen (TAN) - The sum of the unionized ammonia (NH_3) and the ionized ammonium (NH_4^+). Ammonia/ammonium is a weak acid (pKa~9.5) and rapidly changes from one species to the other as pH change. At a pH of 9.5, approximately 50% of the TAN is present as ammonia and 50% as ammonium ion. The colorimetric analyses used measures TAN, which is often referred to as ammonia-nitrogen (ammonia-N), as is the case in this report.

Total Nitrogen (TN) - The sum of total inorganic and total organic nitrogen in a sample. TN was measured by a high temperature persulfate digestion step that converts all of the nitrogen to nitrate, which is then measured by colorimetric or other method.

Verification – to establish evidence on the performance of nutrient reduction technologies under specific conditions, following a predetermined study protocol(s) and test plan(s).

Verification Report – a written document containing all raw and analyzed data, all QA/QC data sheets, descriptions of all collected data, a detailed description of all procedures and methods used in the verification testing, and all QA/QC results. The Verification Test Plan(s) shall be included as part of this document.

Abbreviations and Acronyms

ANSI	American National Standards Institute
BOD	Biochemical Oxygen Demand (five day)
CBOD	Carbonaceous Biochemical Oxygen Demand (five day)
COC	Chain of Custody
COD	Chemical oxygen demand
CV	Coefficient of variation
DO	Dissolved Oxygen
EPA	United States Environmental Protection Agency
ERGF	Enhanced Recirculating Gravel Filter
ETV	Environmental Technology Verification
gal	gallons
gpm	gallons per minute
gpd	gallons per day
hp	horsepower
HAR	Hydraulic application rate
mg/L	milligrams per liter
mL	milliliters
NIST	National Institute of Standards and Technology
NH_3-N	Ammonia-nitrogen which is used in the report to represent the total ammoniacal nitrogen.
NO_2-N	Nitrite-nitrogen
NO_3-N	Nitrate-nitrogen
NOx-N	Sum of NO_2-N and NO_3-N
NSF	NSF International
O&M	Operation and maintenance
OWTS	On-site wastewater treatment system
QA	Quality assurance
QAPP	Quality assurance project plan
QC	Quality control
QMP	Quality management plan
RGF	Recirculating gravel filter

RVFCW	Recirculating vertical flow constructed wetland
SCOD	Soluble COD
SOP	Standard operating procedure
STE	Septic tank effluent
TKN	Total Kjeldahl Nitrogen
TN	Total Nitrogen
TO	Testing Organization
TSS	Total suspended solids
VRGF	Vegetated Recirculating Gravel Filter
VSS	Volatile suspended solids
VTP	Verification Test Plan
Ecology	Washington State Department of Ecology
Health	Washington State Department of Health
WRF	Water Reclamation Facility
UWCEE	University of Washington Civil and Environmental Engineering

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- Tom Holmes - Wastewater Superintendent
- Lyle Beach - Laboratory Analyst
- Brian Richardson - Senior Operator

1.0 Introduction and Objectives

1.1 Background and Objectives

Nitrogen is a major constituent of concern in wastewater management. On average, individuals in the United States discharge 6 to 17 grams of nitrogen per day. Total nitrogen (TN) concentrations in the septic tank effluent (STE) typically range from 50-90 mg/L (Crites and Tchobanoglous, 1998) and is in the form of ammonia-nitrogen (ammonia-N) and organic-nitrogen (organic-N). Nitrogen in subsurface discharge from typical septic tank-drainfield on-site wastewater treatment systems (OWTS) have the potential to cause nitrate contamination in subsurface drinking water supplies and can worsen eutrophication by providing nitrogen for algae growth via subsurface flows into surface waters. Excess nitrogen may fuel the growth of algae, which can lead to severe dissolved oxygen (DO) depletion from oxygen consumption by bacteria during algal die-off and decay. Depleted DO conditions are harmful to aquatic fauna and can eventually cause fish kills.

Many regions of Puget Sound have chronically low DO, and suffer from periodic fish kills. Although marine circulation is the primary source of nitrogen to these sub-basins, given the chronically low oxygen concentrations all prudent measures should be taken to minimize nitrogen inputs. Residential on-site sewage systems have been identified as a significant source of nitrogen in some near shore developments of Puget Sound. Such conditions clearly indicate a need for OWTS that go beyond the traditional septic tank-drainfield practice and can be more effective for nitrogen removal.

Biological nitrification and denitrification have been proven to be the most cost-effective approach for nitrogen removal in wastewater treatment. The design of OWTS for nitrogen removal should be simple with consideration to the application for single or multiple residences, have minimal mechanical equipment, and preferably not require daily chemical additions. There are a number of system designs that have been developed for nitrogen removal in OWTS, but many are unreliable, unstable, have high maintenance, require chemical addition and/or are very expensive for system owners.

The overall goal of this project was to evaluate cost effective, reliable, and low maintenance public domain treatment technologies that have high nitrogen removal efficiencies. In addition to meeting low effluent concentrations of biochemical oxygen demand (BOD) and total suspended solids (TSS) and sufficient bacteriological reductions. A critical treatment objective was to produce an effluent TN concentration below 20 mg/L (Washington State technology-based standard). Three passive nitrogen removal systems that involved the use of a recirculating gravel filter (RGF) for nitrification were tested for over 12-months at the Snoqualmie, WA water reclamation facility (WRF). This report addresses the testing and performance of one of these processes; the Enhanced Recirculating Gravel Filter (ERGF). A protocol that was established between NSF International and the United States Environmental Protection Agency (EPA) for on-site systems, termed the "Environmental Technology Verification" (ETV) program was adopted for this technology evaluation program

1.2 Environmental Technology Verification Protocol

The ERGF technology evaluation in this studied followed protocols from the ETV program, which involves a standardized testing and data collection program developed by the EPA and NSF International (NSF). NSF was established in 1944 as the National Sanitation Foundation and has continued as an independent organization to provide standards and certification programs for the protection of food, water, consumer products, and the environment.

NSF operated the Water Quality Protection Center (WQPC) under the EPA's ETV Program. ETV Program was created by the EPA to facilitate the use of innovative or improved environmental technologies through performance verification and dissemination of information. The overall goal of the ETV program was to accelerate the acceptance and use of improved and more cost-effective technologies for environmental protection. The program evaluated the performance of innovative technologies by developing test plans that involved field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer reviewed reports. The test program assures that the technology evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and verifiable quality are generated and that the results are defensible. The ETV testing program for the evaluation of on-site technologies was followed and considered start-up time and performance testing and data collection over a 12-month period. Identical operating conditions as used in previous on-site technologies ETV program evaluations were employed in this study, and included diurnal flow variations and a series of *stress tests*, which simulated changes in wastewater flow due to various activities that might occur at real single-home residence. Influent and effluent composite sampling and specific sample analyses parameters were defined as well as quality assurance and quality control (QA/QC) procedures.

The ETV testing protocols were incorporated into a quality assurance project plan (QAPP) that was developed jointly by University of Washington Civil and Environmental Engineering (UWCEE) faculty members and the Washington State Department of Health (Health) staff involved in this technology evaluation program. The plan was submitted to and approved by the Washington Department of Ecology (Ecology). This QAPP set forth the experimental design, methods, measurements, quality assurance/quality control goals and reports to be used by the research team to test and verify the nutrient removal performance of three treatment technologies. In addition to the UWCEE's verification measures, Health provided support and maintenance for the field operation and conducted field measurements of treatment process parameters.

1.3 Testing Participants and Responsibilities

The technology evaluation and verification testing program was a combined effort between the Ecology, the Health and UWCEE professors and graduate students. The personnel involved in the project are summarized on Table 1-1. The Health and UWCEE project team produced the project QAPP that was reviewed and approved by Ecology project members. The UWCEE and Health members worked together to finalize the technology designs and the project testing plan and QAPP that was reviewed and approved by the Ecology. The final design, plans and specifications for each process installation was done by Health who also arranged for the site construction, installation, and start-up of the on-site treatment technologies. Health also was responsible for the operation and maintenance (O&M) of the on-site treatment technologies. The UWCEE team participated in the technology designs and treatment system start-up. The UWCEE team was responsible for the composite sampling, sample delivery to the UWCEE lab, sample analyses (with the exception of fecal coliform), QA/QC of the analytical methods, and data synthesis, technology performance evaluation, and reporting. The Snoqualmie WRF laboratory provided fecal coliform analyses of samples collected by the UWCEE field person. On occasions when the Snoqualmie lab services were not available, samples were delivered to AmTest laboratories in Kirkland, WA who were able to provide fecal coliform analyses by a state certified laboratory.

Table 1-1. Project staff and responsibilities.

Project Participants	Role/Organization
Michael Cox US Environmental Protection Agency Region 10	NEP Grant Coordinator
Andrew Kolosseus Washington State Department of Ecology – Water Quality	Project Officer
Tom Gries Washington State Department of Ecology – Environmental Assessment Program	NEP Quality Assurance Coordinator
William R. Kammin Washington State Department of Ecology – Environmental Assessment Program	Ecology Quality Assurance Officer
John Eliasson Washington State Department of Health – Wastewater Management Section	Health Project Manager
Lynn Schneider Washington State Department of Health – Wastewater Management Section	Health Project Coordinator
Andrew Jones Washington State Department of Health – Wastewater Management Section	Health Project Engineering Assistant
David Stensel University of Washington – Civil and Environmental Engineering	UWCEE Project Coordinator

Table 1-1 (continued). Project staff and responsibilities.

Project Participants	Role/Organization
Michael Brett University of Washington – Civil and Environmental Engineering	UWCEE Project Quality Assurance Manager
Crystal Grinnell University of Washington – Civil and Environmental Engineering	Research Assistant Sample analyses and field support
Stephany Wei University of Washington – Civil and Environmental Engineering	Research Assistant Sample analyses and field support
Songlin Wang University of Washington – Civil and Environmental Engineering	UWCEE test site sampling manager
Lyle Beach Snoqualmie Wastewater Treatment Laboratory	WRF Laboratory Manager

1.3.1 Testing Program Organization

An organizational chart for the project is shown in Figure 1-1. The QAPP (Health and UWCEE, 2012) outlined the project test plan and data collection methods and further defined the responsibilities of the project members shown in Figure 1-1.

1.3.2 Test Site

A test site at a local WRF was desired to assure a constant supply of wastewater for the technology testing. A number of facilities were considered and evaluated by UWCEE staff to select a site that had the space and willingness to accommodate the testing installation, a wastewater that was primarily domestic and of sufficient strength to meet the ETV protocol, and within a reasonable distance for site data collection by UWCEE staff. The Snoqualmie WRF met all of the above requirements and the staff of this facility was of great assistance in the installation, operation, and data collection.

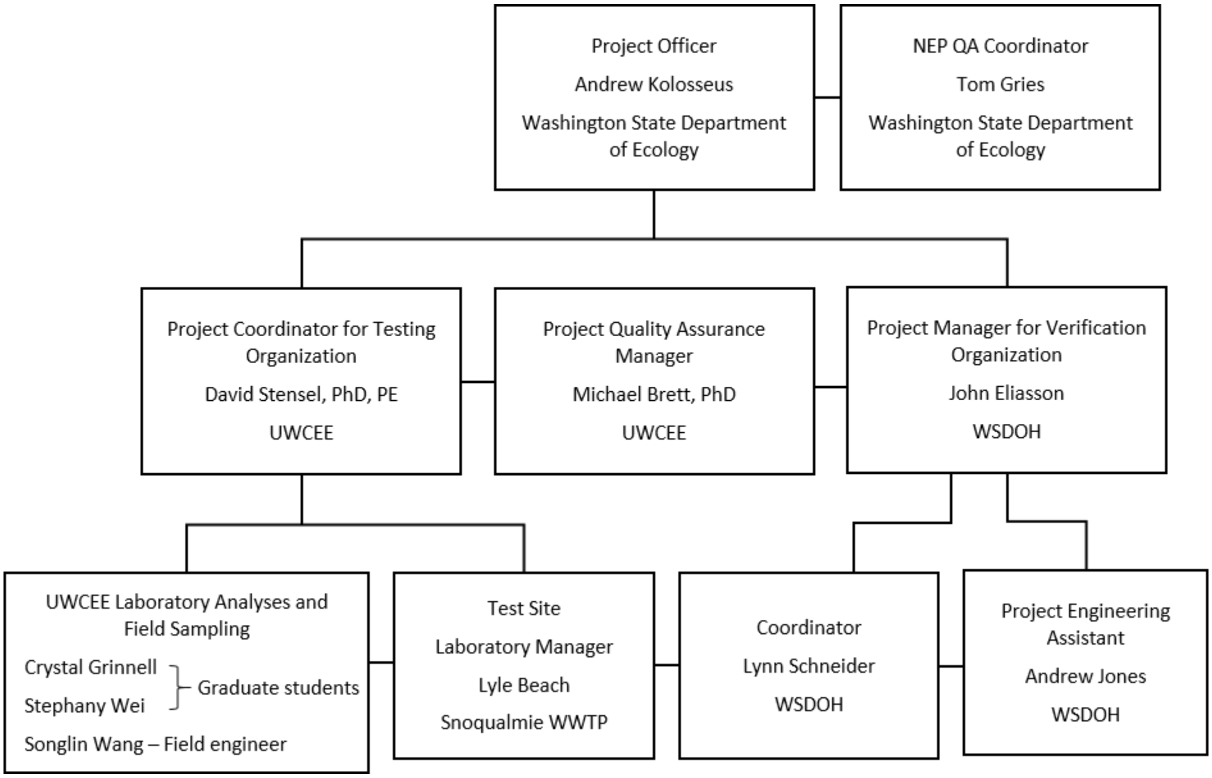


Figure 1-1. Technology verification test program organization.

1.4 Stakeholder Advisory Committee

Representatives from the Stakeholder Advisory Panel assisted the Verification Organization in reviewing and commenting on the QAPP. The Stakeholder Advisory Panel consists of technical experts from the Stakeholder Advisory Committee and other volunteer participants with specific knowledge if wastewater treatment processes. A list of current participants is available from Health.

1.5 Fundamentals of Biological Nitrogen Removal Mechanisms

Biological processes are the most effective nitrogen removal process for on-site wastewater treatment (Health, 2005) and are used after septic tank treatment. The nitrogen entering septic tanks in OWTS is composed of organic nitrogen and ammonia. Between 2 to 10 percent of the influent nitrogen may be removed due to sedimentation of particulate matter (EPA, 1980). A large portion of the organic nitrogen is converted to ammonia-N in the septic tank by ammonification (NH_3-N), so that the STE nitrogen is 85-90 percent ammonia-N (Lowe et al., 2009).

Biological transformation of ammonia-nitrogen (ammonia-N) involves a biological nitrification step to oxidize ammonia to nitrate/nitrite prior to a biological denitrification step, which is the biological reduction of nitrate/nitrite to nitrogen gas.

1.5.1 Biological Nitrification

Nitrification is a two-step biological oxidation of ammonia to nitrate by autotrophic bacteria. In the first step, nitroso-bacteria (common genera are *Nitrosomonas*, *Nitrosococcus*, and *Nitrosospira*) oxidize ammonia to nitrite (NO_2^-). In the second step nitro-bacteria (common genera are (*Nitrospira* and *Nitrobacter*) oxidize nitrite to nitrate (NO_3^-). The bacteria that perform nitrification are chemolithoautotrophs, meaning they use carbon dioxide as carbon source and derive energy from chemical reactions in which inorganic compounds are used as the electron donor. For the nitrification process, ammonia is used as the electron donor and oxygen is the electron acceptor as follows.

Ammonia oxidation: $NH_4^+ + 1.5O_2 \rightarrow NO_2^- + 2H^+ + H_2O$ (1)

Nitrite oxidation: $NO_2^- + 0.5O_2 \rightarrow NO_3^-$ (2)

Overall reaction: $NH_4^+ + 2.0O_2 \rightarrow NO_3^- + 2H^+ + H_2O$ (3)

From the above overall nitrification reaction, 2.0 moles of O_2 are consumed and 2.0 moles of acid are produced per g of ammonia-N oxidized. This equates to 4.57 g of O_2 and 7.14 g of alkalinity (as $CaCO_3$) consumption per g of ammonia-N oxidized. The nitrogen assimilated by bacteria for cell tissue is neglected in the above overall nitrification, so the actual amount of oxygen and alkalinity consumed per gram of ammonia-N removed are less than the stoichiometric values predicted above. Accounting for biomass synthesis results in the use of 4.33 g O_2/g and 7.07 g alkalinity (as $CaCO_3$) per g of ammonia-N removed. Nitrifying bacteria are slow growers compared to heterotrophic bacteria that consume BOD in biological wastewater treatment processes, and are also more sensitive to potential toxic substances, such as metals (especially copper), high sodium concentration, cleaning solvents, and strong oxidizers. However, more nitrification toxicity problems originate from industrial discharges than from domestic wastewater. Important factors affecting nitrification rates and ammonia removal efficiency are (1) DO, (2) pH and alkalinity, and (3) temperature (Tchobanoglous et al., 2013).

Having an ample oxygen supply in a biological nitrification process is important for supplying a sufficient amount of oxygen for ammonia oxidation (4.33 g O_2/g NH_3-N removed) and for maintaining adequate nitrification rates to accomplish the level of ammonia removal needed within the reactor detention time. The effect of DO concentration on nitrification rates is shown in Table 1-2. For systems with lower DO concentration, a lower ammonia loading and longer detention time is needed for the same level on nitrification. Recirculating gravel filters have varying DO concentrations within the media as a function of dosing frequency but have such low ammonia loading rates that there is adequate time for efficient nitrification. The ammonia-N loading rate for the ERGF system in this study was approximately 8.7 g N/m^3-d, which compares to a value of about 720 g N/m^3-d for commonly used fixed film nitrification reactors in municipal wastewater treatment facilities (Tchobanoglous et al., 2013). Thus, the low loadings used in RGFs provides a more than adequate detention time for efficient nitrification provided that proper dosing and uniform flow distribution is maintained.

Table 1-2. Effect of dissolved oxygen concentration on nitrification rate (Tchobanoglous et al., 2013).

DO mg/L	Percent of maximum rate
0.1	17
0.3	38
0.5	50
1.0	67
1.5	75
2.0	80
3.0	86
4.0	89

Alkalinity and pH are critical factors for efficient nitrification in on-site systems. The wastewater alkalinity is decreased and the pH drops due to acid production by the nitrifying bacteria during ammonia oxidation. Optimal pH for nitrification is in the range of 7.5 to 8.0, but many wastewater treatment systems operated very well at pH values in the range of 7.0 to 7.2. Nitrification rates are hindered significantly at pH below 6.8 (Tchobanoglous et al., 2013). Typically, an alkalinity of 50-60 mg/L as $CaCO_3$ is needed to maintain pH of 6.8 or greater (Tchobanoglous et al., 2013). Because of the low loading in RGF nitrifying systems it is possible to obtain satisfactory levels of nitrification at pH values as low as 6.3 to 6.5, but there is a limit to the amount of nitrification possible as a function of the relative influent ammonia-N and alkalinity concentrations. Considering an alkalinity consumption of 7.07 g as $CaCO_3$ per g NH_3-N removed, the alkalinity production from deamination of the feed organic nitrogen, and about 30 percent denitrification in the RGF, the amount of influent alkalinity needed to meet a specified effluent NH_3-N concentration (Ne) would be as follows.

$$A = 6.0\left(Na\text{-}Ne\right) + 40.0 \qquad (4)$$

where A = influent alkalinity needed, mg/L as $CaCO_3$

Na = influent NH_3-N concentration available, mg/L

Ne = effluent NH_3-N concentration, mg/L

The influent nitrogen available (Na) is a function of how much nitrogen is removed in the septic tank, the amount of nitrogen used for biomass growth following BOD removal, and the amount of nonbiodegradable organic nitrogen. Assuming an influent BOD of about 300 mg/L and the need for 10 mg/L N for biomass growth, 2.0 percent of the influent TN as nonbiodegradable, and 10 percent TN removal in the septic tank the available ammonia-N concentration in the feed to the RGF is as follows:

$$Na = No - 0.10No - 0.02No - 10 \qquad (5)$$

where No = RGF feed ammonia-N concentration, mg/L

Using Eq. (4) and (5), the approximate amount of alkalinity needed in the influent to a septic tank to produce an effluent NH_3-N concentration of 1.0 mg/L after RGF treatment is illustrated in Table 1-3. It is important to note that the nitrification performance for an RGF system is a function of the relative wastewater alkalinity and TN concentrations. For areas with low alkalinity water supply (soft water), the nitrification efficiency may be limited unless alkalinity is added.

Table 1-3. Approximate septic tank influent alkalinity needed to produce a nitrified effluent NH_3-N concentration of 1.0 mg/L from a recirculating gravel filter as a function of the influent TN concentration.

Influent TN mg/L	Influent alkalinity as $CaCO_3$ mg/L
70	313
60	265
50	218
40	170
30	123

Nitrification rates are temperature dependent. The rate at 10^0C is about half the rate at 20^0C. However, for low loaded systems the effluent ammonia-N concentration at 10^0C is similar to that at 20^0C because the system has a high nitrifier biomass inventory and excess nitrification capacity.

1.5.2 Biological Denitrification

Nitrification changes the form of influent nitrogen to nitrate or nitrite but denitrification is then needed for nitrogen removal. In the denitrification process nitrite or nitrate is biologically reduced to nitrogen gas. There is a wide range of denitrifying bacteria, but the majority of them are facultative heterotrophs. In the absence of oxygen, the organisms will use nitrate or nitrite as an electron acceptor with reduction to nitrogen gas. Though any biological reaction that occurs without oxygen is defined as anaerobic, the term *anoxic* has been coined in the wastewater treatment field to distinguish an environment in which the major electron acceptor is nitrate or nitrite. Since organic carbon is the electron donor for denitrification, the complete denitrification equation depends on the type of electron donor, but can be generally represented by the following unbalanced equation.

$$NO_3^- + \text{organic matter} \rightarrow N_2 + OH^- + CO_2 + H_2O \qquad (6)$$

For on-site wastewater treatment applications, the organic carbon required for the denitrification process can either be supplied by the influent BOD or by an exogenous source, such as methanol and acetate. The following oxidation-reduction reaction is an example of a biological denitrification reaction using the organic matter in wastewater as the carbon source (Tchobanoglous et al., 2013).

$$C_{10}O_{19}H_3N + 10NO_3^- \rightarrow 5N_2 + 10OH^- + 5CO_2 + 3H_20 + NH_3 + \text{biomass} \qquad (7)$$

From the above equation, 3.57 g of alkalinity (as $CaCO_3$) are produced per g of NO_3-N reduced, which recovers about half of the alkalinity consumed from biological ammonia oxidation. The alkalinity recovery is only useful if denitrification precedes the nitrification step so that the alkalinity produced is available to offset the alkalinity consumed in nitrification. The type of process that provides denitrification before nitrification is termed a *preanoxic* process. Internal recycle from the downstream nitrification zone provides the nitrate/nitrite to the preanoxic reactor.

Denitrification rates and removal efficiency are affected by the amount of biodegradable substrate added to the anoxic reactor, the presence of DO, and temperature. Biodegradable substrate (BOD) must be available to the anoxic reactor to drive the biological demand for an electron acceptor; in this case nitrate or nitrite. The ratio of BOD to nitrate-N is a function of the type of substrate. As a rule of thumb an influent BOD: TN ratio of 4.0 is considered sufficient for 90 percent nitrogen removal in a biological nitrification-denitrification process fed domestic wastewater (Tchobanoglous et al., 2013). At lower ratios there is insufficient BOD so that higher effluent nitrate-N concentrations would be present. For nitrite reduction the amount of BOD needed is about 60 percent of that needed for nitrate reduction. If DO is present or added to the influent to an anoxic process approximately 1.4 g BOD will be consumed by oxygen per g of DO, leaving less BOD available for denitrification. If air is provided to an anoxic reactor a residual DO concentration is present and the denitrification rate is significantly reduced.

Denitrification rates are temperature dependent. The rate at 10^0C is 60 to 70 percent of the rate at 20^0C. However, for low loaded systems such as used for on-site treatment processes and with a sufficient influent BOD/N ratio, the effluent NOx-N concentration at 10^0C can be similar to that at 20^0C because the preanoxic zone has a long detention time and thus a high heterotrophic biomass inventory and excess denitrification capacity. As an illustration of the relative low preanoxic nitrogen loading for the on-site systems tested in this study, the average nitrogen loading was about 8.0 g TN/m^3-d, which compares to typical design loadings of 800 to 2,000 g TN/m^3-d for higher rate systems used in municipal WRF processes that produce effluent NO_3-N concentrations below 2.0 mg/L.

2.0 Technology Description

The ERGF system was designed to provide BOD, suspended solids, fecal coliform, and nitrogen removal for the treatment a daily flow of 480 gallons (gal), deemed to be an appropriate design flow by the Health for a 4 bedroom home single residence. The treatment system consists of a 1250-gal, two-compartment septic tank followed by a modified recirculation gravel filter design with an upper aerobic zone and lower anoxic zone. Details of the ERGF are provided in the following section.

2.1 Septic Tank

A 1250 gal two-compartment septic tank provided pretreatment of the wastewater before the ERGF system. During each dosing, wastewater entered through the septic tank inlet and displaced effluent, which then flowed by gravity to the ERGF. An OSI 4” Biotube® effluent filter was attached to the septic tank outlet pipe to remove grease and fibers from the STE to help prevent plugging in the anoxic zone media of the ERGF system.

2.2 Enhanced Recirculating Gravel Filter Process Description

A schematic of the ERGF system is shown in Figure 2-1 and Figure 2-2. The system aerial dimensions were 18 ft by 10 ft for a footprint area of 180 ft^2. An upper aerobic nitrification zone was located above an anoxic zone. The two zones were separated by a 30-mil PVC liner across the entire area of the aerobic bed.

An 18-in. depth of fine gravel media with an effective size of 2-3 mm was used for the upper aerobic bed. A 6-in. deep layer of oyster shell was placed directly on top of the fine gravel media, for the purpose of adding alkalinity. Dosing of flow from the recirculation pump to the top of aerobic bed was done under pressure through five 1-in. diameter PVC lateral pipes equally spaced at 2 ft with the outer pipes at 1 ft from the outer wall. The lateral pipes had 1/8-in. diameter orifices, placed 24 in. on center and aimed upward at 90 degrees to eject the feed flow against the inside of Hancor ARC 24 chambers (Hancor, 1999-2013) to help spread the feed flow across the top area. Each lateral pipe was covered by a chamber with a total of five chambers used for the five lateral pipes.

The anoxic bed was filled with 0.5-0.75 in. washed gravel to a 26 in. depth. An underdrain system located on the bottom of the aerobic zone was used to collect the nitrified water and direct it to a contact chamber. The 8-ft long contact chamber had a 24-in. inner diameter and was placed laterally across the inlet width of the anoxic zone. The nitrified water collected by the underdrain system entered at the midpoint of the contact chamber through a 4-in. diameter pipe. STE entered by gravity into the same contact chamber through the same 4-in. diameter pipe. The nitrified water was contacted with the septic tank effluent in this chamber. The combined flow exited the contact chamber through three 4-in. diameter perforated upflow distribution pipes extending out from the bottom of the contact chamber and along the bottom of the anoxic zone. The liquid in the anoxic zone flowed through the two 4-in. diameter slotted collection pipes, located 18 in. above the bottom of the anoxic zone, leading to a single 4-in. diameter outlet tee, and then got discharged to the recirculation basin.

The water level in the anoxic zone was controlled by the two slotted collection pipes that discharged the liquid in the anoxic zone to the recirculation basin. The bottom of the slotted collection pipes was at about 18 in. above the bottom of anoxic zone. Therefore, the depth during the start-up and initial period of the verification testing was at about 18 inches. In late October 2012, the water level in the contact chamber was measured at a height of 35 inches, which was well above the design water level of 18 inches. Solids accumulation in the bottom of the contact chamber was also observed. The anoxic zone feed distribution piping connects at the bottom of the contact chamber, and thus it is likely that solids from the contact chamber were collected in the feed distribution piping or in the media above the feed piping to create excessive headloss. To reduce headloss, the flow rate to the anoxic feed piping was reduced by dropping the recirculation ratio from 8.0 to 5.0 on November 1st, 2012.

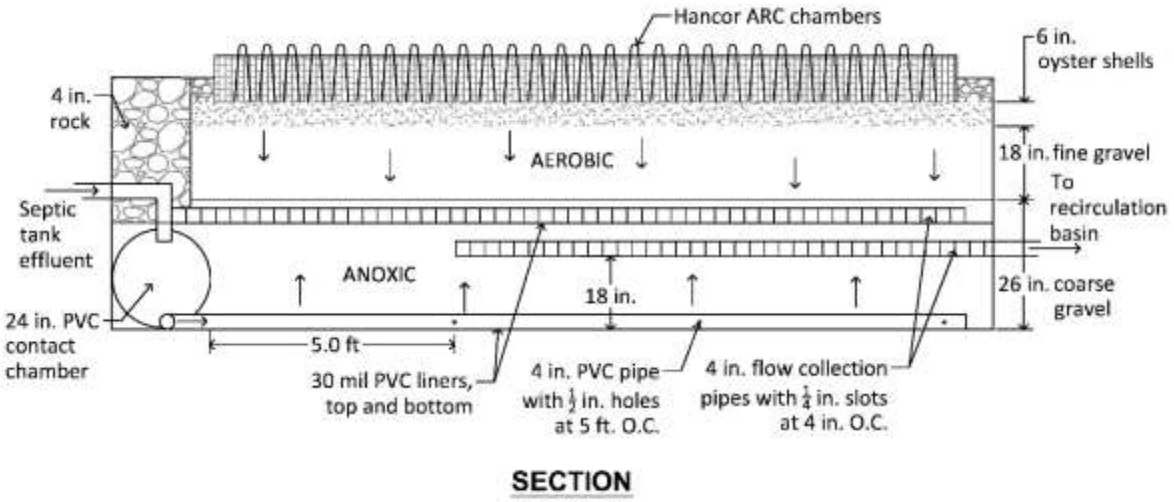
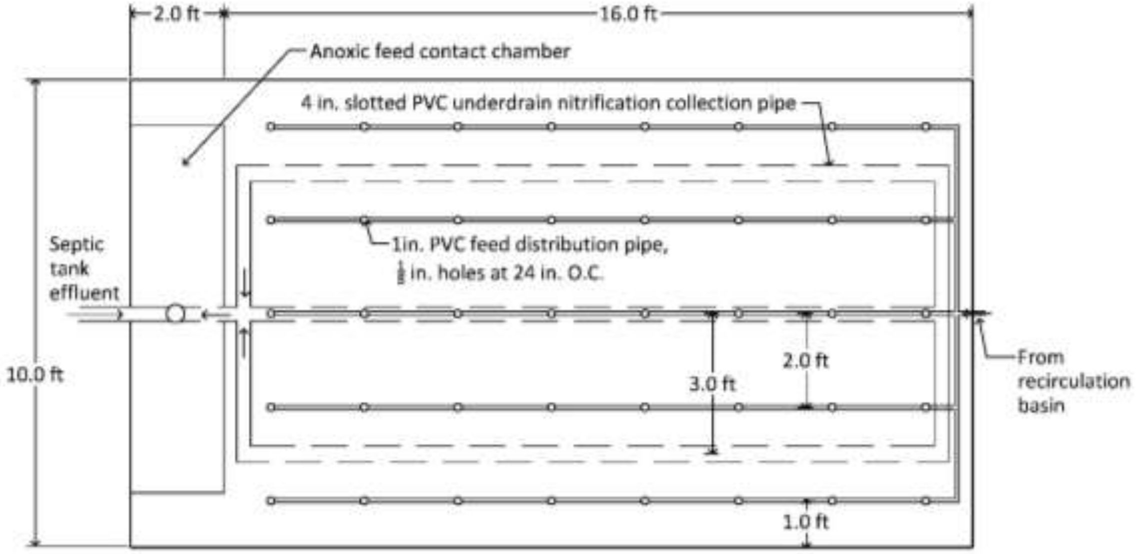
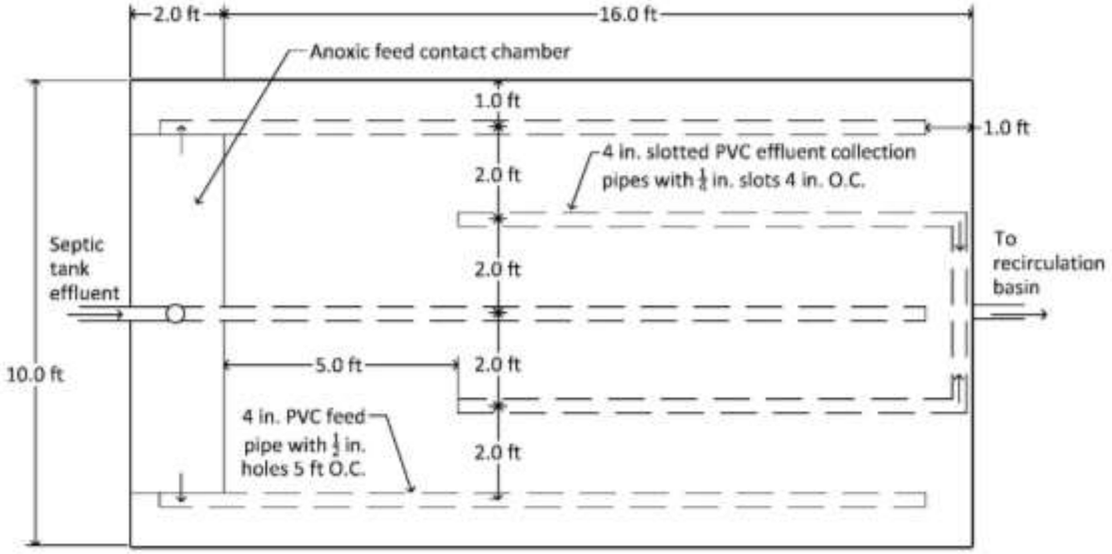


Figure 2-1. Schematic of the Enhanced Recirculating Gravel Filter system



PLAN VIEW (Top Nitrification Section)



PLAN VIEW (Bottom Anoxic Section)

Figure 2-2. Schematics of the top aerobic and bottom anoxic sections of the Enhanced Recirculating Gravel Filter system

The effluent from the anoxic zone overflowed into a 30-in. diameter by 7.5-ft high recirculation basin (Figure 2-3). A sample line was placed inside the 4-in. diameter outlet tee, located in the sampling basin. An autosampler peristaltic pump pulled ERGF effluent samples from this outlet tee into the autosampler container.

A 0.33 hp centrifugal pump (Gould PE31) in the recirculation basin fed flow to the distribution piping at the top of the aerobic bed. The recirculation pump was activated every 24 min by the programmable controller for a period of 2.3 min to result in 60 uniform doses per day. Before November 1st, the pump rate was about 27.7 gpm for a total daily recirculation flow volume of 3820 gal, which is a recirculation ratio of 8.0 based on a daily influent flow of 480 gal. The pump flow rate after November 1st, 2012 was about 17.3 gpm for a total daily recirculation flow of approximately 2400 gal, which equates to an average recirculation ratio of about 5.0. The system effluent overflowed from the recirculation basin from a 4-in. diameter outlet tee located at about 4.5 ft above the bottom of the basin.

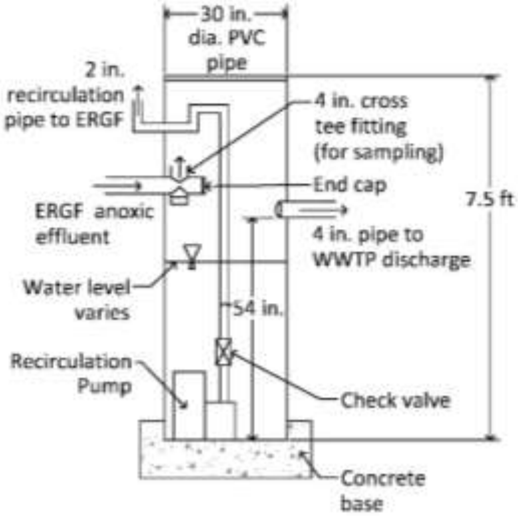


Figure 2-3. Schematic of the recirculation basin for the Enhanced Recirculating Gravel Filter System.

2.3 Process Design Summary of the Enhanced Recirculation Gravel Filter System

The process design summary for the ERGF is given in Table 2-1. The total footprint area and depth were 180 ft^2 and 4.2 ft, respectively. The aerobic zone media covered 160 ft^2 of the total footprint area. At 480 gpd, the nominal hydraulic application rate (HAR) was 3.0 gal/ft^2-d. Assuming even upward flow through distribution pipes on the bottom of anoxic bed, the average anoxic HAR was 2.7 gal/ft^2-d. Note that the instantaneous HARs were 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, was 5.0 and 4.2 days, respectively. At an estimated porosity of 0.4, the average pore volume contact time was 2.0 and 1.7 days for the aerobic and anoxic zone, respectively.

Table 2-1. Process design summary of the Enhanced Recirculating Gravel Filter system.

Parameter	Unit	Value
Dimensions (length × width × depth)	ft	18 × 10 × 4.2
Top area	ft^2	180
Surface vegetation		None
Aerobic bed (oyster shell)		
Size	in	0.75 - 2.5
Depth	in	6
Aerobic bed (fine gravel)		
Effective size	mm	2 - 3
Depth[a]	in	18
Anoxic bed (coarse gravel)		
Size	in	0.5 - 0.75
Depth	in	26
Recirculation ratio		5.0[b]
Average hydraulic application rate		
Aerobic[c]	gal/ft^2-day	3
Anoxic[d]	gal/ft^2-day	2.7
Empty bed contact time		
Aerobic	day	5.0
Anoxic[e]	day	4.2

[a] Measured from below bottom of oyster shell layer.
[b] Started with 6.0, increased to 8.0 on 7/23/2012, and decreased to 5.0 on 11/1/2012.
[c] Based on top total cross-sectional area.
[d] Based on top total cross-sectional area with the assumption that liquid flowed upward evenly throughout the distribution pipes. However, it is expected that most flow volume would be distributed toward the inlet end of the distribution pipes.
[e] Based on anoxic water depth of 18 in. above bottom liner.

2.4 Nitrogen Removal Mechanisms

The principles of biological nitrification and denitrification, previously discussed in sections 1.5.1 and 1.5.2, were applied in the design of the ERGF, which is a fixed media, attached growth biological treatment process. Biological nitrification occurs in the top aerobic zone and denitrification occurs in the bottom anoxic zone. Specific design elements related to this are described in the following sections.

2.4.1 Nitrification

Ammonia and organic nitrogen originating in the STE were fed to the upper aerobic zone by the recirculation flow from the recirculation basin. The STE flow first passes through the bottom anoxic zone where some of the organic nitrogen is converted to ammonia by heterotrophic bacteria. It should be noted that some portion of the STE TN leaves in the effluent from the recirculation basin. The STE is diluted by the recirculation flow from the aerobic zone with a portion of it leaving in the effluent flow from the recirculation basin. At a recirculation flow ratio of 5:1, about 1/6th of the influent TN leaves with the ERGF effluent prior to any ammonia or nitrate transformations.

The ammonia-N fed to the aerobic zone from the recirculation chamber is oxidized to nitrate/nitrite by autotrophic ammonia-oxidizing bacteria in the upper zone media. Heterotrophic bacteria in the aerobic zone also convert biodegradable organic nitrogen to ammonia. Because of the large surface area available for bacteria growth and long detention time a high inventory of nitrifying bacteria is possible.

Oxygen needed by the nitrifying bacteria is provided by oxygen contained in the pore spaces in the aerobic zone media when the bed drains between dosing. Oxygen is also added in the recirculation flow when it is sprayed into the air by the feed lateral orifices and subsequently trickles down through the aerobic zone media.

2.4.2 Denitrification

The nitrite and nitrate contained in the aerobic zone effluent flow enters the anoxic zone through the distribution pipes extending out from the bottom of the contact chamber, where it can be reduced by heterotrophic bacteria contained in the gravel media pore spaces if sufficient BOD is available. A relatively high BOD concentration is contained in the STE that enters into the same contact chamber and gets distributed to the anoxic zone together with the nitrified water. Similar to the ammonia oxidation step, a large inventory of heterotrophic bacteria is possible due to the large surface area available for bacteria growth and long detention time. With sufficient BOD and good contact between the STE flow and aerobic zone flow, an effluent NOx-N concentration of less than 2.0 mg/L can be expected.

2.5 Operation and Maintenance

Health provides recommended standards and guidance (RS&G) for recirculating gravel filters to installers, designers and homeowners with important information about the technology’s O&M requirements. A copy of this document is available at http://www.doh.wa.gov/Portals/1/Documents/Pubs/337-011.pdf

Based on the owner responsibilities for operating, monitoring and maintaining on-site sewage systems in the Washington State Board of Health rules (WAC 246-272A-0270), minimum annual system inspections are required for the treatment technologies such as recirculating gravel filters. Some counties may require quarterly or semi-annual inspections and sampling of the effluent. The RS&G for Recirculating gravel filters requires the system designer to develop an O&M Manual. The maintenance manual must include the following items:

- Type of use.
- Age of system.
- Specifications of all electrical and mechanical components installed.
- Nuisance factors, such as odors or user complaints.

- Septic tank: inspect yearly for structural integrity, proper baffling, screen, ground water intrusion, and proper sizing. Inspect and clean effluent baffle screen and also pump tank as needed.
- Dosing and Recirculating/Mixing Tanks: clean the effluent screen (spraying with a hose is a common cleaning method), inspect and clean the pump switches and floats yearly. Pump the accumulated sludge from the bottom of the chambers, whenever the septic tank is pumped, or more often if necessary.
- Pumpwell: Inspect for infiltration, structural problems and improper sizing. Check for pump or siphon malfunctions, including problems related to dosing volume, pressurization, breakdown, clogging, burnout, or cycling. Pump the accumulated sludge from the bottom of the pumpwell, whenever the septic tank is pumped, or whenever necessary.
- Check monitoring ports for ponding. Conditions in the observation ports must be observed and recorded by the service provider during all O&M activities for the recirculating gravel filter and other system components. For reduced sized drainfields, these observations must be reported to the local health jurisdiction responsible for permitting the system.
- Inspect and test yearly for malfunction of electrical equipment such as timers, counters, control boxes, pump switches, floats, alarm system or other electrical components, and repair as needed. System checks should include improper setting or failure, of electrical, mechanical, or manual switches.
- Mechanical malfunctions (other than those affecting sewage pumps) including problems with valves, or other mechanical or plumbing components.
- Malfunction of electrical equipment (other than pump switches) such as timers, counters, control boxes, or other electrical components.
- Material fatigue, failure, corrosion problems, or use of improper materials, as related to construction or structural design.
- Neglect or improper use, such as loading beyond the design rate, poor maintenance, or excessive weed growth.
- Installation problems, such as improper location or failure to follow design.
- Overflow or backup problems where sewage is involved.
- Recirculating Gravel Filter / exposed-surface filter bed: weed and remove debris from the bed surface, quarterly.
- Specific chemical/biological indicators, such as BOD, TSS, fecal or total coliforms, etc. Sampling and testing may be required by the local Health Officer on a case-by-case basis, depending on the nature of the problem, availability of laboratories, or other factors.
- Information on the safe disposal of discarded filter media.

3.0 Environmental Technology Verification Testing Program and Methods

The verification testing to evaluate the performance of three on-site nitrogen reduction systems was conducted at the Snoqualmie WRF. This section provides a description of the test site, including the basis for the site selection, the site layout, and wastewater feeding method. Details of the testing program are described including the sampling schedule, field sampling activities and data collection, and analytical methods.

3.1 Test Site Description

3.1.1 Site Selection

The test site was located at the Snoqualmie WRF, which is 28 miles east of Seattle, at approximately 425-feet (ft) elevation. The WRF has an average design capacity of 3.0 million gallons per day (gpd) 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 WRF 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 3-1 (Health and UWCEE, 2012). Total Kjeldhal nitrogen (TKN) concentrations were not measured for the Snoqualmie WRF 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.

3.1.2 Description of the On-site Testing Facility

A layout and flow schematic of the pilot study site is shown in Figure 3-1. The ERGF was one of three on-site nitrogen removal technologies evaluated in the testing program. All three systems were designed around the use of a RGF for nitrification. Each of the three 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 ERGF system, the STE entered at the front of the bottom anoxic zone as described in section 2.2. Effluent from the ERGF recirculation basin was discharged via a drain line to the influent of the WRF oxidation ditch treatment system.

Five automatic samplers are shown in Figure 3-1 for sample collection of the influent wastewater fed to the septic tanks, the final treated effluents from the three nitrogen removal test systems, and for the RGF effluent the combined RGF and Vegetated Woodchip system.

Table 3-1. Comparison of the ETV protocol influent wastewater characteristics criteria and the Snoqualmie WRF average influent data for 2010.

	ETV Protocol Criteria	Snoqualmie WRF 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.

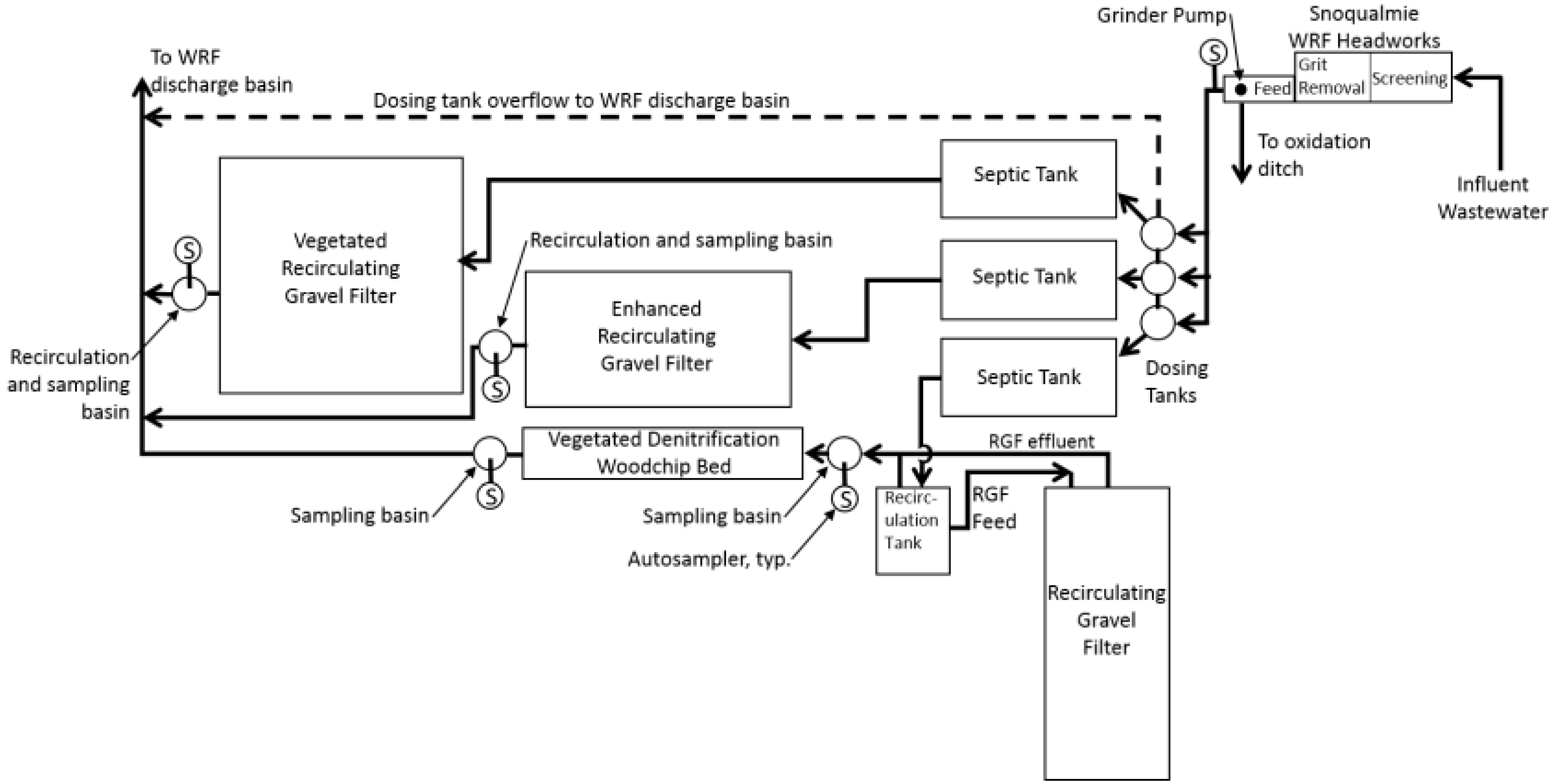


Figure 3-1. Flow schematic and layout of the on-site treatment nitrogen removal test systems.

3.1.2.1 Wastewater Feeding System

Each system received 480 gpd of STE, as specified by the Health for a design daily flow from a 4 bedroom home (Health and UWCEE, 2012). Feed for the test system was obtained from a wet well after raw influent screening and grit removal. A feed control system consisting of a grinder pump and three dosing tanks provided equal flow at selected times to each of the three systems. A Liberty LSG202M grinder pump transported influent wastewater through a 2-inch (in.) diameter PVC pipe to fill three 18-in diameter dosing tanks to overflow. 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 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 3-2:

Table 3-2. Dosing schedule to represent a typical diurnal wastewater flow from a single-family 4 bedroom home and total daily flow of 480 gal/day.

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

3.1.2.2 Automatic Samplers

Teledyne ISCO automatic samplers were used for sample collection of the influent wastewater fed to the septic tank and the ERGF effluent. The automatic samplers contained a peristaltic pump that delivered liquid from the sampling location to a container inside the automatic sampler. The pump was coupled with a liquid detector allowing accurate and repeatable sample volumes. The samplers were 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 were collected at the same frequency as the feed doses to make up the 24-hr composite sample.

The wastewater feed samples was taken just before the feed system grinder pump using the Teledyne ISCO sampler model 6712FR, which is a refrigerated sampler. A Teledyne ISCO sampler model 6712 was used for the effluent sample and was filled with ice just before the start of a 24-hour sampling event to provide sample storage during collection at 4^0C.

3.2 System Installation and Start-up

A private contractor installed the systems in accordance with construction documents created by Health. Installation of all three systems began in March 2012. Construction activities were complete in June 2012 and the project start-up period began immediately thereafter. Health adjusted and calibrated the 16-gal dose volume for each dosing tank for feed events. The ERGF system was seeded by UWCEE staff, using 5 gal buckets to transport mixed liquor with nitrifying bacteria by pouring 15 gal of the Snoqualmie WRF oxidation ditch mixed liquor evenly across the top of the bed. Effluent ammonia concentrations were monitored regularly by DOH with a probe (YSI ISE, Model #605104) during start-up. During the fourth week of start-up, samples were collected for three consecutive days and analyzed in the UWCEE laboratory for ammonia-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 start-up and initiate the verification testing program.

3.3 Verification Test Plan and Procedures

3.3.1 Testing and Sampling Schedule

The 12-month technology verification testing program began on July 30, 2012. At least once per month the testing program involved sampling the system with additional sampling events took place with the 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 including the stress test schedule is summarized in Table 3-3. For each sample event, 24-hour composite samples were obtained for the influent wastewater and treated effluent.

Table 3-3. Verification test site sampling schedule from July 2012 to July 2013. Week 1 of testing period was on July 30, 2012.

Period	Comment	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

Table 3-3 (continued). Verification test site sampling schedule from July 2012 to July 2013. Week 1 of testing period was on July 30, 2012.

Period	Comment	Week Start Date (Monday)	Sample Collection
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.

3.3.2 Description of the Stress Test Conditions

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 family home. The following lists the stress test names and the operating conditions for each one are described below:

- 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. The volume of wash load was 16 gallons per wash load. High efficiency laundry detergent containing non-chlorine bleach (Tide HE Liquid Laundry Detergent) was added with each wash load at the manufacturer recommended amount during the stress test, the total feed volume was maintained at 480 gpd.

The Working Parent Stress simulated a household in which the occupants are at work during weekdays with most of the daily flow 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 flow was delivered during the evening. The evening dosing of the day also included one wash load. The total daily flow was 480 gal.

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, and 40 percent during the evening.

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 and the influent flow and recirculation pumping in each system were 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 including 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 period. The influent flow was then stopped for 8 consecutive days, but power maintained 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.

3.3.3 Site Sampling and Data Collection

3.3.3.1 Influent and Effluent Composite Samples

Influent and effluent twenty four-hour composite samples were collected in refrigerated or iced composite samplers that pumped 30 equal subsample volumes (100-200 mL) 15 minutes after the dosing tank delivered wastewater to the ERGF system septic tank. The field samples were transported in coolers packed with ice to the UWCEE laboratory for analysis. Upon arrival, the temperature of each sample was taken and recorded.

3.3.3.2 Influent and Effluent Grab and In Situ Samples

Effluent and influent grab samples were taken for pH, temperature, and fecal coliform measurements for each sampling event. Influent and effluent grab samples were collected at the project site by UWCEE staff within an hour of the time that the 24-hour composite samples were removed. The samples were obtained by manually activating the peristaltic pumps in the autosamplers to collect approximately 400 mL into 500 mL Nalgene bottles. The pH, DO concentration and temperature values were determined using YSI EcoSens pH100A and YSI ProODO probe/meter instruments. The meters were calibrated just before the field sampling.

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

3.4 Analytical Testing and Record Keeping

With the exception of the fecal coliform measurements that were done by Washington State Certified laboratories, all the influent and effluent parameters for the project were measured by the UWCEE staff in the UW Environmental Engineering laboratory. The protocol and standard operating procedures (SOPs) specified in the project QAPP (Health and UWCEE, 2012) were followed.

3.4.1 Summary of Analytical Methods

Standard Methods for the Examination of Water and Wastewater (21st Edition) (APHA, 2005) was used as the basis for all laboratory analyses. Any modifications to the Standard Methods are described in subsequent sections presented for each parameter.

A list of parameters and tests performed on the composite samples is shown in Table 3-4. 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 3-4.

Table 3-4. 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/CBOD	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 WRF 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.

3.4.1.1 Five-Day Biological Oxygen Demand (BOD)

The BOD test was done in accordance to Standard Methods #5210B. This method consisted of filling a 300 mL bottle with an appropriately diluted sample, sealing it airtight and incubating it at 20°C for 5 days. DO 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 followed to determine if they met a test depletion criteria requirement of between 0.0 and 0.20 mg/L. Three glucose glutamic acid (GGA) standards were analyzed once per month with the acceptance criteria that their average difference from a 200 mg/L 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. All the effluent samples were nitrification inhibited 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.

3.4.1.2 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. A wide-mouth volumetric pipet was used to pipet the influent sample from a beaker to the vial. For soluble COD (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 criterion is that the slope of the calibration curve must be within 1 ± 0.10.

3.4.1.3 Total Suspended Solids and Volatile Suspended Solids

The TSS and VSS were done in accordance with Standard Methods 2540D and 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 for a minimum of one hour. 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 was Whatman® grade 934AH or its equivalent.

3.4.1.4 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 pH of 4.6. 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.

3.4.1.5 Ammonia

Ammonia-nitrogen was measured using Standard Method 4500-NH3-G and Seal Analytical 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 Millipore 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 10 mm flowcell. Reagent preparation and additional procedure information has been documented in the UWCEE SOP for Ammonia.

3.4.1.6 Nitrate plus Nitrite

Nitrate + nitrite nitrogen was measured using Standard Method 4500 NO3 H and Seal Analytical Method No. G-109-94 Rev 7 with the AA3.

Samples were filtered immediately upon arrival at the UWCEE laboratory, using 0.45um Millipore 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 10 mm flowcell. The reagent preparation and additional procedure information has been documented in the UWCEE SOP for Nitrate + Nitrite.

3.4.1.7 Total Nitrogen

TN was determined using a two-step process; Standard Method 4500 PJ for digestion followed by 4500 NO3 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. Following digestion, samples were filtered before being analyzed by the AA3 for NOx-N as described in section 3.4.4.6. Reagent preparation and additional procedure information has been documented in the UWCEE SOP for Total Nitrogen Digestion and the SOP for Nitrate + Nitrite.

3.4.1.8 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 is documented in the UWCEE SOP for Total Phosphorus.

3.4.2 Record Keeping

3.4.2.1 Chain of Custody

The QAPP (Health and UWCEE, 2012) chain of custody (COC) procedures were followed for all samples. COC forms were filled out prior to sample transportation to the Snoqualmie WRF laboratory or to the AmTest laboratory for fecal coliform analyses. A copy of the COC form was also retained by the respective laboratories.

Upon receipt of samples from the test site to the UWCEE laboratory, the sample custodian noted the date of receipt, client demographic information, the condition of samples and documented any deficiencies. All original COC forms are stored at the UWCEE laboratory.

3.4.2.2 Analytical Data Management

All analytical results were reported on standard laboratory data sheets for each method and reviewed by the project QA/QC manager to determine if the test results met the analytical method acceptance criteria. The accepted data was then tabulated on a performance data spreadsheet. The laboratory data sheets are kept in a file cabinet by the QA/QC manager.

3.5 Residuals Monitoring and Sampling

Solids in the raw wastewater settled in the primary (septic) tank and accumulated slowly over time. Measurements of the solids depth in the septic tank were completed on April 23, 2013 after nine months of operation, and again on July 30, 2013 near the end of the testing period thirteen months after start-up. A coring solids measurement tool (Sludge-Judge®) was used to estimate the depth of sludge/solids in the first and second chamber of the 1250 gallon septic tank. The depth of the solids was recorded in the Field Log. The sampling device is a clear tube with a check valve on the bottom. The tube is pushed through the solids to the bottom of the tank. The valve closes and the entire sample column, water and solids, are removed from the tank. The column height is checked to ensure that no sample has leaked from the device. The solids depth is then determined by measuring the height of the solids in the clear tube using a tape measure. This approach gives a direct measurement of the depth of solids. The thickness of any scum layer present is measured similarly. Three measurements of solids depth were made at each of the two access manholes.

Samples of solids were recovered from the Sludge Judge® during the final measurement period by emptying the probe contents into a clean container and sending the sample to the UWCEE laboratory for TSS and VSS analysis. This sample included both the solids and the water present in the tube. Thus, the concentration measurements for solids represent the concentration as if the entire contents of the tank were mixed. To estimate the solids concentration in the settled material at the bottom of the tank, the depth of solids and the depth of water column need to be accounted for and the ratio used to calculate an estimated solids percent.

3.6 Operation and Maintenance Performance

Operation and maintenance performance of the ERGF was monitored throughout the verification test. A field log was maintained that included all observations made during the start-up of the system and throughout the verification test. Data were collected on in situ measurements of effluent quality parameters (DO, turbidity, pH, conductivity, nitrate, ammonia, and temperature). Observations were also recorded on the condition of the system, any changes in setup or operation (influent wastewater timer adjustments, cleaning, etc.), or any problems that required resolution. There were no major mechanical component failures during the verification test.

3.6.1 Electric Use

Electrical use was estimated using power consumption information from the pump manufacturer rather than monitored by a dedicated electric meter.

3.6.2 Noise

Noise levels associated with mechanical equipment (1/3 horse power effluent pump) were not measured during the verification period because the pump’s noise level could not be distinguished from the loud background noise coming from the headworks of Snoqualmie WRF, which was in close proximity to the effluent pump basin.

3.6.3 Odors

Odor observations were made during the final eight months of the verification test. The observation was qualitative based on odor strength (intensity) and type (attribute). Intensity was classified as not discernible; barely detectable; moderate; or strong. Observations were made during periods of low wind velocity (<10 knots). The observer stood upright at a distance of three (3) feet from the treatment unit, at 90° intervals in four (4) directions. All observations were made by the same Health personnel.

3.6.4 Mechanical Components

Performance and reliability of the mechanical components, such as wastewater pumps, were observed and documented during the test period. These observations included recording in the Field Log of equipment failure rates, replacement rates, and the existence and use of duplicate or standby equipment.

3.6.5 Electrical/Instrumentation Components

Electrical components, particularly those that might be adversely affected by the corrosive atmosphere of a wastewater treatment process, and instrumentation and alarm systems were monitored for performance and durability during the course of verification testing. Observations of any physical deterioration were noted in the Field Log. Any electrical equipment failures, replacements, and the existence and use of duplicate or standby equipment were recorded in the Field Log.

4.0 Results and Discussion

This chapter presents the treatment performance results obtained from the start-up period and verification testing program. A summary of the start-up phase data is presented first followed by the verification testing results. The verification testing results include the average treatment performance over the 12-month testing period, the performance during the stress testing periods, and the effect of temperature on the treatment performance.

4.1 Start-up Period

The start-up period was from June 26, 2012 to July 29, 2012. During the first week of the system start-up, various activities were performed on the treatment systems. These activities included calibrating the dosing tanks to deliver 16 gal per feed event, programming the influent and effluent autosamplers, and setting the programmable controller to deliver feed at specified times during each day according to the diurnal feed pattern. The ERGF system also received activated sludge seed to help reduce the time needed for building up the nitrifying bacteria population. The start-up activity proceeded as planned over a two week period without any problems or mechanical issues.

According to the QAPP (Health and UWCEE, 2012), effluent ammonia-N concentrations had to be less than 10 mg/L for three consecutive days prior to initiating the verification testing program. For samples collected on July 25-27, 2012, effluent ammonia-N concentrations averaged 3.8 for the ERGF effluent composite samples. Therefore, the 12-month verification testing program was initiated on July 30, 2012. A summary of these ammonia-N data and data for other parameters measured during sampling days in the July start-up period are shown in Table 4-1.

Table 4-1. Summary of composite influent and effluent concentrations (mg/L) during start-up period.

Sample Date	Temp ^{0}C	Total N	NH_3-N	NOx-N	BOD or CBOD*	TSS	COD or SCOD*	Alkalinity as $CaCO_3$
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	-	-	-	-	-
ERGF** Effluent								
17-Jul-12	20.8	9.4	10.9	0.5	14.4	6.9	50.3	234
25-Jul-12	22.8	8.6	4.1	2.4	9.7	4.6	28.2	221
26-Jul-12	-	-	3.7	-	-	-	-	-
27-Jul-12	22.5	-	3.7	-	-	-	-	-

*Effluent.
**ERGF= Enhanced Recirculating Gravel Filter.

4.2 Treatment Performance of the Enhanced Recirculating Gravel Filter

4.2.1 Average Treatment Performance

A summary of the average influent and effluent concentrations over the 12-month verification testing period is shown in Table 4-2. The effluent TN concentration averaged 8.6 mg/L, which is below the target treatment goal of 20 mg/L. The 95th percentile effluent concentration was 12.3 mg/L (Table 4-2). Effluent concentrations from wastewater treatment processes vary as a function of influent concentration changes, temperature, and other factors. Temperature measurements in the ERGF effluent on the sampling dates ranged from a high of 25°C in the summer months to a low of 7°C in January. The 95th percentile data parameter was selected to indicate an upper range for most of the effluent concentrations, exclusive of outliers or extreme events. The average TN removal efficiency for the 12-month testing period was 82 percent (Table 4-3).

The average alkalinity concentration was 203 mg/L as $CaCO_3$, which is 28 mg/L lower than the average influent concentration due to alkalinity depletion from nitrification. The residual alkalinity was still high enough to support an average pH of 6.9. The pH was below 6.7 for 10 percent of the data. While the optimal pH range for nitrification is 7.5 to 8.0, most domestic wastewater treatment processes are operated with pH values in the range of 6.8 to 7.2 and experience acceptable nitrification rates. The nitrification rate at a pH of 6.7 is only about 28 percent less than the nitrification rate at 7.0 (Tchobanoglous et al., 2013). At a pH of 6.6 the rate is decreased by about 35 percent. Low loaded, long detention time nitrification systems like the

RGF are able to produce good nitrification performance at lower pH values up to a point. At a pH value of 6.3 for example the rate is decreased by about 50 percent.

Table 4-2. Summary of the average influent and effluent concentrations for the 12-month verification testing period for the enhanced recirculating gravel filter system. Arithmetic standard deviation values are given in parenthesis. The 95th percentile is the value for which 95 percent of the data is equal to or less. The geometric mean is used for the influent and effluent fecal coliform data.

Parameter	units	Average Influent	Effluent Average	95th percentile
Total N	mg/L	48.6 (9.5)	8.6 (2.2)	12.3
NH_3-N	mg/L	29.3 (5.3)	6.8 (1.9)	10.0
NOx-N	mg/L	-	0.6 (0.6)	1.7
Org-N	mg/L	-	1.3 (0.5)	2.0
BOD/CBOD*	mg/L	314.1 (97.8)	8.6 (1.9)	11.2
TSS**	mg/L	353.9 (137.1)	5.3 (2.2)	9.8
VSS**	mg/L	324.4 (131.2)	4.4 (2.0)	8.7
COD/SCOD*	mg/L	715.0 (222.9)	24.6 (5.7)	33.1
Total Phosphorus	mg/L	5.8 (1.3)	3.5 (1.4)	5.4
Fecal Coliform***	CFU/100 mL	8.4E+6	4.6E+5	2.1E+7
Alkalinity as $CaCO_3$	mg/L	231 (36)	203 (27)	240
pH		7.4 (0.3)	6.9 (0.2)	7.2

*Effluent
**For measurements under detection limit, half of the detection limit was used (1.25 mg/L)
***Influent and effluent fecal coliform is based on geometric mean

Table 4-3. Summary of average percent removal or log reduction for the Enhanced Recirculating Gravel Filter system for the 12-month verification testing period. The log reduction for fecal coliform is based on the influent and effluent geometric mean fecal coliform concentrations.

Parameter	Percent Removal	Log Reduction
Total N	82	
BOD	97	
TSS	99	
VSS	99	
Total Phosphorus	40	
Fecal Coliform		1.3

The effluent NOx-N concentrations were consistently low, as 95 percent of the effluent NOx-N was 1.7 mg/L or less. However, the effluent NH_3-N concentration averaged 6.8 mg/L, which represents 79 percent of the average effluent TN concentration. This elevated NH_3-N concentration is a result of the recirculation basin design and the system influent and effluent overflow locations. The recirculation basin received the combined aerobic nitrification zone effluent flow and the STE flow after traveling through the anoxic zone. The ammonia in the STE cannot get transformed to NOx in the anoxic zone due to the lack of oxygen. A portion of the STE feed exits the recirculation basin as effluent from the treatment process. For a recirculation ratio of 5.0, 1/6th of the STE flow entering the anoxic zone exits in the effluent from the recirculation basin. Some portion of the influent ammonia-N in that flow is used for biomass growth from BOD removed in the anoxic zone. As an illustration, a hypothetical effluent NH_3-N concentration of 7.4 mg/L is calculated assuming (1) an average influent TN concentration of 48.6 mg/L (Table 4-2), (2) 10 percent TN removal in the septic tank, (3) an effluent NH_3-N concentration of 0.8 mg/L from the aerobic nitrification zone flow and (4) an influent BOD concentration of 314 mg/L (Table 4-2) and 0.01 g N removed per g of BOD removed for net biomass synthesis. The average value in Table 4-2 is close to the hypothetical estimated value based on the above assumptions. This analysis illustrates that it is not possible to get effluent NH_3-N concentrations to low levels of 0.50 to 1.0 mg/L, typical of conventional nitrification wastewater treatment systems because of the feed location, effluent location, and recirculation basin configuration.

The BOD and TSS removal across the system were excellent with average effluent concentrations of 8.6 and 5.3 mg/L and 97 and 99 percent removal, respectively. This treatment level exceeds that for state of the art processes used in publically owned wastewater treatment systems.

The total phosphorus removal efficiency averaged 40 percent, which is a little better than expected for typical secondary treatment applications (Tchobanoglous et al., 2013). The phosphorus removal mechanisms are phosphorus trapped in solids and removed in the bed and phosphorus uptake by biological growth in the ERGF from BOD removal.

A 1.3 log reduction in fecal coliform occurred between the septic tank influent and ERGF effluent. The geometric mean of the effluent fecal coliform concentrations was 4.6×10^5, which is similar to a typical value of between 10^4 and 10^6 given for a filtered effluent following a nitrification activated sludge wastewater treatment system (Tchobanoglous et al., 2013).

4.2.2 Analysis of Performance during the Verification Testing Period

The effluent concentrations for the constituents of interest in this study (TN, NH_3-N, NOx-N, BOD, TSS, TP, and fecal coliform) were expected to be affected by changes in influent concentration and temperature, and possibly by the stress testing operating conditions over the 12-month evaluation period. Five stress tests operating conditions were imposed on the system during the 12-month study. Chronological performance graphs presented in Figure 4-1 to Figure 4-5 show changes in influent and effluent concentrations for constituents of interest and temperature over the 12-month testing period. The start and completion dates of the five stress tests are also indicated by shaded areas on the plots. These data are evaluated in this section with regards to the changes in performance with time and effects of the stress test operating conditions.

It should be noted that influent and effluent samples were collected on the same day, but due to the hydraulic detention in the system, the effluent sample concentrations would be affected by influent conditions a few days prior and the attenuation effect of the recirculation flow on influent variation. The average empty bed contact time of the ERGF at an average daily flow of 480 gpd was 5.6 days in the aerobic zone and 4.2 days for the anoxic zone. The nominal detention times with consideration for the 5.0 recirculation ratio were 0.9 and 0.7 days. Although the septic tank had a 2.6 day detention time based on its volume, the actual liquid time was less because the system is not expected to have ideal plug flow hydraulics. With this in mind, it was possible that the effect of changes in the influent TN, TSS, BOD, TP, and fecal coliform concentrations may be realized in the effluent samples from the recirculation basin after about 2 days. Changes in influent concentration provide information on trends in the loadings to the ERGF and possible effects on performance.

4.2.2.1 Effluent Nitrogen

Influent TN and ERGF effluent TN, NH_3-N, and NOx-N concentrations with time are shown in Figure 4-1 as well as the effluent temperature. Higher effluent TN concentrations occurred in the early months of the verification testing (August to mid-October) and after the low loading stress test. None of the other stress tests appeared to affect the nitrogen removal efficiency. There was also a sudden increase of effluent TN starting from May to the end of the project. The higher effluent TN concentrations during the early months of the verification testing were associated with higher effluent NH_3-N and NOx-N concentrations, which appeared to be related to the higher influent TN concentrations, as will be discussed in Section 4.2.3.2.

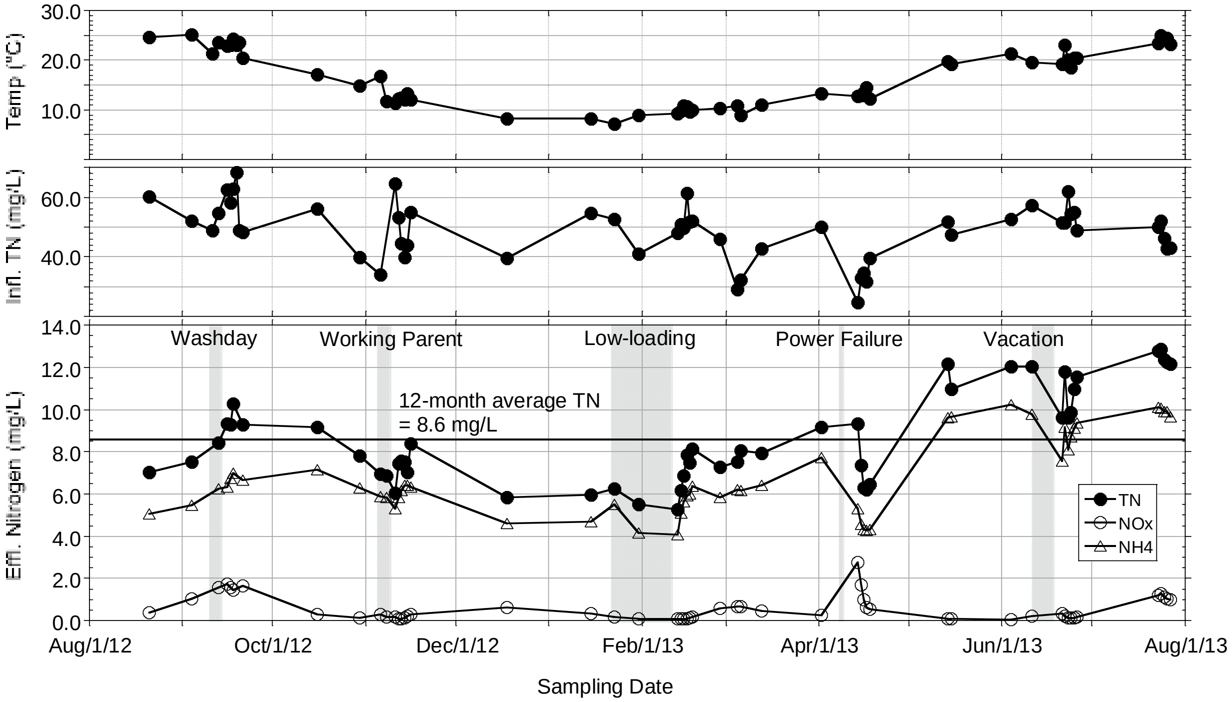


Figure 4-1. Influent TN and effluent TN, NH_3-N, and NOx-N concentrations and temperature versus time for the Enhanced Recirculating Gravel Filter during the 12-month verification testing period.

The increase in effluent TN concentrations after the low loading stress were associated with increase of effluent NH_3-N concentrations. The effluent NH_3-N concentration increased from 2.2 mg/L two days after end of low loading stress to 3.3 mg/L another five days after. However, it cannot be concluded that such increase of NH_3-N concentrations was due to the stress test because (1) the highest NH_3-N point of 3.3 mg/L occurred seven days after the end of the low loading stress, when the effect of stress test on the system effluent could have already passed, and (2) there were other high NH_3-N data points in March that were not associated with any stress tests. It should be noted that even with an increase of TN concentration after the low loading stress, these data points were still below the annual average effluent TN concentration and also well below the treatment goal of less than 20 mg/L.

The effluent NOx-N concentration was the most stable of the nitrogen species shown, with the exception of a 2.5 mg/L increase after the power failure stress test. Such an increase may be due to lower influent BOD concentrations during that time compared to the 12-month average influent BOD. The average influent BOD measured during the elevated effluent NOx-N concentrations was 210 mg/L and the 12-month average was 314 mg/L. Therefore, the higher effluent NOx-N concentrations might be due to lower influent BOD concentrations that resulted in lower denitrification rate, rather than the result of the power failure stress.

The increase of effluent TN concentrations first observed in May 2013 were associated with the increase in effluent NH_3-N concentrations, which was likely related to operational issues associated with high headloss across the anoxic zone. The headloss across the anoxic zone increased over time by greater solids accumulation in the contact chamber and solids collection in the upflow distribution piping or in the media above the upflow distribution piping. Increasing headloss resulted in higher water level measurements in the contact chamber, which would cause flooding in the bottom depth of the aerobic zone to limit oxygen transfer and nitrification.

In summary, there were changes of effluent concentrations for the nitrogen species, but none of them can be concluded as related to the effect of stress tests. The nitrogen removal performance was impacted more by changes in the influent TN concentrations and the high headloss across anoxic zone of the ERGF.

4.2.2.2 Effluent BOD and TSS

The Enhanced RGF effluent BOD and TSS concentrations during the 12-month verification testing period are shown in Figure 4-2 and Figure 4-3. There were increases of effluent BOD concentrations after the working parent, low-loading, and vacation stress tests. However, the effect of stress tests on these higher effluent BOD concentrations was not clear since there were other high and low effluent BOD concentrations that were not associated with any stress tests. The effluent BOD concentrations from samples collected for the stress tests ranged from 5.7 to 11.5 mg/L, and the range of effluent BOD concentrations from regular samples ranged from 5.1 to 10.6 mg/L. The highest effluent BOD concentrations from the above two ranges only differed by 0.9 mg/L. Based on the assumption that variations within 2.0 mg/L are not considered conclusive due to the accuracy of the BOD tests at such low concentrations or the importance in terms of treatment needs, it cannot be concluded that stress tests were the cause of these variations in effluent BOD concentrations. The changes in effluent BOD concentrations may be due to natural variations associated with the biological processes.

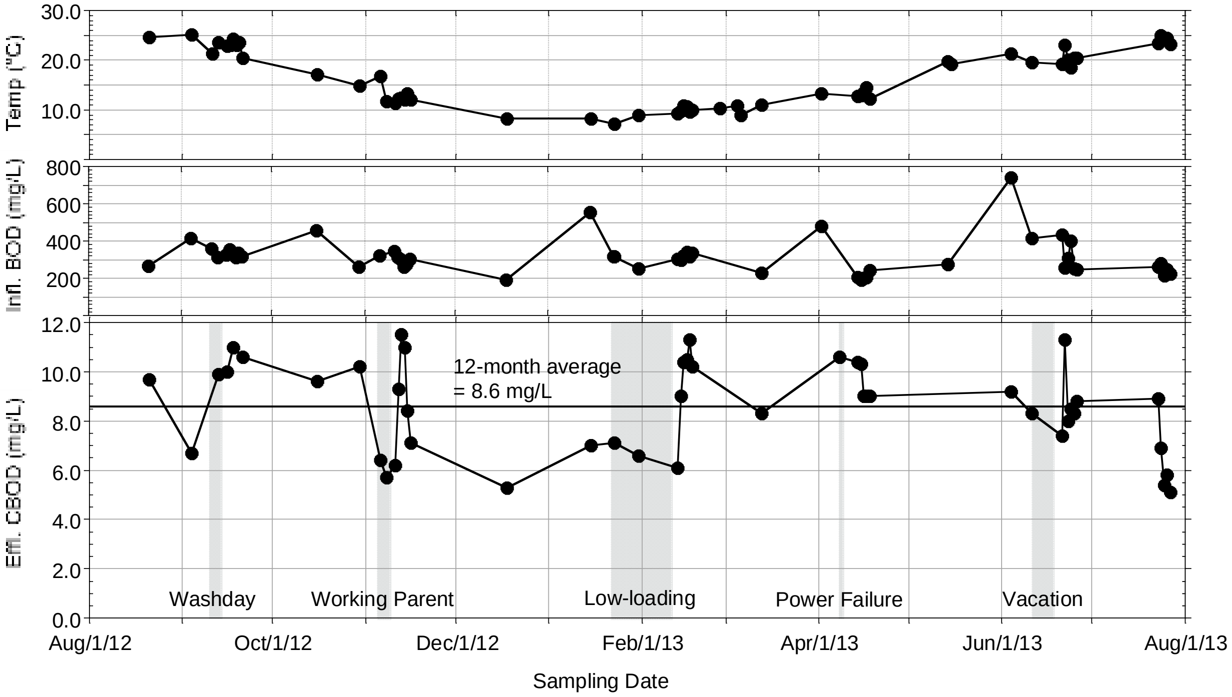


Figure 4-2. Influent and effluent BOD concentrations and temperature versus time for the Enhanced Recirculating Gravel Filter during the 12-month verification testing period.

There were modest increases in effluent TSS concentrations (2 to 4 mg/L) after the washday, power failure, and vacation stress tests. None of the other stress test conditions had a significant effect. For the vacation stress, there was a lack of feed for 8 days. The starvation conditions could cause increased bacteria sloughing and increased effluent TSS concentration. The increase in TSS concentration after the power failure stress may be due to a short term starvation period and sloughing due to the lack of feed and recirculation.

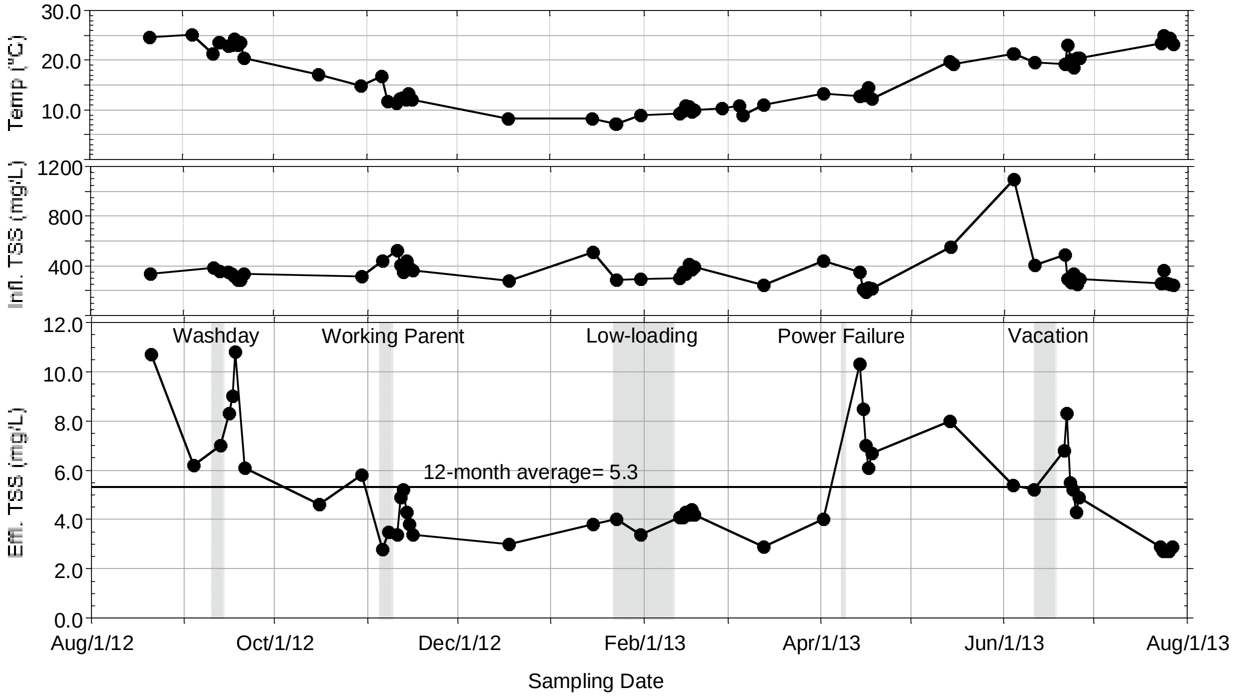


Figure 4-3. Influent and effluent TSS concentrations and temperature versus time for the Enhanced Recirculating Gravel Filter during the 12-month verification testing period.

4.2.2.3 Effluent Total Phosphorus

As shown in Figure 4-4, effluent TP concentrations varied widely and tended to follow the patterns in the influent TP concentrations. None of the stress test conditions had a significant effect on the effluent TP. For example, there was an increase in the effluent TP concentration starting day 9 of the low-loading stress test to three days after the end of the stress test from 2.8 to 4.5 mg/L. A similar increase can be seen in the influent TP concentration from 5.0 mg/L on day 9 of the low-loading stress test to 6.2 mg/L three days after the stress test. No conclusions can be made about the effect of stress tests on the effluent TP concentrations.

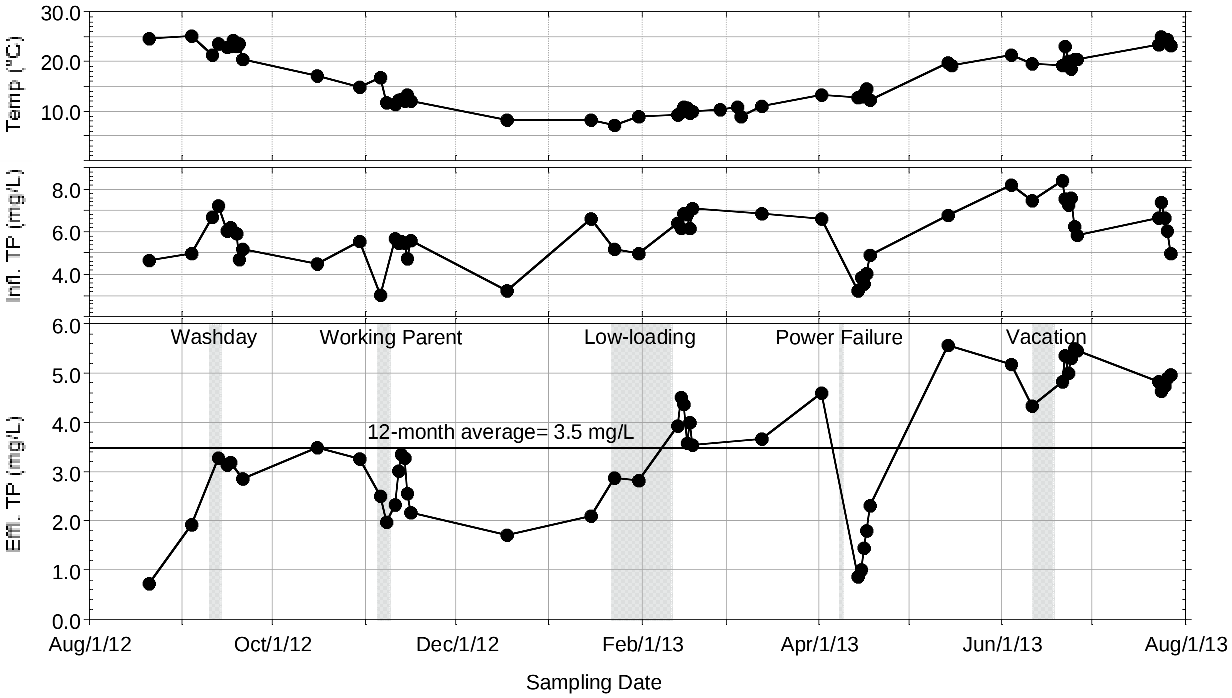


Figure 4-4. Influent and effluent total phosphorus concentrations and temperature versus time for the Enhanced Recirculating Gravel Filter during the 12-month verification testing period.

4.2.2.4 Effluent Fecal Coliform

A wide variation in effluent fecal coliform concentrations ranging from 3.0×10^4 to 2.6×10^6 CFU/100ml is shown in Figure 4-5. The only exception was an increase in effluent fecal coliform concentration for a number of days after the vacation stress test. This same increase was seen for effluent TSS concentration (Figure 4-3), which was attributed to an increase in effluent biomass due to sloughing. That explanation is consistent with an increase in fecal coliform as more biomass would be released into the effluent during increased sloughing.

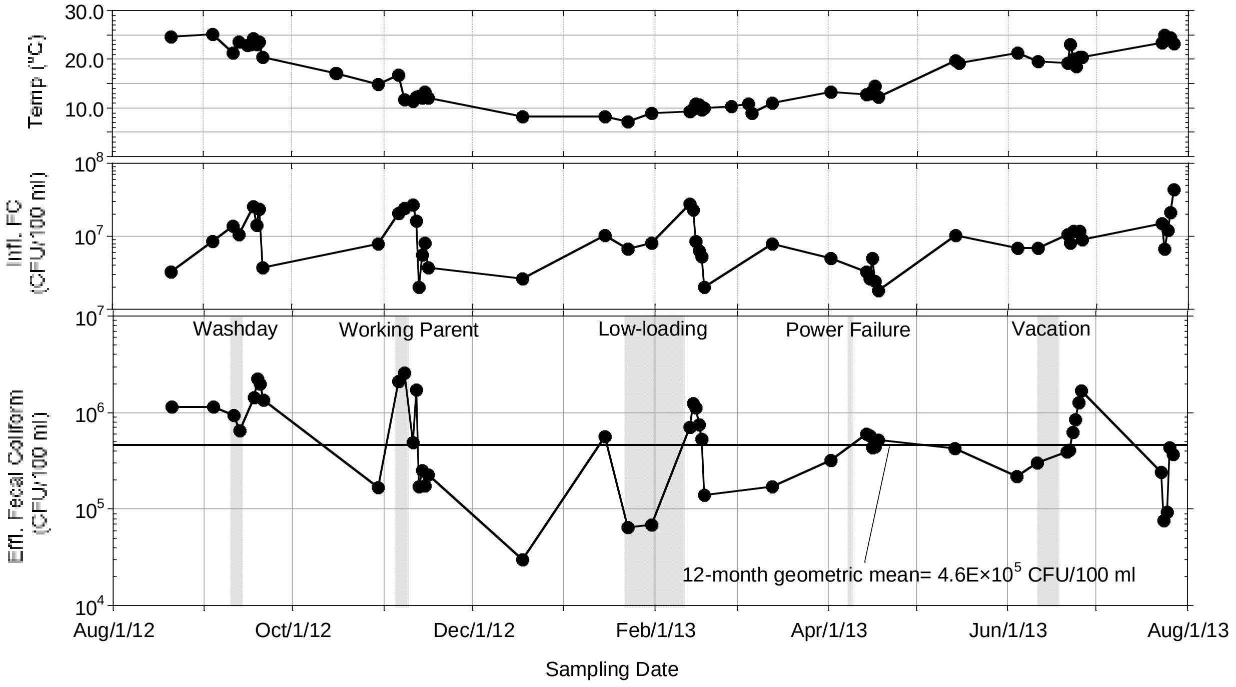


Figure 4-5. Influent and effluent fecal coliform concentrations and temperature versus time for the Enhanced Recirculating Gravel Filter during the 12-month verification testing period.

4.2.3 Effect of Temperature

Temperature is an important factor in biological treatment process performance as rates of BOD removal, denitrification, and nitrification decrease with temperature (Tchobanoglous et al., 2013). Of these, ammonia oxidation kinetics are the most sensitive to temperature. For systems with very low loadings, such as recirculation gravel filters in on-site treatment, there may be little effect of temperature on removal of certain constituents due to sufficient biomass inventory and relatively long hydraulic detention time which compensates for the slower biodegradation rates at lower temperatures. The effect of temperature on the ERGF performance is evaluated here by comparing the performance during warm and cold operating periods. Because of possible time effects on the biofilm development and solids collection in the system, two warm periods are identified; the first just two months after system start-up and the second eleven months after system start-up. The first warm period included sampling dates from August to November with temperatures of >15°C. Similarly, the second warm period included sampling dates with temperatures of >15°C, from May to July. The cold period included data from November to March with temperatures of <12°C.

4.2.3.1 Effluent BOD, TSS, Total Phosphorus, and Fecal Coliform

Average percent removal or log removal of BOD, TSS, total phosphorus, and fecal coliform for the three temperature periods is shown in Table 4-4. There was no noticeable effect of temperature on the removal of BOD and TSS as the biggest difference between the two average percent removal values, among the three temperature periods, was merely 0.2 and 1.2 percent for

BOD and TSS, respectively. The average TP removal for the second warm period was 19.6 percent lower than the cold period. However, no conclusion can be made about the effect of temperature since the average TP removal for the first warm period was very close to the cold period with a difference of 2.4 percent. The average log reduction of fecal coliform between the three temperature periods only differed by 0.06 for the highest, suggesting that removal of fecal coliform was not affected by the temperature.

Table 4-4. Average removal performance for BOD, TSS, total P and fecal coliform (FC) by temperature range for the Enhanced Recirculating Gravel Filter for the three temperature periods.

	Warm 1	Cold	Warm 2
Months	Aug to Nov*	Nov* to Mar	May to Jul
Temperature range, °C	16.7 - 25.1	7.1 - 11.8	18.6 - 24.9
Average temperature, °C	22.1	9.8	21.5
Average BOD removal, %	97.2	97.3	97.4
Average TSS removal, %	97.7	98.9	98.6
Average Total P removal, %	47.7	45.3	25.7
Average FC log reduction	1.92	1.97	1.98

*Temperature data in November had both <12°C and >15°C measurements.

4.2.3.2 Effluent Nitrogen

Average influent TN and alkalinity and effluent TN, NOx-N, and NH_3-N concentrations are shown in Table 4-5. As mentioned in Section 4.2.2.1 and shown in Figure 4.1, the effluent NOx-N concentration was the most stable of the nitrogen species shown and effluent TN concentration changes were associated more with changes in influent TN and effluent NH_3-N. The amount of TN removal for the 1st warm period, cold period, and 2nd warm period was 46.0, 40.9, and 39.5 mg/L, respectively. Thus, the higher effluent TN concentration for the 1st warm period compared to the cold period was related to it having a higher influent TN concentration. The TN removal efficiency is lower for the 2nd warm period compared to the 1st warm period. An increase in the average effluent NH_3-N concentration for the 2nd warm period accounts for the higher average TN concentration to suggest that NH_3-N removal is the limiting factor on the effluent TN concentration.

Table 4-5. Average influent alkalinity, influent TN, and effluent pH, TN, NOx-N, and NH3-N concentrations for the Enhanced Recirculating Gravel Filter for the three temperature periods.

	Warm 1	Cold	Warm 2
Months	Aug to Nov*	Nov* to Mar	May to Jul
Temperature range, °C	16.7 - 25.1	7.1 - 11.8	18.6 - 24.9
Average temperature, °C	22.1	9.8	21.5
Average Influent alkalinity, mg/L as $CaCO_3$	267	219	244
Average effluent pH	7.0	7.0	7.0
Average influent TN, mg/L	54.6	47.7	51.0
Average effluent nitrogen, mg/L			
TN	8.6	6.8	11.5
NOx-N	1.1	0.3	0.5
NH_3-N	6.3	5.5	9.4
Average removal efficiency, %	84	86	78

*Temperature data in November had both ≤12°C and ≥15°C measurements.

The higher average effluent NH_3-N concentration for the 2nd warm period may be related to operational issues with increasing headloss with time across the anoxic zone of the ERGF system. Over time, the solids accumulated in the contact chamber and collected in the upflow distribution piping resulted in high water level measurements in the contact chamber, which may have resulted in flooding of the bottom depth of the aerobic zone to limit nitrification.

The average effluent NH_3-N concentration for the cold period was 0.8 mg/L lower than the average for the 1st warm period, which was unexpected because nitrification kinetics decrease with lower temperature. The lower effluent NH_3-N concentrations during cold period was not due to more alkalinity as the cold average influent alkalinity was 48 mg/L as $CaCO_3$ lower than the average alkalinity for the 1st warm period and the two temperature periods had the same effluent pH. The lower average effluent NH_3-N concentrations for the cold period may be related to (1) lower influent TN concentrations and (2) a higher DO concentration in the nitrification zone due to increased oxygen solubility in water at colder temperature, if oxygen supply was the limiting factor for nitrification efficiency.

In summary, the effluent TN concentrations were impacted more by operational issues and changes in the influent TN concentration than the temperature. The higher average effluent NH_3-N concentrations for the warm periods as compared to the cold period were likely due to higher influent TN concentrations and the operational issues that limited nitrification efficiency.

4.2.4 Effect of Oyster Shells on pH

An added feature for the ERGF system was a 6-inch layer of oyster shells at the top of the aerobic zone. Oyster shells are rich in calcium carbonate and previous work has shown that alkalinity can be released from the oyster shells in a wastewater treatment system (Liu et al., 2010).

The Vegetated Recirculating Gravel Filter (VRGF) was another one of the three systems tested under the same pilot study. Details of the VRGF system design, verification testing data, and analysis of the system performance are documented in a separate ETV report (insert final URL). An estimate of the alkalinity contribution from the oyster shells was determined by carrying out mass balances with average measured values for effluent NH_3-N, NO_x-N, and alkalinity concentrations for the VRGF and ERGF systems. For the entire 12-month verification testing period, the average alkalinity production by the oyster shells was 10.3 mg/L as $CaCO_3$. While the test results do show that alkalinity can be provided from oyster shells in the treatment process, the amount produced in the ERGF system was relatively small compared to the alkalinity produced from denitrification and was too low to significantly affect the system effluent pH. The amount of alkalinity produced from the oyster shells was likely limited by the intermittent wetting and short contact time.

4.2.5 Effect of Rainfall

The effluent flow from the ERGF system is equal to the influent flow from the septic tank plus the contribution of water collected across the top surface area during precipitation events. The rainfall volume could conceivably dilute the treated effluent concentration. It could also dilute the influent TN concentration, depending on the amount of infiltration and inflow to the collections system for the Snoqualmie WRF. The effect of rainfall is analyzed by comparing the influent TN concentrations and effluent TN and NOx-N concentrations to the system average effluent concentrations with data on days of significant recorded precipitation during the composite sampling days and sampling time period as shown in Table 4-6. The data shown includes any rainfall that accounted for more than a 2 percent increase in the daily effluent flow volume. The increase in effluent flow due to rainfall was estimated by calculating the water added to the bed based on the total top surface area and ignoring any losses due to evapotranspiration or plant interception.

The effect of the rainfall dilution volume on effluent constituent concentrations is not immediately seen because of the attenuation effects in the ERGF system due to recirculation flow and the long hydraulic retention time. The recirculation pump is activated approximately every 24 minutes and the system liquid detention time is about 3.9 days based on an estimated 40 percent pore volume. The rainwater volume, as a percentage of the pore volume, is shown to indicate the amount of dilution that might occur within the system bed.

There was no consistent correlation between the magnitude of water added from a rainfall period and dilution of the influent or effluent TN concentrations. The days of the largest increases in effluent flow from rainwater were in order of days with the highest to lowest percent increases, from 17.3 to 9.8 percent on 4/14, 11/12, 10/30, 10/16, 2/17 and 6/21. Though the influent TN concentration was much lower on 4/14 (percent effluent flow increase of 17.3 at 24.7 mg/L), there was no correlation with influent TN concentration to amount of rainfall when considering the other high rainfall events and the overall rainfall events. A spike in the effluent NOx-N concentration was observed for the 4/14 sample day which also had one of the lowest influent BOD concentrations to suggest that the influent BOD was weaker and did not provide sufficient carbon for denitrification. The influent BOD concentration was weak on 4/14 (207 mg/L compared to the average BOD of 314 mg/L) but the effect of the influent flow would be delayed by the detention time for the feed flow in the septic tank. In general there was no correlation between effluent TN concentration and the amount of rainfall. Most of the effluent TN concentration values in all cases, with or without rain, were within the standard deviation range around the mean for over the 12-month operation. Note that the higher effluent TN concentrations after May were due to an increase in effluent ammonia-N caused by increased headloss in the anoxic zone.

It should be noted that such an evaluation is very qualitative due to the many factors affecting effluent concentration. These include not having effluent samples the day before the rain event, changes in influent concentrations and changes in temperature compared to previous days without rainfall, and attenuation effects built into the system. However, the higher amount of water from the rainfall event was only from 0.5 to 3.6 percent of the ERGF pore volume to indicate that its dilution effect is relatively small and that an immediate effect on effluent concentration would be within the measurement variation.

Table 4-6. Summary of rainfall events for the Enhanced Recirculating Gravel Filter system. The reported total amount of precipitation is shown for the sample collection day time period. The average daily increase in effluent flow from the rainfall event, percent of rainfall water relative to the ERGF pore volume, and influent total nitrogen, effluent total nitrogen and effluent NOx-N concentrations are shown for sampling days that had a greater than 2 percent increase in effluent flow due to precipitation.

Sample collection date	Rainfall during sampling[1], in.	Rainfall as % of feed flow	Rainfall as % of pore volume	Influent TN, mg/L	Effluent TN, mg/L	Effluent NOx, mg/L
10/16/2012	0.63	14.7	3.0	56.2	9.2	0.3
10/30/2012	0.66	15.4	3.2	39.8	7.8	0.1
11/12/2012	0.73	17.1	3.5	53.2	7.4	0.1
11/13/2012	0.11	2.6	0.5	44.6	7.6	0.1
11/14/2012	0.1	2.3	0.5	39.8	7.5	0.1
12/18/2012	0.1	2.3	0.5	39.6	5.8	0.6
1/31/2013	0.11	2.6	0.5	41.0	5.5	0.1
2/17/2013	0.58	13.6	2.8	51.7	7.5	0.1
2/27/2013	0.11	3.7	0.8	46.0	7.3	0.6
3/13/2013	0.26	6.1	1.2	42.7	8.0	0.5
4/14/2013	0.74	17.3	3.6	24.7	9.3	2.8
4/16/2013	0.17	4.0	0.8	34.7	6.3	1.0
5/14/2013	0.11	2.6	0.5	51.8	12.2	0.1
6/21/2013	0.42	9.8	2.0	51.4	9.6	0.3
6/24/2013	0.23	5.4	1.1	54.4	9.9	0.1
6/25/2013	0.12	2.8	0.6	55.0	11.0	0.1
6/26/2013	0.14	3.3	0.7	48.9	11.5	0.2
Annual average concentrations (standard deviation)				48.6 (9.5)	8.6 (2.2)	0.6 (0.6)

1- From 5 pm on sample setup day to 2 pm on sample collection day

4.3 Residuals Results

During the treatment of wastewater in the ERGF, solids accumulate in the first and second compartment of the septic tank. Inert solids are removed in the primary tank system just as in a normal septic tank. Eventually, a buildup of solids reduces the capacity of the primary tank and the solids will need to be removed.

The approximate quantity of the residuals accumulated in the system was estimated in each compartment of the septic tank at the end of the test period. Measurement of solids depth was difficult in the septic tank, as access to the tank is limited to access openings in the top of the unit. Solids depth was estimated at three locations from each of the two openings using a Sludge Judge® solid- measuring device. A column of water and solids is removed from the tank, and the undisturbed solids depth in the clear tube measured with a tape measure. The measurements were made in April 2013, and again in July 2013 after approximately thirteen months of operation. The results are presented in Table 4-7.

Table 4-7. Solids/Scum Depth Measurement Primary Tank Solids/Scum Depth in Inches.

Manhole Location	East	Middle	West	Average
April 23, 2013 Outlet	0	14	0	14
April 23, 2013 Scum Depth Outlet	0	4	0	0
July 30, 2013-Inlet	6.0	5.5	7.125	6.2
July 30, 2013-Outlet	9.0	10.5	7.50	9.0
July 30, 2013 Scum Depth Inlet	0	0	0	0
July 30, 2013 Scum Depth Outlet	0	0	0	0

Note: Measurement is estimated solids depth in the Primary Tank

In order to characterize the solids in the septic tank, total suspended solids and volatile suspended solids were measured in the samples collected in July 2013. These data are presented in Table 4-8. These concentrations represent the solids concentration in the total sample collected, which includes the solids and water present in the sample tube. Based on an average of 7.6 inches of solids present in the tube in July, and an additional 32 inches of water (39.75 inch total depth in the septic tank), the concentration of solids must to be multiplied by a factor of 5.2 to estimate the actual solids concentration in the settled solids layer.

Table 4-8. TSS and VSS Results for the ERGF Solids Sample.

Date	Location	TSS (mg/L)	VSS (mg/L)
7/30/13	1st Compartment	2467	1844
7/30/13	2nd Compartment	5200	3600

The mass of solids present in the septic tank can be estimated from these data. The average concentration of solids in the septic tank, 3,833mg/L multiplied by the tank total volume of 1,250 gallons shows that the solids accumulated during the test was approximately 40 pounds.

The total mass of solids can also be estimated using the settled solids concentration and the tank dimensions. The septic tank holds a volume of approximately 31.45 gallons per inch of depth. Therefore, the solids volume, based on an average 7.6 inches depth (July data), was about 239 gallons. The settled solids concentration is estimated to be 2.0 percent (20,000 mg/L) using the ratio of total depth to solids depth described above (factor of 5.2). Based on a settled solids concentration of 20,000 mg/L, the weight of dry solids accumulated was approximately 40 pounds. The data also show that the VSS represent 75% of the TSS in the first compartment and 69% of the TSS in the second compartment.

4.4 Operations and Maintenance

Operation and maintenance performance of the ERGF was monitored throughout the verification test. A field log was maintained that included all observations made over the thirteen-month test period. Data was collected on electrical and chemical usage, noise, and odor. Observations were recorded on the condition of the ERGF, any changes in setup or operation (pump adjustments, orifice cleaning, etc.) or any problems that required resolution.

4.4.1 Operation and Maintenance Observations

The ERGF system is relatively simple to operate and maintain. The only mechanical/electrical components are the small effluent pump and pump control panel. During the test, no problems were encountered with the mechanical operation of the system.

The only operational change that can be made to the system is to change the timer setting in the control panel to adjust the runtime on the pump and the rest period between pump cycles. On July 23, 2012, during the start-up period, staff from Health adjusted the timer to increase the recirculation ratio from 6:1 to 8:1. This adjustment was made in an attempt to produce a lower effluent NH3-N concentration in the recycled flow within the system. On November 1, 2012 (after three months of operation), a timer setting adjustment was made to lower the recirculation ratio to 5:1 to reduce the flow rate to the feed distribution piping in the anoxic zone. This adjustment was necessary to address a high water level operational problem in the contact chamber, which caused flooding in the lower section of the aerobic zone. No other timer changes or adjustments were needed through the remaining period of the test.

Two operational problems involving clogging in the aerobic and anoxic zones occurred during the 13 months of operation. Within the second month of system operation (mid-August), a growth of Thiothrix spp. bacteria started to accumulate on the inlet pipe and in the water inside the recirculation basin. On October 3, 2012 (after three months of operation) Health staff noticed significant orifice clogging from the Thiothrix spp. mats inside the recirculation basin when conducting a lateral distal head check. A SIM/TECH Pressure Filter (filter screen 0.62 in diameter openings) was installed on the pump discharge line to the pressure distribution network on October 29 to keep the mats from clogging the orifices. The laterals were flushed, bottlebrushed, and reflushed on the same day the filter was installed. After the cleaning, a lateral distal head check showed the head pressure to be back to the normal operating pressure of 5 feet.

The SIM/TECH Pressure Filter needed cleaning on six different occasions through the remaining period of the test (October 29, November 7, December 27, January 22, and April 18). However, the filter was effective in preventing additional clogging by Thiothrix spp. as at the end of the test period an inspection of the pressure distribution network showed no clogging in any of the orifices.

On October 26, 2012, the water level in the contact chamber was measured at a height of 35 inches, which was well above the design water level of 18 inches. Solids accumulation in the bottom of the contact chamber was also observed. The anoxic zone feed distribution piping connects at the bottom of the contact chamber, and thus it is likely that solids from the contact chamber were collected in the feed distribution piping or in the media above the feed piping to create excessive headloss. As noted above, the flow rate to the feed piping was reduced by dropping the recirculation ratio from 8.0 to 5.0 on November 1st, 2012 to reduce the headloss.

Proper operation of the distribution feed pipe network in the anoxic zone is important to the performance of the ERGF system. After the recirculation ratio was lowered to 5:1, the solids that accumulated in the contact chamber and collected in the upflow distribution piping continued to result in high water level measurements in the contact chamber through the remaining period of the test. The water level ranged from 35 inches to the highest level at 44 inches recorded on May 29, 2013. The high headloss caused flooding of the lower section of the aerobic zone, which then can limit oxygen availability and nitrification efficiency in the aerobic zone.

During the fifth month of system operation, a clog occurred in the overflow discharge line of the influent flow control basins. The discovery of the problem was based on observation of raw sewage flowing in the ERGF recirculation basin from the effluent outlet pipe in the basin during an early morning influent dosing event on November 26, 2012. When the ERGF was installed the effluent discharge line was connected to the sewage overflow discharge line from the influent control basins to convey raw sewage and treated effluents to the final pump basin, which discharged all of the wastewater back to the headworks of the Snoqualmie WRF. The problem was corrected by the system's installation contractor who disconnected the sewage overflow discharge line from the ERGF effluent discharge line, removed the clog in the line, and installed a separate sewage overflow discharge line for the influent flow control basins on December 3, 2013.

The effluent filter (OSI 4" Biotube®) on the outlet from the septic tank requires periodic cleaning. During the test, the filter was cleaned after ten months (one month of start-up and nine months of testing). The cleaning was done on the same day (April 23, 2013) solids/scum tank measurements were conducted.

The routine operation and maintenance of the ERGF system was straightforward with the exception of the anoxic zone feed distribution pipe clogging problem described above. The discovery of this clogging problem was based on water level measurements inside the contact chamber. When the problem was identified, the recirculation ratio reduction did not reduce the headloss on a long term basis. While pumping the water out in anoxic zone was discussed as a method to remove the solids, it was not considered as a cost effective maintenance approach for the ERGF at the rate the solids accumulated and moved into the feed distribution pipe network.

Maintenance activities, provided by a qualified service provider, should include checking the contact chamber in the anoxic zone for solids depth and, if solids have built up in the chamber, pumping of the tank should be scheduled. The pump should be cycled, and the timer, alarm, and float should be checked for proper operation. The pressure distribution system orifices should be checked for clogging and be cleaned as needed. In situ effluent quality measurements for ammonia and nitrate should be conducted as needed to verify treatment performance.

A qualified service provider should also check the septic tank for solids depth and the tank's effluent filter should be cleaned. If solids have built up in the tank, pumping the septic tank should be scheduled. In a typical or standard residential septic tank system pumping can be expected to occur every 3 to 5 years. More frequent pumping of solids from the septic tank can be expected based on the additional solids load generated by the ERGF System. Health recommends that a measurement of solids level in the tank occur once a year to ensure that good solids separation continues in the tank (a standard recommended practice in residential systems).

Based on the observations during the verification test, annual inspection and cleaning may be adequate, but semiannual maintenance checks would appear to be more appropriate during the first year of operation to address any problems in a timely manner and ensure system performance. Based on 12 months of observations, it is estimated that normal maintenance checks would require less than one hour to ensure that the system is in good operating condition.

No other problems were encountered during the test. No particular design considerations are necessary relative to placement, as the system makes very little noise. The basic components of the system appear durable and should perform well under typical home wastewater conditions with exception of the anoxic zone feed distribution pipe network.

4.4.2 Electric Use

The ERGF used only one single phase one-third horsepower water pump (Goulds PE31M 1/3HP 1/60/115 12.0MA) to dose the media and all other flow (recirculation, influent wastewater, effluent discharge) was by gravity. Electrical use was estimated by using the AC/single phase formula to determine input power in Kilowatts (kW).

$$kW = \frac{E \text{ x } I \text{ x } PF}{1000} = \frac{115 \text{ x } 12 \text{ x } .8}{1000} = \frac{1104}{1000} = 1.1 \text{ kW}$$

where E=volts, I= Amps, PF = Power Factor (0.8 for single phase)

The average power usage (kWh) per day was estimated by multiplying the hours per day the pump ran by the input power (KW). 2.3 hours/day x 1.1 kW = 2.53 kWh/day. Multiplying the daily consumption in kWh per day by an average utility rate of $0.10 per kWh show that the daily electrical cost to run the ERGF was appropriately $0.25/day.

4.4.3 Noise

Noise levels associated with mechanical equipment (effluent pump) were not measured during the verification period. It should be noted that the noise level from the ERGF pump is similar to other small sewage effluent pumps commonly used in low pressure distribution systems. Noise levels for the pump during the verification test period was difficult to distinguished from the loud background noise coming from the headworks of Snoqualmie WRF in close proximity to the effluent pump basin.

4.4.4 Odor Observations

Monthly odor observations were made over the last eight months of the verification test. The observation was qualitative based on odor strength (intensity) and type (attribute). Intensity was classified as not discernible; barely detectable; moderate; or strong. Observations were made during periods of low wind velocity (<10 knots). The observer stood upright at a distance of three (3) feet from the treatment unit, and recorded any odors at 90 ° intervals in four (4) directions (minimum number of points). All observations were made by the same Health personnel. Table 4-9 summarizes the results for the odor observations. As can be seen, there were no discernible odors found during any of the observation periods.

Table 4-9. Odor Observations.

Date	Number of Observations	Observation Points Observed
12/13/2012	8	No discernible odor
1/22/2013	8	No discernible odor
2/26/2013	8	No discernible odor
4/1/2013	8	No discernible odor
4/29/2013	8	No discernible odor
5/20/2013	8	No discernible odor
6/11/2013	8	No discernible odor
7/30/2013	8	No discernible odor

4.5 Quality Assurance/ Quality Control

A number of Quality Assurance and Quality Control (QA/QC) procedures were completed to ensure the precision, accuracy and quality of the data gathered for the project. The QA/QC procedures included sample replication (to measure precision), spike recovery and blind performance evaluation (to quantify accuracy), and blind field samples and field duplicates to determine the adequacy of the field sampling, transport and laboratory procedures. A summary of the precision, accuracy, and completeness of the analytical tests performed for the parameters of interest is shown in Table 4-10 and Table 4-11. These summaries combine results of QA/QC measures for all three on-site nitrogen removal technologies.

Table 4-10. Summary of precision, accuracy, and completeness of NOx-N, NH_3-N, TN, and TP data for the 12-month verification testing period.

	NO_X-N	NH_3-N	TN	TP
Precision (CV)				
Mean	1.8%	0.9%	2.2%	3.7%
SD	2.1%	1.4%	2.3%	5.8%
Median	1.2%	0.5%	1.6%	2.0%
90th percentile	4.1%	2.2%	4.9%	9.0%
% Passed	99.1%	100%	99.7%	98.4%
Accuracy (% recovery)				
Mean	100%	101%	103%	104%
SD	7%	3%	7%	11%
Median	98%	101%	102%	105%
10th percentile	91%	99%	94%	92%
90th percentile	108%	104%	111%	117%
% Passed	100%	100%	96.4%	100%
Completeness (% planned sample analyses)				
	97.4%	97.2%	97.0%	98.0%

Table 4-11. Summary of precision and completeness of alkalinity, BOD, COD, TSS, and VSS data for the 12-month verification testing period.

	Alkalinity	BOD	COD	TSS	VSS
Precision					
Mean	0.5%	3.1%	5.7%	4.9%	6.5%
SD	0.5%	2.7%	5.0%	4.7%	7.6%
Median	0.4%	2.6%	4.0%	3.8%	4.6%
90th percentile	1.1%	5.9%	12.8%	10.6%	12.1%
% Passed	100.0%	100.0%	100.0%	97.0%	96.0%
Completeness					
	96.7%	93.5%	96.5%	93.5%	93.5%

4.5.1 Precision

4.5.1.1 Nitrate plus Nitrite (NOx-N)

All NOx-N samples were processed in duplicate. For 99 percent of samples (212 out of 214) the acceptance criteria goal of ± 10 percent coefficient of variation (i.e., CV = replicate SD/mean) was met for the VRGF, ERGF, RGF and spike recovery samples. The average CV for these samples was 1.8 ± 2.1 percent (± SD), with a median and 90th percentile of 1.2 percent and 4.1 percent, respectively.

The ± 10 percent CV goal for NOx-N precision was met in 73 percent of the samples for the Woodchip bed samples. Failure to meet the acceptance goal in these cases always occurred when the average sample concentrations were very close to the method detection limit (i.e., 0.01 mg NOx/L). For example, during the final week of the project the NOx-N concentration for the Woodchip bed effluent samples collected on July 24, 2013, averaged 0.009 ± 0.005 mg/L. So in this case, and many others, the NOx-N replication was excellent in absolute terms, even when the 10 percent CV goal was not met. In general, when sample concentrations approach the analytical detection limit, the CV criterion loses its relevance because even excellent absolute replication (i.e., very low SD values) will give high CV values due to the extremely low denominator in the formula for the CV.

4.5.1.2 Ammonia

All ammonia samples were processed in duplicate. The acceptance criteria goal of ± 20 percent CV was met for 100 percent of cases (n = 315). In fact, for 99.7 percent of the samples (314 of 315) the CV was within ± 10 percent. The average CV for the ammonia samples was 0.9 ± 1.4 percent, with a median and 90th percentile of 0.5 percent and 2.2 percent, respectively.

4.5.1.3 Total Nitrogen

All total nitrogen samples were processed in duplicate. For 99.7 percent of the samples (320 of 321) the CV was ± 10 percent, which is well below the acceptance criteria goal of ± 20 percent. The average CV for the total nitrogen samples was 2.2 ± 2.3 percent, with a median and 90th percentile of 1.6 percent and 4.9 percent, respectively.

4.5.1.4 Total Phosphorus

All total phosphorus samples were processed in duplicate. For 98.4 percent of samples (245 of 249) the acceptance criteria goal of ± 20 percent CV was met. The average CV for the total phosphorus samples was 3.7 ± 5.8 percent, with a median and 90th percentile of 2.0 percent and 9.0 percent, respectively.

4.5.1.5 Alkalinity

One of the four effluent alkalinity samples (VRGF, ERGF, RGF, or Woodchip Bed) was run in duplicate for each sampling date. The acceptance criteria goal of ± 20 percent CV was met in all cases (n = 55). The average CV for the alkalinity replicates was 0.5 ± 0.5 percent, with a median and 90th percentile of 0.4 percent and 1.1 percent, respectively.

4.5.1.6 Total Suspended Solids

All influent TSS, and one of the four effluent TSS samples (VRGF, ERGF, RGF, or Woodchip Bed), was run in duplicate for each sampling date. The CV goal for TSS samples was ± 20 percent, which was met for 97.0 percent of the samples (98 of 101). Failure to meet the CV goal occurred when the TSS concentration was very low. The average CV for the TSS replicates was 4.9 ± 4.7 percent, with a median and 90th percentile of 3.8 percent and 10.6 percent, respectively.

4.5.1.7 Volatile Suspended Solids

All influent VSS, and one of the four effluent VSS samples (VRGF, ERGF, RGF, or Woodchip Bed), was run in duplicate for each sampling date. The CV goal for VSS samples was ± 20 percent, which was met for 96.0 percent of the samples (97 of 101). Failure to meet the CV goal occurred when the VSS concentration was very low. The average CV for the VSS replicates was 6.5 ± 7.6 percent, with a median and 90th percentile of 4.6 percent and 12.1 percent, respectively.

4.5.1.8 Biochemical Oxygen Demand

All influent BOD, and one of the four effluent BOD samples (VRGF, ERGF, RGF, or Woodchip Bed), was run in duplicate for each sampling date. The CV goal for BOD samples was ± 20 percent, which was met for all samples (n = 101). The average CV for the BOD replicates was 3.1 ± 2.7 percent, with a median and 90th percentile of 2.6 percent and 5.9 percent, respectively.

4.5.1.9 Soluble Chemical Oxygen Demand

All influent SCOD, and one of the four effluent SCOD samples (VRGF, ERGF, RGF, or Woodchip Bed), was run in duplicate for each sampling date. The CV goal for SCOD samples was ± 20 percent, which was met for all samples (n=109). The average CV for the SCOD replicates was 5.7 ± 5.0 percent, with a median and 90th percentile of 4.0 percent and 12.8 percent, respectively.

4.5.2 Accuracy

Analytical accuracy for the nutrient samples was assessed via spike recovery analyses. The QAPP spike recovery goal for ammonia was for the measured spike recovery value to be within 80 to 120 percent of the known spike amount. The spike recovery goals for NOx-N, total nitrogen and total phosphorus were for the measured spike recovery value to be within 60 to 140 percent of the known spike amount. Spike recovery for the NO_X samples averaged 99.7 ± 7.1 percent, which was well within the 60 to 140 percent goal in all 55 cases. Spike recovery for the ammonia samples averaged 101.4 ± 3.3 percent, which was well within the 80 to 120 percent goal in all 54 cases. With the exception of two outliers, the total nitrogen spike recovery averaged 102.9 ± 6.9 percent, which was within the 60 to 140 percent goal for 96.4 percent of the samples (53 of 55). In two cases, which occurred for samples collected during the first two weeks of the project, the total nitrogen spike recovery far exceeded the 140 percent limit. Those samples are suspected of receiving a double spike. If these samples were in fact double-spiked, then the correct spike recovery for these two samples would be ≈ 90 percent. Total phosphorus spike recovery averaged 104.5 ± 10.7 percent, which was well within the 60 to 140 percent goal for all 51 samples.

The BOD and SCOD analyses did not employ spike additions, but they did include regular determinations for known standards. In the case of BOD, the average recovery for the known standard solution was 105 ± 4 percent, which was well within the BOD accuracy goal as indicated by Standard Methods (i.e., ± 15 percent of the real concentration). Similar results were obtained for known standards run in tandem for SCOD analyses. In this case, the average accuracy for SCOD was 104 ± 4 percent. The accuracy goal for BOD was passed in 12 of 12 cases, and for SCOD it was passed in 55 of 55 cases.

The accuracy of the analytical methods was also assessed twice using blind commercial standards, which is also called Performance Evaluation (PE). Performance evaluation was conducted prior to field sampling in May 2012 and in the middle of the field campaign in December 2012-January 2013. PE samples for pH, alkalinity, BOD, CBOD, COD, TSS, TKN, NH_3-N, NO_x-N, and TP were purchased from Ultra Scientific and ERA. The concentrations of the blind standards were only known to the QA/QC manager for the project after the analyses were completed. Laboratory personnel performed the analyses of the PE samples and reported the results to the QA/QC manager. The QA/QC manager then opened the sealed envelope from Ultra Scientific or ERA and compared the results with answers obtained from the PE sample suppliers. The comparison was used to assess the accuracy of the testing results obtained by the laboratory personnel. Results from the two PE sample testing events (Table 4-12) show very good agreement between the UWCEE laboratory results and the PE samples.

Table 4-12. Analytical results of PE samples and the correct values.

	1st PE Testing			2nd PE Testing		
Parameter[a]	Analytical Result	Correct Value	Accuracy-recovery	Analytical Result	Correct Value	Accuracy-recovery
pH	9.2	9.1	101%	9.3	9.1	102%
Alkalinity[b]	116	117	99%	167	168	99%
BOD	65.2	69	94%	155.2	140	111%
CBOD	64.7	59.4	109%	155.1	120	129%
COD	64.7	59.4	109%	218.1	226	97%
TSS	110	114	96%	79.7	84.1	95%
TKN	9.1	9.3	98%	1.1	1.2	92%
NH_3-N	6.9	6.8	101%	13	13.8	94%
NO_x-N	12.1	12.5	97%	7.9	8	99%
TP	2.6	2.5	104%	5.9	5.2	113%

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

4.5.3 Completeness:

On account of general electrical outages at the Snoqualmie WRF and several Autosampler malfunctions, not all of the planned samples were collected. For NOx-N, ammonia, total nitrogen, and total phosphorus 97.0-98.0 percent of the planned samples were actually collected and processed. For similar reasons, the planned analyses for BOD, TSS and VSS were 93.5 percent complete, and the planned analyses for Alkalinity and SCOD were 96.5 percent complete.

4.5.3.1 Blind Samples

The purpose of the blind samples was to evaluate the analytical precision and accuracy 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 4-13. For each test, the QA/QC manager selected an effluent from one of the three systems, known only to the QA/QC manager and the individual responsible for site sampling. The selected sample was split into two; one was labeled as usual and the other was labeled as the blind. Laboratory personnel then performed analytical analyses on the blind sample without being informed of its identity. Comparison of the blind sample result with its corresponding effluent was used to evaluate analytical precision. The results in Table 4-13 show excellent duplication of the analytical values for the blind and selected effluent sample.

Table 4-13. Results of blind samples and the corresponding selected effluents[a].

Sample Date	CBOD	SCOD	TSS	VSS	Alka[b]	TN	NH_3-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
Absolute Error	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
Absolute Error	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
Absolute Error	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
Absolute Error	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
Absolute Error	4.9%	4.5%	-	-	0.4%	4.3%	0.0%	0.4%	0.0%

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

4.5.3.2 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 4-14. Similar results between the field duplicates showed that the composite samples collected were representative and there was no contamination of the composite containers.

Table 4-14. Results of field duplicate samples and the corresponding effluents[a].

Sample Date	CBOD	SCOD	TSS	VSS	Alka[b]	TN	NH_3-N	NO_x-N	TP
10/16/2012									
VRGF	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
Absolute Error	0.0%	3.1%	15.0%	12.9%	0.4%	5.1%	2.0%	6.9%	2.9%
10/30/2012									
ERGF	10.2	31.3	5.8	4.5	189.0	7.8	6.3	0.1	3.3
Field Duplicate	10.9	35.1	6.2	5.2	189.0	7.9	6.4	0.1	3.2
Absolute Error	4.7%	8.1%	4.7%	10.2%	0.0%	0.5%	0.7%	6.7%	1.8%
11/8/2012									
Woodchip	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
Absolute Error	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] Alka=Alkalinity. Unit in mg/L as $CaCO_3$.

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Appendix A

Tables of Data Summary

Table A-1. Influent and Enhanced Recirculating Gravel Filter effluent nitrogen species concentrations for the 12-month verification testing period. Units are in mg/L as N.

Sample	Influent		Effluent		
Date	TN	NH_3	TN	NO_X	NH_3
8/21/12	60.2	34.0	7.0	0.4	5.1
9/4/12	52.1	28.3	7.5	1.0	5.5
9/11/12	48.7	34.2	-	-	-
9/13/12	54.6	32.8	8.4	1.6	6.2
9/16/12	62.4	42.3	9.3	1.7	6.3
9/17/12	58.3	34.4	9.3	1.6	6.8
9/18/12	62.8	34.0	10.3	1.5	7.0
9/19/12	68.2	36.2	-	-	-
9/20/12	48.9	30.5	-	-	-
9/21/12	48.3	33.8	9.3	1.6	6.7
10/16/12	56.2	25.7	9.2	0.3	7.2
10/30/12	39.8	26.7	7.8	0.1	6.3
11/6/12	34.0	26.2	6.9	0.3	5.9
11/8/12	-	-	6.9	0.2	5.9
11/11/12	64.6	39.4	6.0	0.2	5.3
11/12/12	53.2	30.6	7.4	0.1	5.9
11/13/12	44.6	27.0	7.6	0.1	6.2
11/14/12	39.8	25.7	7.5	0.1	6.4
11/15/12	43.8	26.2	7.0	0.2	6.4
11/16/12	54.8	29.7	8.4	0.3	6.3
12/18/12	39.6	21.6	5.8	0.6	4.6
1/15/13	54.8	28.5	6.0	0.3	4.7
1/23/13	52.7	31.3	6.3	0.2	5.5
1/31/13	41.0	25.1	5.5	0.1	4.2
2/13/13	48.0	27.7	5.3	0.1	4.1
2/14/13	51.0	29.4	6.2	0.1	5.1
2/15/13	49.7	30.6	6.9	0.1	5.6
2/16/13	61.3	33.3	7.8	0.1	5.9
2/17/13	51.7	30.6	7.5	0.1	6.0
2/18/13	52.1	30.6	8.2	0.2	6.4
2/27/13	46.0	26.0	7.3	0.6	5.8
3/5/13	29.0	17.3	7.5	0.7	6.2
3/6/13	32.3	25.7	8.1	0.7	6.2
3/13/13	42.7	26.2	8.0	0.5	6.4
4/2/13	50.1	30.5	9.2	0.2	7.7
4/14/13	24.7	17.0	9.3	2.8	5.3
4/15/13	32.7	19.0	7.4	1.7	4.6

Table A-1 (continued). Influent and Enhanced Recirculating Gravel Filter effluent nitrogen species concentrations for the 12-month verification testing period. Units are in mg/L as N.

Sample	Influent		Effluent		
Date	TN	NH_3	TN	NO_X	NH_3
4/16/13	34.7	20.7	6.3	1.0	4.3
4/17/13	31.8	19.5	6.2	0.6	4.3
4/18/13	39.4	23.2	6.5	0.6	4.3
5/14/13	51.8	33.0	12.2	0.1	9.6
5/15/13	47.3	29.2	11.0	0.1	9.7
6/4/13	52.5	26.6	12.1	0.1	10.3
6/11/13	57.2	37.1	12.0	0.2	9.8
6/21/13	51.4	27.6	9.6	0.3	7.6
6/22/13	51.5	31.9	11.8	0.2	9.2
6/23/13	61.8	40.0	9.6	0.1	8.1
6/24/13	54.4	33.8	9.9	0.1	8.7
6/25/13	55.0	32.9	11.0	0.1	9.1
6/26/13	48.9	29.3	11.5	0.2	9.4
7/23/13	49.9	31.5	12.8	1.2	10.1
7/24/13	52.0	32.0	12.9	1.3	10.1
7/25/13	46.3	30.2	12.4	1.1	9.9
7/26/13	42.6	29.3	12.2	1.0	9.9
7/27/13	43.0	26.8	12.1	1.0	9.7

Table A-2. Influent and Enhanced Recirculating Gravel Filter effluent BOD, COD, TSS, and VSS concentrations for the 12-month verification testing period. Units are in mg/L.

Sample	Influent					Effluent			
Date	BOD	COD	SCOD	TSS	VSS	BOD	SCOD	TSS	VSS
8/21/12	266	717	173	334	302	9.7	36	10.7	9.4
9/4/12	414	1001	150	-	-	6.7[a]	22	6.2	5.3
9/11/12	357	897	150	386	321	-	-	-	-
9/13/12	313	639	101	357	285	9.9	21	7.0	4.8
9/16/12	327	726	160	352	285	10.0	24	8.3	6.2
9/17/12	353	729	188	337	299	-	30	9.0	7.7
9/18/12	334	649	179	316	292	11.0	26	10.8	9.8
9/19/12	313	732	173	287	257	-	-	-	-
9/20/12	335	580	147	287	257	-	-	-	-
9/21/12	317	631	161	335	303	10.6	21	6.1	5.2
10/16/12	457	1424	121	-	673	9.6	31	4.6	2.9
10/30/12	259	582	152	312	279	10.2	31	5.8	4.5
11/6/12	320	819	98	440	387	6.4	23	2.8	2.4
11/8/12	-	-	-	-	-	5.7	21	3.5	2.7
11/11/12	343	916	198	523	484	6.2	18	3.4	2.9
11/12/12	313	917	200	406	345	9.3	20	4.9	4.1
11/13/12	305	672	175	350	310	11.5	30	5.2	4.7
11/14/12	259	562	126	442	408	11.0	21	4.3	3.8
11/15/12	277	585	128	387	361	8.4	20	3.8	3.2
11/16/12	305	731	192	364	346	7.1	27	3.4	2.9
12/18/12	191	466	114	282	267	5.3	21	3.0	2.7
1/15/13	555	1049	201	512	442	7.0	22	3.8	3.3
1/23/13	318	776	226	288	252	7.1	29	4.0	3.0
1/31/13	251	566	157	296	268	6.6	17	3.4	2.8
2/13/13	303	737	148	299	281	6.1	11	4.1	3.1
2/14/13	298	831	177	353	328	9.0	13	4.1	3.6
2/15/13	321	702	160	333	306	10.4	29	4.3	3.8
2/16/13	341	743	192	410	384	10.5	34	4.2	3.6
2/17/13	315	865	178	370	342	11.3	32	4.4	3.7
2/18/13	337	859	197	389	354	10.2	30	4.2	3.6
2/27/13	-	629	118	-	-	-	23	-	-
3/5/13	-	499	168	-	-	-	25	-	-
3/6/13	-	556	153	-	-	-	31	-	-
3/13/13	229	486	127	246	218	8.3	25	2.9	2.2
4/2/13	480	1069	162	444	377	10.6	31	4.0	3.8
4/14/13	207	494	100	349	316	10.4	16	10.3	9.3
4/15/13	193	444	104	213	201	10.3	22	8.5	7.6

Table A-2 (continued). Influent and Enhanced Recirculating Gravel Filter effluent BOD, COD, TSS, and VSS concentrations for the 12-month verification testing period. Units are in mg/L.

Sample	Influent					Effluent			
Date	BOD	COD	SCOD	TSS	VSS	BOD	SCOD	TSS	VSS
4/16/13	201	436	116	188	180	9.0	22	7.0	6.0
4/17/13	204	399	97	226	204	9.0	22	6.1	3.7
4/18/13	244	473	122	221	200	9.0	13	6.7	5.6
5/14/13	274	758	145	551	482	-	23	8.0	6.9
5/15/13	-	574	151	-	-	-	35	-	-
6/4/13	740	1550	182	1094	978	9.2	21	5.4	4.6
6/11/13	414	829	212	405	367	8.3	26	5.2	4.2
6/21/13	435	1040	138	492	447	7.4	22	6.8	6.2
6/22/13	256	625	150	292	264	11.3	28	8.3	7.2
6/23/13	306	718	193	266	256	8.0	27	5.5	5.1
6/24/13	401	751	219	336	304	8.5	29	5.2	4.6
6/25/13	250	583	169	253	226	8.3	30	4.3	3.8
6/26/13	247	575	162	292	283	8.8	26	4.9	4.7
7/23/13	260	645	168	263	234	8.9	26	2.9	2.5
7/24/13	282	627	174	362	314	6.9	33	2.7	2.5
7/25/13	216	610	162	256	214	5.4	28	2.7	2.3
7/26/13	247	640	155	254	209	5.8	24	2.7	2.5
7/27/13	222	511	126	244	208	5.1	18	2.9	2.5

[a] Less than indicated value (DO depletion of more than 2.0 mg/L was not met, so 2.0 mg/L assumed in calculation).

Table A-3. Influent and Enhanced Recirculating Gravel Filter effluent temperature, alkalinity, and pH for the 12-month verification testing period. Alkalinity units are in mg/L as $CaCO_3$.

Sample Date	Influent			Effluent		
	Temp. ^{0}C	Alkalinity	pH	Temp. ^{0}C	Alkalinity	pH
8/21/12	20.5	291	7.9	24.6	228	7.4
9/4/12	23.3	281	7.7	25.1	244	7.3
9/11/12	21.5	280	7.3	21.3	-	7.0
9/13/12	21.3	282	7.3	23.5	233	6.8
9/16/12	20.9	327	7.4	22.9	237	6.9
9/17/12	22.4	264	7.2	23.1	237	7.0
9/18/12	22.9	259	7.5	24.3	242	7.0
9/19/12	21.1	272	7.3	23.0	-	7.0
9/20/12	20.2	255	7.6	23.5	-	6.9
9/21/12	17.7	257	7.6	20.5	231	6.9
10/16/12	17.1	226	6.9	17.1	215	6.7
10/30/12	14.9	194	7.1	14.9	189	6.7
11/6/12	16.3	206	7.3	16.7	185	6.8
11/8/12	12.3	-	6.7	11.8	186	6.9
11/11/12	12.4	248	6.7	11.4	176	6.7
11/12/12	13.7	216	7.0	12.3	182	6.8
11/13/12	14.4	203	7.1	12.4	187	6.7
11/14/12	13.1	195	7.1	12.0	190	6.9
11/15/12	13.9	193	7.2	13.3	186	6.8
11/16/12	14.4	213	7.0	12.0	180	6.8
12/18/12	6.5	164	7.7	8.2	153	7.1
1/15/13	9.4	211	7.4	8.2	166	7.1
1/23/13	10.0	230	7.5	7.1	187	7.2
1/31/13	10.9	184	7.6	9.0	175	6.9
2/13/13	10.0	213	7.5	9.3	183	7.1
2/14/13	11.7	226	7.5	9.8	192	7.1
2/15/13	10.5	232	7.4	10.8	195	7.1
2/16/13	13.8	261	7.4	10.7	196	7.2
2/17/13	11.7	241	7.7	9.7	197	7.0
2/18/13	11.7	243	7.6	9.9	198	7.1
2/27/13	11.9	218	7.5	10.4	192	7.1
3/5/13	12.6	179	6.9	10.8	192	6.9
3/6/13	11.5	214	7.0	8.9	190	6.7
3/13/13	13.2	218	7.7	11.0	195	6.7
4/2/13	12.2	248	7.5	13.2	222	6.9
4/14/13	12.9	155	7.2	12.8	171	6.7
4/15/13	13.0	167	7.0	13.0	162	6.7

Table A-3 (continued). Influent and Enhanced Recirculating Gravel Filter effluent temperature, alkalinity, and pH for the 12-month verification testing period. Alkalinity units are in mg/L as $CaCO_3$.

Sample Date	Temp. ^{0}C	Influent Alkalinity	pH	Temp. ^{0}C	Effluent Alkalinity	pH
4/16/13	13.6	176	7.0	13.5	160	6.8
4/17/13	14.7	178	7.6	14.5	160	6.8
4/18/13	12.4	193	7.7	12.2	160	6.8
5/14/13	20.0	229	7.2	19.8	218	7.0
5/15/13	18.7	219	7.1	19.3	219	6.9
6/4/13	20.5	221	7.4	21.3	234	6.9
6/11/13	17.2	227	7.2	19.5	227	6.9
6/21/13	18.1	204	7.5	19.3	204	6.9
6/22/13	21.1	253	8.2	23.1	230	7.0
6/23/13	19.4	291	7.7	20.1	228	7.0
6/24/13	17.0	259	7.3	18.6	239	7.0
6/25/13	22.8	265	7.6	20.4	241	7.0
6/26/13	20.3	246	7.4	20.5	243	7.0
7/23/13	24.0	246	7.3	23.4	231	7.0
7/24/13	25.0	245	7.2	24.9	228	7.1
7/25/13	25.0	246	7.3	24.4	227	7.0
7/26/13	22.9	244	7.5	24.4	224	7.0
7/27/13	21.8	258	7.5	23.3	221	7.0

Table A-4. Enhanced Recirculating Gravel Filter effluent dissolved oxygen concentrations for the 12-month verification testing period. Units are in mg/L.

Sample Date	Effluent DO
8/21/12	0.63
9/4/12	0.56
9/11/12	0.72
9/13/12	0.52
9/16/12	0.56
9/17/12	0.5
9/18/12	0.62
9/19/12	0.59
9/20/12	-
9/21/12	0.62
10/16/12	0.79
10/30/12	-
11/6/12	0.81
11/8/12	0.73
11/11/12	0.89
11/12/12	0.76
11/13/12	0.87
11/14/12	0.87
11/15/12	0.74
11/16/12	0.83
12/18/12	0.70
1/15/13	0.47
1/23/13	0.72
1/31/13	0.51
2/13/13	0.67
2/14/13	0.60
2/15/13	0.58
2/16/13	0.50
2/17/13	0.62
2/18/13	0.51
2/27/13	0.70
3/5/13	0.52
3/6/13	0.47
3/13/13	0.55
4/2/13	0.40
4/14/13	0.66
4/15/13	0.58
4/16/13	0.62
4/17/13	0.65
4/18/13	0.65
5/14/13	0.39
5/15/13	0.42
6/4/13	0.80
6/11/13	0.43
6/21/13	0.65
6/22/13	0.55
6/23/13	0.61
6/24/13	0.56
6/25/13	0.55
6/26/13	0.62
7/23/13	0.58
7/24/13	0.59
7/25/13	0.58
7/26/13	0.61
7/27/13	0.72

Table A-5. Influent and Enhanced Recirculating Gravel Filter effluent total phosphorus concentrations for the 12-month verification testing period. Units are in mg/L.

Sample Date	Total P	
	Influent	Effluent
8/21/12	4.7	0.7
9/4/12	5.0	1.9
9/11/12	6.7	-
9/13/12	7.2	3.3
9/16/12	6.0	3.1
9/17/12	6.2	3.2
9/18/12	-	-
9/19/12	5.9	-
9/20/12	4.7	-
9/21/12	5.2	2.9
10/16/12	4.5	3.5
10/30/12	5.5	3.3
11/6/12	3.0	2.5
11/8/12	-	2.0
11/11/12	5.7	2.3
11/12/12	5.5	3.0
11/13/12	5.6	3.4
11/14/12	5.5	3.3
11/15/12	4.7	2.6
11/16/12	5.6	2.2
12/18/12	3.2	1.7
1/15/13	6.6	2.1
1/23/13	5.2	2.9
1/31/13	5.0	2.8
2/13/13	6.4	3.9
2/14/13	6.2	4.5
2/15/13	6.9	4.4
2/16/13	6.8	3.6
2/17/13	6.1	4.0
2/18/13	7.1	3.5
3/13/13	6.9	3.7
4/2/13	6.6	4.6
4/14/13	3.2	0.9
4/15/13	3.8	1.0
4/16/13	3.5	1.5
4/17/13	4.1	1.8
4/18/13	4.9	2.3
5/14/13	6.8	5.6
6/4/13	8.2	5.2
6/11/13	7.5	4.3
6/21/13	8.4	4.8
6/22/13	7.6	5.4
6/23/13	7.2	5.0
6/24/13	7.6	5.3
6/25/13	6.3	5.5
6/26/13	5.8	5.5
7/23/13	6.6	4.8
7/24/13	7.4	4.6
7/25/13	6.6	4.7
7/26/13	6.1	4.9
7/27/13	5.0	5.0

Table A-6. Influent and Enhanced Recirculating Gravel Filter effluent fecal coliform for the 12-month verification testing period. Units are in CFU/100 ml.

Sample Date	Fecal Coliform	
	Influent	Effluent
8/21/12	3.3E+6	1.2E+6
9/4/12	8.5E+6	1.2E+6
9/11/12	1.4E+7	9.5E+5
9/13/12	1.1E+7	6.5E+5
9/16/12	-	-
9/17/12	-	-
9/18/12	2.6E+7	1.4E+6
9/19/12	1.4E+7	2.2E+6
9/20/12	2.4E+7	2.0E+6
9/21/12	3.7E+6	1.3E+6
10/16/12	-	-
10/30/12	7.8E+6	1.7E+5
11/6/12	2.1E+7	2.1E+6
11/8/12	2.4E+7	2.6E+6
11/11/12	2.7E+7	4.9E+5
11/12/12	1.6E+7	1.7E+6
11/13/12	2.0E+6	1.7E+5
11/14/12	5.5E+6	2.5E+5
11/15/12	8.2E+6	1.7E+5
11/16/12	3.7E+6	2.3E+5
12/18/12	2.6E+6	3.0E+4
1/15/13	1.0E+7	5.6E+5
1/23/13	6.7E+6	6.5E+4
1/31/13	8.2E+6	6.8E+4
2/13/13	2.8E+7	7.1E+5
2/14/13	2.3E+7	1.2E+6
2/15/13	8.6E+6	1.1E+6
2/16/13	6.5E+6	7.5E+5
2/17/13	5.3E+6	5.4E+5
2/18/13	2.0E+6	1.4E+5
3/13/13	7.8E+6	1.7E+5
4/2/13	5.0E+6	3.2E+5
4/14/13	3.3E+6	6.0E+5
4/15/13	2.6E+6	5.8E+5
4/16/13	5.0E+6	4.4E+5
4/17/13	2.5E+6	4.5E+5
4/18/13	1.8E+6	5.2E+5
5/14/13	1.0E+7	4.3E+5
6/4/13	6.9E+6	2.2E+5
6/11/13	6.9E+6	3.0E+5
6/21/13	1.1E+7	3.9E+5
6/22/13	8.1E+6	4.1E+5
6/23/13	1.2E+7	6.3E+5
6/24/13	-	8.5E+5
6/25/13	1.2E+7	1.3E+6
6/26/13	9.0E+6	1.7E+6
7/23/13	1.5E+7	2.4E+5
7/24/13	6.8E+6	7.6E+4
7/25/13	1.2E+7	9.4E+4
7/26/13	2.1E+7	4.3E+5
7/27/13	4.4E+7	3.7E+5

Table A-7. Rainfall data and flow increase through Enhanced Recirculating Gravel Filter system on sampling days. Note that these rainfall values shown are for the time frame from 5 pm on sample setup day to 2 pm on sample collection date.

Sampling Date	Rainfall (inch)	Percent of 480 gallon per day
8/21/2012	0	0.0
9/4/2012	0	0.0
9/11/2012	0.02	0.5
9/13/2012	0	0.0
9/16/2012	0	0.0
9/17/2012	0.01	0.2
9/18/2012	0	0.0
9/19/2012	0	0.0
9/20/2012	0	0.0
9/21/2012	0	0.0
10/16/2012	0.63	14.7
10/30/2012	0.66	15.4
11/6/2012	0.01	0.2
11/8/2012	0.01	0.2
11/11/2012	0	0.0
11/12/2012	0.73	17.1
11/13/2012	0.11	2.6
11/14/2012	0.1	2.3
11/15/2012	0.01	0.2
11/16/2012	0	0.0
12/18/2012	0.1	2.3
1/15/2013	0	0.0
1/23/2013	0	0.0
1/31/2013	0.11	2.6
2/13/2013	0.08	1.9
2/14/2013	0.04	0.9
2/15/2013	0.01	0.2
2/16/2013	0.02	0.5
2/17/2013	0.58	13.6
2/18/2013	0	0.0
2/27/2013	0.11	2.6
3/5/2013	0	0.0
3/6/2013	0.03	0.7
3/13/2013	0.26	6.1
4/2/2013	0	0.0
4/14/2013	0.74	17.3

Table A-7 (continued). Rainfall data and flow increase through Enhanced Recirculating Gravel Filter system on sampling days.

Sampling Date	Rainfall (inch)	Percent of 480 gallon per day
4/15/2013	0.02	0.5
4/16/2013	0.17	4.0
4/17/2013	0	0.0
4/18/2013	0.02	0.5
5/14/2013	0.11	2.6
5/15/2013	0	0.0
6/4/2013	0	0.0
6/11/2013	0.01	0.2
6/21/2013	0.42	9.8
6/22/2013	0.01	0.2
6/23/2013	0.03	0.7
6/24/2013	0.23	5.4
6/25/2013	0.12	2.8
6/26/2013	0.14	3.3
7/23/2013	0.01	0.2
7/24/2013	0	0.0
7/25/2013	0	0.0
7/26/2013	0	0.0
7/27/2013	0	0.0

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