Geotextile Biofiltration of Primary Treated Municipal Wastewater Under Simulated Artic Summer Conditions

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ABSTRACT

Wastewater stabilization ponds (WSPs) are common for wastewater treatment in remote Canadian Arctic communities. In this paper, two geotextiles of different mass/unit areas are examined as a potential biofiltration upgrade to existing WSPs in arctic summer conditions. The intended role of the geotextile is to provide additional treatment of municipal wastewater seeping from these WSPs. Column filtration experiments were performed using municipal wastewater in a controlled laboratory environment at either 10℃ or 2℃. The columns contained one of two different nonwoven geotextiles over 10 cm of gravel, simulating a WSP berm in contact with exfiltrating wastewater. Weekly wastewater samples were taken upstream and downstream of the geotextile/gravel filter and were analyzed for a suite of water quality parameters; the hydraulic conductivity of the columns was also measured weekly. Results showed that it is possible to accumulate biomass on geotextile material over a 3 month period at these temperatures, which corresponded with 1 -2 log reductions in hydraulic conductivity. Significant removal of total suspended solids, 5-day biochemical oxygen demand, total nitrogen, and total phosphorus was observed; however, removal efficiencies for most parameters were reduced at the lower temperature. This study demonstrates that geotextiles could be used to enhance the performance of WSP systems operating in arctic climates.

1. INTRODUCTION

1.1 Background

Passive wastewater treatment systems, such as wastewater stabilization ponds (WSPs), are a common method of treating wastewater in the Canadian Arctic. Remote communities and restricted transportation methods often limit the availability of the materials, equipment, and energy required to construct and operate conventional treatment systems more commonly found in more southern climates (Wootton et al. 2008). The abundance of land in the Canadian Artic makes a constructed WSP system ideal for dealing with municipal wastewater (Horan, 1990), with the majority of the communities in the Canadian Arctic Territory of Nunavut (Nunavut) using a WSP for municipal wastewater management (Ragush et al. 2015). Treatment in a WSP is accomplished by sedimentation of solids, in combination with suspended-growth microbial processes (Crites and Tchobanoglous, 1998). Krkosek et al. (2012) described treatment in these WSPs as highly dependent on temperature and retention time. Unfortunately, the berms of WSP systems in Canada's north are constructed of local fill and in some of these WSP locations, the fill is typically highly permeable if thawed (Bölter et al. 2006). The resulting porous WSP berms allow for wastewater to seep or exfiltrate through the berms which, in some cases, compromises the treatment performance of the WSP and downstream treatment components.

The Government of Canada has recently implemented national regulations for municipal wastewater effluent, which includes mandatory performance standards for five day carbonaceous oxygen demand ($CBOD_5 < 25$ mg/l), total suspended solids ($TSS < 25$ mg/l) and un-ionized ammonia-nitrogen ($NH_3\text{-}N < 1.25$ mg/l) (Government of Canada, 2012). However, a five year grace period was granted to northern regions of Canada, including Nunavut, as it was recognized that technical and financial challenges may exist by imposing these performance standards on wastewater systems in small, remote, northern communities (CCME, 2009).

One potential approach to improving treatment performance in the semi-permeable northern WSPs is to line the inner berm slopes of a WSP with a geotextile which could act as a substrate for physical (Franks et al. 2015) and biological clogging (Wetzel et al., 2011); this would slow the release of wastewater to a more controlled rate. Geotextiles have been used in drainage and soil filtration applications for over 70 years (Bertram, 1940) and much research has been devoted to the study of geotextile clogging under leachate flow (Cancelli and Cazzuffi, 1987; Koerner and Koerner, 1988; Koerner and Koerner, 1990; Rowe et al. 1995; Armstrong, 1998; Rowe et al., 2000; Rowe et al. 2002; Palmeira et al. 2008). Considering the clogging potential of geotextiles as a positive attribute, a clogged geotextile layer on the upstream side of a WSP berm would serve two functions: (i) to lessen the wastewater seepage rate, increasing the retention time of effluent in the WSP; and (ii) to provide fixed-growth biofiltration (Bayon et al. 2015; Jechalkea et al. 2010) as wastewater passes through the geotextile. The challenge with implementing this strategy within an arctic context is the extreme climate. WSP systems typically remain frozen for 9-10 months of the year, with biological treatment occurring only within a short 2-3 month summer season where average air temperatures range from 7 – 10 ºC (Ragush et al. 2015). Previous investigations into hydraulically-similar biofilters operating under low temperature conditions indicates that a dramatic decrease in microbial growth (Ratkowsky et al. 1982; Koerner and Koerner, 1990; Rowe et al. 1995; Armstrong, 1998) and treatment performance (Gullicks and Cleasby, 1986; Gullicks and Cleasby, 1990; Moll et al. 1999) can be expected. The goal of this paper is to examine the potential level of wastewater treatment and the expected hydraulic conductivity reduction in a geotextile biofilter under low arctic temperatures (i.e. 2 ºC and 10ºC) and a short arctic summer treatment season (i.e. 3 months). By evaluating the hydraulic performance and treatment potential of a geotextile filter, this study will help improve WSP design to better meet effluent discharge regulations for the protection of environmental and public health in arctic regions.

2. MATERIALS AND METHODS

To assess the feasibility of using geotextile liners in an arctic WSP, bench-scale models of a geotextile filtration unit were evaluated. Two primary objectives were identified to address the intended effect of a geotextile:

1. To examine if significant decreases in hydraulic conductivity are achievable within the time and temperature constraints of an arctic summer. This was tested by analyzing changes in geotextile hydraulic conductivity.
2. To examine if significant water quality improvement is achievable within the time and temperature constraints of an arctic summer. This was tested by comparing influent and effluent concentrations of several standard water quality indicators: total suspended solids (TSS), 5-day biochemical oxygen demand (BOD_5), phosphorus and nitrogen species, and *Escherichia coli* (*E. coli*). Other water quality parameters such as pH, Dissolved Oxygen (DO), specific conductivity, and Total Organic Carbon (TOC) were also monitored during

the testing in an attempt to better understand any biofiltration observed during testing. The experimental details used in this study are described in the following sections.

2.1 Experimental Approach

In this research, biomat development on geotextiles in a simulated arctic environment and its wastewater treatment capacity was analyzed in a set of experiments using a reactor designed to allow for water quality measurements of the influent and effluent parameters as well as hydraulic conductivity of the geotextile in a temporal fashion. One set of experiments was performed at 10℃, and the second set of experiments at 2ºC. These two temperatures were selected to examine potential biomat development at a range of arctic summer temperatures. The experiments were conducted under low flow conditions, similar to the flow rates observed from exfiltrating WSPs in Nunavut. This set of experiments represents a slightly modified experimental setup from Bridson-Pateman et al. (2013), but for clarity, the details of the experimental apparatus and procedures are provided in the sections that follow.

Literature on geotextile clogging and water treatment has shown that nonwoven geotextiles generally afford better water treatment capabilities (Yaman et al. 2005; McIsaac and Rowe, 2006) compared to woven products. Korkut et al. (2006) showed that continuous filament and stapled fiber nonwoven geotextiles performed similarly with respect to water treatment. However, continuous filament geotextiles resulted in greater accumulation of shear biomass than stapled fiber, a favorable characteristic in northern climates, where less overall growth is predicted due to temperature constraints (Ratkowsky et al. 1982; Rowe et al. 1995). As such, nonwoven geotextiles were chosen for experimentation in this study. Samples of nonwoven, continuous filament geotextiles were acquired from Terrafix® Geosynthetics Inc. from Toronto, Ontario. Geotextile products denoted as 400R and 600R were chosen to encompass a common apparent opening size range. Manufacturer supplied properties and measured properties of these geotextiles are shown in Table 1.

2.2 Experimental Apparatus

ASTM standard testing method D1987-07 (2012) is often used to compare biological clogging of geotextile and soil-geotextile systems. This standard served as a basis for the design of the experimental apparatus used for this research. In total, six columns were manufactured out of clear acrylic. Each column was designed to hold a 10 cm diameter cutout (coupon) of geotextile between the two halves of the column. The lower half of all columns was filled with gravel to simulate the contact of the geotextile with a WSP berm. Coupons of the 400R or 600R geotextiles were then cut for the columns (with duplicates run for each geotextile type) and placed over top of the gravel in all columns. Two additional columns with no geotextile over the gravel were also prepared. The top half of the columns was then secured in place prior to permeation with wastewater.

For each column test setup, the gravel was rinsed thoroughly beforehand to remove any fines. The d_{50} size of berm material collected from an exfiltrating WSP in Coral Harbor, Nunavut was used as a basis for the selection of the gravel material (i.e. the d_{50} size of the gravel used in this experiment was 7 mm). The measured porosity of the unpacked gravel filling the bottom half of the column averaged 0.58.

As described by Bridson-Pateman et al. (2013), an elevated distribution tank was used to feed wastewater to the columns, and maintain a constant head of wastewater. Outflows from each of the columns were collected in individual receptacles to allow for measurement of various water quality parameters. The receptacle elevations were individually controlled to adjust the difference in head across the column, thus allowing control of flow rate individually for each column. The six columns were connected in parallel to the distribution tank to ensure each column received the same quality of wastewater. A reservoir tank supplied wastewater to the distribution tank by a combination of gravity feed and pumping, and only overflow from the distributor was recirculated. A flow diagram of this experimental approach is provide in Figure 1.

The entire system was housed in a refrigerated room at Dalhousie University. The temperature of this room was adjustable, and remained within ±1℃ of the set temperature for the full duration of the experiment. To inhibit the growth of photoautotrophs, the columns, reservoir, and distributor were covered between sampling runs.

2.3 Experimental Procedure

Wastewater for experiments was acquired from Timberlea Wastewater Treatment Plant (TWTP), located in the Halifax Regional Municipality of Nova Scotia, Canada. The TWTP uses a 3-stage biological treatment process. Wastewater is screened as it enters the plant before entering a primary settling unit with a 3 to 4 hour hydraulic retention time. Secondary treatment is provided by a rotating biological contactor. Tertiary oxidation and clarification is provided before discharge. The wastewater collected for use in these experiments was taken between the primary and secondary treatment stages to mimic the treatment level typical in arctic WSPs. TWTP was chosen as the source of wastewater to ensure the best approximation to the wastewater of small northern communities. Municipal wastewater in Nunavut is almost exclusively residential wastewater, with limited industrial inputs (Krkosek et al. 2012). The TWTP receives primarily residential wastewater from the community of Timberlea, Nova Scotia. Although there was high variability in TWTP water quality, a comparison between the primary-treated wastewater collected from TWTP and typical arctic WSP effluent showed average concentrations were similar.

After preparing all columns with new geotextile coupons and gravel, each column was individually primed with 30L of wastewater. This was done to simulate higher flows through the berm in spring thaw conditions as well as to create a "seeding" effect through each filter column prior to starting the experiment. This volume was determined from prior experiments which showed 30L of the wastewater to cause a noticeable decrease in flow rate through the column. The columns were then connected to the experimental system. Wastewater was applied to the filters once per week. The goal of these trials was to operate the system under very low flow rates, representing the seepage of water through a WSP berm. The weekly sampling routine consisted of the following. First, the water that had been stagnant in the columns since the previous week was drained at 1 – 2 mL/s. After draining, an "influent" sample was then taken from the distributor for analysis. Water from the distributor was then allowed to flow through all columns at 1 – 2 mL/s. After passing through the filters, this water was collected from each individual receptacle for analysis as the "effluent" sample.

In the experiments, various water quality parameters were analyzed at Dalhousie University in Halifax, Nova Scotia. Standard Methods for the Examination of Water and Wastewater (Clescerl et al. 1998) were used to determine total suspended solids (TSS) (Std. Method 2540D) and five day biological oxygen demand (BOD_5) (Std. Method 5210B). *E. coli* was quantified using membrane filtration onto m-ColiBlue24 culture media (HACH Company, 2012a). Ammonia-nitrogen (NH_4-N) concentrations were determined using TNTplusTM 832 kits (HACH Company, 2012b), while nitrate-nitrogen (NO_3-N) concentrations were determined with TNTplusTM 835 kits (HACH Company, 2012c). Total nitrogen (TN) was analyzed with Test 'n Tube kit 0-25 mg/L (HACH Company, 2012d). Total phosphorus (TP) was analyzed with Test 'n Tube kit 0-100 mg/L (HACH Company, 2012e). Final concentrations from the four above kits were determined using a DR 5000 spectrophotometer (HACH Canada, Mississauga, Ontario). Total organic carbon (TOC) was measured with a TOC-VCSH analyzer (Shimadzu America Inc., Columbia, Maryland) which uses a high-heat combustion and catalytic oxidation method. Finally, specific conductivity, pH, and DO were measured using a 600R multiparameter sonde (YSI Inc., Yellow Springs, Ohio).

Once determined, influent and effluent wastewater concentrations were compared using paired student's t-tests at a 95% confidence level that assumes unequal variances. Furthermore, average effluent concentrations between the duplicates of each geotextile type were compared against the average effluent concentrations from the columns with gravel only. In all cases, arithmetic means were used for statistical analysis, with the exception of bacteria counts, where geometric means were used.

Filter hydraulic performance was also assessed by observing changes in hydraulic conductivity resulting from physical and biological clogging. After completing the weekly sampling of wastewater for water quality monitoring, hydraulic conductivity was measured. Using height adjustments on the effluent receptacles, it was possible to accurately control and measure the head difference (ΔH) across the columns. The system was then allowed to flow to fill a known volume of water, and the length of time was recorded. This timed fill was repeated three times, and the average time was calculated. Friction and minor head losses were calculated based on the characteristics of the tubing and valve fittings used, as well as the flow rate through the system and the temperature of the water.

Biomat (defined as a combination of microbes and trapped solids) development was analyzed by determining biomat dry weight per unit area. After completion of the experiments, the geotextile coupons were removed from the columns and placed on sterilized aluminum foil sheets. The sheets were baked at 60℃ for 24 hours to remove moisture without volatilizing solids. The dry geotextile coupons were cut into rectangles representative of the whole biomat. The weight of each cutting was recorded and the rectangle area was measured.

3. RESULTS

The time series of weekly hydraulic conductivity measurements are shown in Figure 2. Exponential regressions of the hydraulic conductivity time series are also shown. At 10°C, no change in hydraulic conductivity was observed in the gravel control from weeks 2 to 10. However, during the same period, a 0.92 log-reduction in hydraulic conductivity was observed in the 400R columns and a 1.62 log-reduction was observed in the 600R columns. For 2ºC, over the same period of time (week 2 to week 10), no change in hydraulic conductivity was observed in the gravel control. However, a 1.06 log-reduction in hydraulic conductivity was observed in the 400R columns, and a 1.76 log-reduction was observed in the 600R columns. Overall, there was no statistical difference between hydraulic conductivity measurements at 10ºC and 2ºC. The temporal decrease in hydraulic conductivity in the geotextiles (Franks et al. 2013) appeared to follow exponential functions, which is consistent with the literature (Rowe et al. 2000). This may be an indication of microbial biomat formation, as microorganisms are known to follow an exponential growth curve. After 3 months of hydraulic conductivity and water quality data collection, the columns were disassembled and the geotextile coupons recovered. The results of biomat accumulation measurements on the geoxtiles are shown in Table 2 for the two test temperatures. It was noted that greater biomat was accumulated at the warmer temperature.

During the 10°C trial, influent pH fluctuated between 7.5 and 9, averaging approximately 8.5. At 2°C, influent pH reached a maximum of 10.1 during one week, but returned to its average of 9.3 shortly thereafter. At 10ºC, a statistically significant pH decrease was observed in all columns. This may be due to nitrification of ammonia; a process that produces excess hydrogen ions which acidify the water (Crites and Tchobanoglous, 1998). This pH decrease was not observed at 2ºC. Dissolved oxygen (DO) was also measured to develop a better understanding of the oxygen state of the wastewater, and if oxygen limitations would inhibit biological growth. For the most part, influent and effluent DO concentrations remained above 1 mg/L. It was only in the last 3 weeks of the 10ºC trial that influent DO dropped below 1 mg/L. Otherwise, oxygen was never entirely depleted within the biofilters.

All columns at both 10°C and 2°C produced statistically significant reductions in TSS, as compared to influent concentrations (Tables 3 and 4). In fact, mean and median effluent concentrations from all columns at 10°C were below 25 mg/L (Table 3). The same could not be said at 2°C, as only the 600R column produced effluent with TSS below 25 mg/L. This is interesting considering the higher influent concentrations at 10°C. At 10°C, TSS removal efficiency appeared to improve with time, achieving over 80% removal 5 weeks into the experiment (Figure 3). On the whole, both geotextiles removed significantly more TSS than the gravel controls at 10°C. Of the two, the 600R geotextile was statistically more efficient. At 2°C, TSS removal increased in the first week, followed by relatively constant removal between 35-45% in the 400R column, and 40-50% in the 600R (Figure 3). In contrast, the gravel controls were more unstable, and averaged 21% after the first week. A statistical comparison showed that both geotextiles produced significantly lower effluent concentrations than the gravel controls. Statistical comparison also confirmed that the 600R column performed better at 2°C.

Comparing the two temperatures, TSS removal was more consistent – albeit lower – at 2°C. This may be attributable to physical filtration being the primary treatment mechanism; as very little biological activity would be expected at this temperature. The observable improvement over time further suggests that more biological development occurred in the 10°C trial.

Overall, no column at either temperature was able to achieve average BOD_5 concentrations below 25 mg/L by the end of the test (Tables 3 and 4). However, at 10°C, 7 weekly measurements of 400R column effluent, 6 weekly measurements of 600R column effluent, and 7 weekly measurements of the control column effluent were below 25 mg/L for BOD_5. However, for half of these sampling days, influent concentrations were below 30 mg/L. At 2°C, only the samples from week 12 were below 25 mg/L, as was the influent.

Statistically significant reductions in BOD_5 were observed in all columns at all temperatures (Table 4). At 10°C, the geotextile and control columns performed similarly, and none were shown to perform any better than the others. All columns achieved 30-45% removal of BOD_5 on average, with 17% of geotextile column samples above an 80% removal rate (Figure 4). At 2°C, the 600R performed statistically better than the 400R and control columns. However, the 600R column only achieved a maximum removal efficiency of 38% (Figure 4). The columns averaged 12.2%, 17.6%, and 11.1% removal of BOD_5 for the 400R, 600R, and control columns, respectively.

Comparing the results from the two temperatures, again, better BOD_5 treatment was observed at the higher temperature. Over a 50% reduction in removal efficiency was observed at the lower temperature. However, like TSS, less variability was evident at the lower temperature. Additionally, comparing the high removal rate of BOD_5 by the 600R column at 2°C to similar removal in the 600R and control columns at 10°C suggests that the effect of the geotextile is more important at lower temperatures.

Average effluent *E. coli* concentrations were statistically similar to influent concentrations in all columns at both temperatures. All columns performed statistically similarly in the 10°C trial. In the 2°C trial, however, both geotextile types outperformed the gravel control. Comparing *E. coli* removal at both temperatures, similar performance is observed, suggesting removal was not dependent on biofilm development.

No statistically significant ammonia removal occurred during the tests (Table 4). However, at 10°C, there were weeks with up to 64% removal; this was still not enough to produce a statistically significant change overall. All columns at both 10°C and 2°C were statistically similar to the control. At neither temperature did ammonia concentrations fall below 10 mg/L in the effluent. The lack of ammonia treatment is likely associated with the amount of BOD_5 remaining in the wastewater, and the low temperatures. As previously noted, dissolved oxygen levels did not reach anoxic conditions, eliminating the issue of lack of available oxygen. The abundance of oxygen did however limit the anaerobic conditions necessary for denitrification. No statistically significant difference in nitrate concentration was observed between influent and effluent, at either temperature.

Although ammonia removal was limited, TN removal was statistically significant at 10°C (Table 3), but concentrations always exceeded 10 mg/L in the effluent (Figure 5). At 10°C, TN removal efficiencies averaged 32%, 33.9%, and 32% for the 400R, 600R, and gravel columns, respectively. However, it could not be shown that any column or control performed statistically better than the others. At 2°C, average removals were much lower, and not statistically significant. Again, all columns and controls performed similarly. It is likely that the dominant removal mechanism was bacterial assimilation and the filtration of particulate-associated N fractions.

Statistically significant TP removal occurred at both 10℃ and 2℃ (Table 4). At 10℃, both of the geotextile columns showed similar treatment to the control column, showing the importance of the gravel layer in phosphorus removal. However, at 2℃ (and under lower contaminant loading) both geotextiles outperformed the gravel control. The 600R geotextile performed statistically better than the 400R.

Even though influent concentrations of TOC were statistically similar at both temperatures, TOC removal was only statistically significant at 10℃ (Tables 3 and 4). However, both geotextile columns and the control columns performed similarly. At 2℃, no significant removal of TOC was observed.

4. DISCUSSION

WSPs have been the preferred technology for wastewater management in Canada's arctic regions due to their passive operation principles. Mechanical system components are challenging to maintain and expensive to operate, in remote northern communities. However, recent studies have demonstrated that WSPs cannot meet conventional secondary wastewater standards (Ragush et al. 2015) and upgrade strategies will need to be developed in order to comply with more stringent regulations. The integration of a passively operated, fixed film biological treatment mechanism within a WSP design could potentially help northern communities meet stricter effluent standards, without resorting to mechanical-chemical treatment alternatives.

Results from this bench scale study demonstrate that biological clogging of a geotextile exposed to primary treated municipal wastewater can occur at the cool temperatures that are experienced within a Canadian Arctic summer. Hydraulic conductivity was observed to undergo 1 – 2 log reductions, even at temperatures as low as 2ºC. For existing arctic WSP systems that possess exfiltrating berms, the installation of a geotextile could be a cost effective option to help increase retention of effluent in the WSP after the spring thaw. This would facilitate treatment, and a better controlled loading of effluent into downstream treatment components or receiving water environments. Tundra wetland systems are commonly used to polish WSP effluent in many northern communities (Yates et al. 2014) and uncontrolled hydraulic loading to tundra wetland systems during the spring melt period has been documented to reduce treatment effectiveness (Hayward et al. 2014).

The geotextile, and associated biofilm, provided significant reductions in the concentrations of key regulatory wastewater parameters such as BOD_5 and TSS. Passage of primary treated wastewater through the geotextile produced an effluent that generally met secondary wastewater treatment standards for TSS (< 25 mg/L). However, the geotextile system alone was not able to consistently produce effluent with BOD_5 concentrations meeting secondary wastewater treatment standards (< 25 mg/L). At these cool temperatures microbial degradation rates are slow, and greater treatment efficiencies would be gained primarily by increasing contact times between soluble wastewater constituents and the biofilm accumulated on the geotextile. One option to facilitate this is to design WSP berms with multi-layer geotextile systems or install internal exfiltrating berms lined with geotextiles.

Nitrogen removal was also modest and largely associated with retention of particulate organic nitrogen within the geotextile. This was not surprising given the low temperatures that these systems were operated at, and the well documented temperature sensitivity of nitrifying bacteria (Rockne and Brezonik, 2006). However, the removal of BOD_5 within the geotextile would assist with nitrification of ammonia in downstream treatment units (e.g. tundra wetlands).

Although this bench scale study has demonstrated the potential benefits of incorporating geotextiles into arctic WSP berm systems, pilot scale studies are needed to better understand how this upgrade strategy would perform under field conditions. In particular, it is expected that some level of maintenance would likely be required as the geotextile becomes progressively clogged over the course of several treatment seasons.

5. SUMMARY AND CONCLUSIONS

The objective of this study was to evaluate the clogging and wastewater treatment potential of geotextiles at low temperatures for use in WSP improvement. Bench scale testing of single-layer geotextile filters over 10 cm of gravel was conducted in a series of 3-month trials at 10°C and 2°C. Interpretation of the results of these experiments led to several conclusions about low-temperature geotextile biofilter performance, specifically:

1. Biomat development was achievable over a 3-month period. A greater mass of biomat developed at 10°C than 2°C.

2. Hydraulic conductivity followed an exponential decline. Overall, a 90% reduction was observed over 3 months at both temperatures. The 600R geotextile on average resulted in a lower hydraulic conductivity than the 400R geotextile, indicating smaller opening sizes will clog easier in wastewater filtration applications.

3. At colder temperatures, biological filtration of constituents was significantly reduced, as evidenced by the dramatic decline in TSS, BOD_5, TN, and TOC removal efficiency. The primarily physical sorption processes responsible for TP removal were unaffected by temperature changes.

4. The 600R geotextile filters resulted in better water quality improvements than the 400R geotextile filters in all cases where there was a significant difference between the geotextiles.

5. Even at 2°C, TSS and BOD_5 removal by geotextiles was still significantly better than the control columns, although the gravel was also responsible for significant treatment at both temperatures.

6. Effective removal of *E. coli* and ammonia was not achieved under seepage conditions at either temperature. This was primarily attributed to the low temperatures, and for ammonia, the elevated concentrations of BOD_5 and competition for oxygen between carbonaceous oxidizing and nitrifying bacteria.

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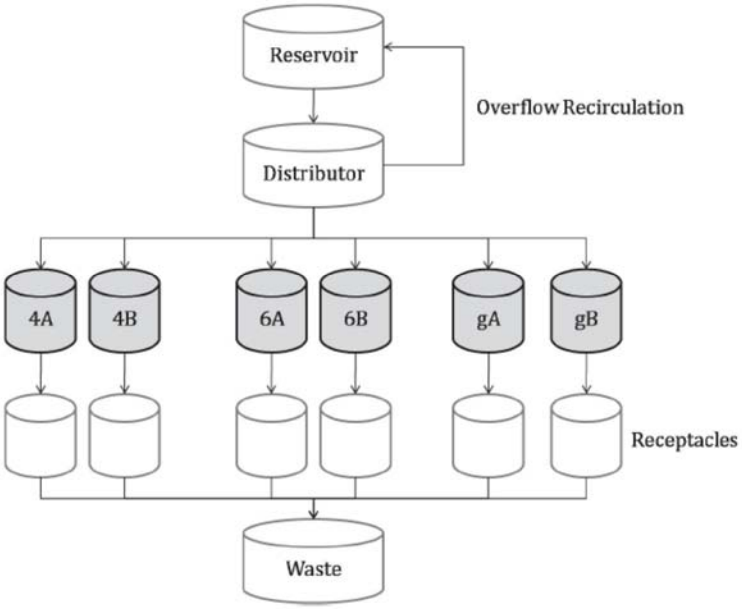

Figure 1. Flow Diagram of Experimental Approach

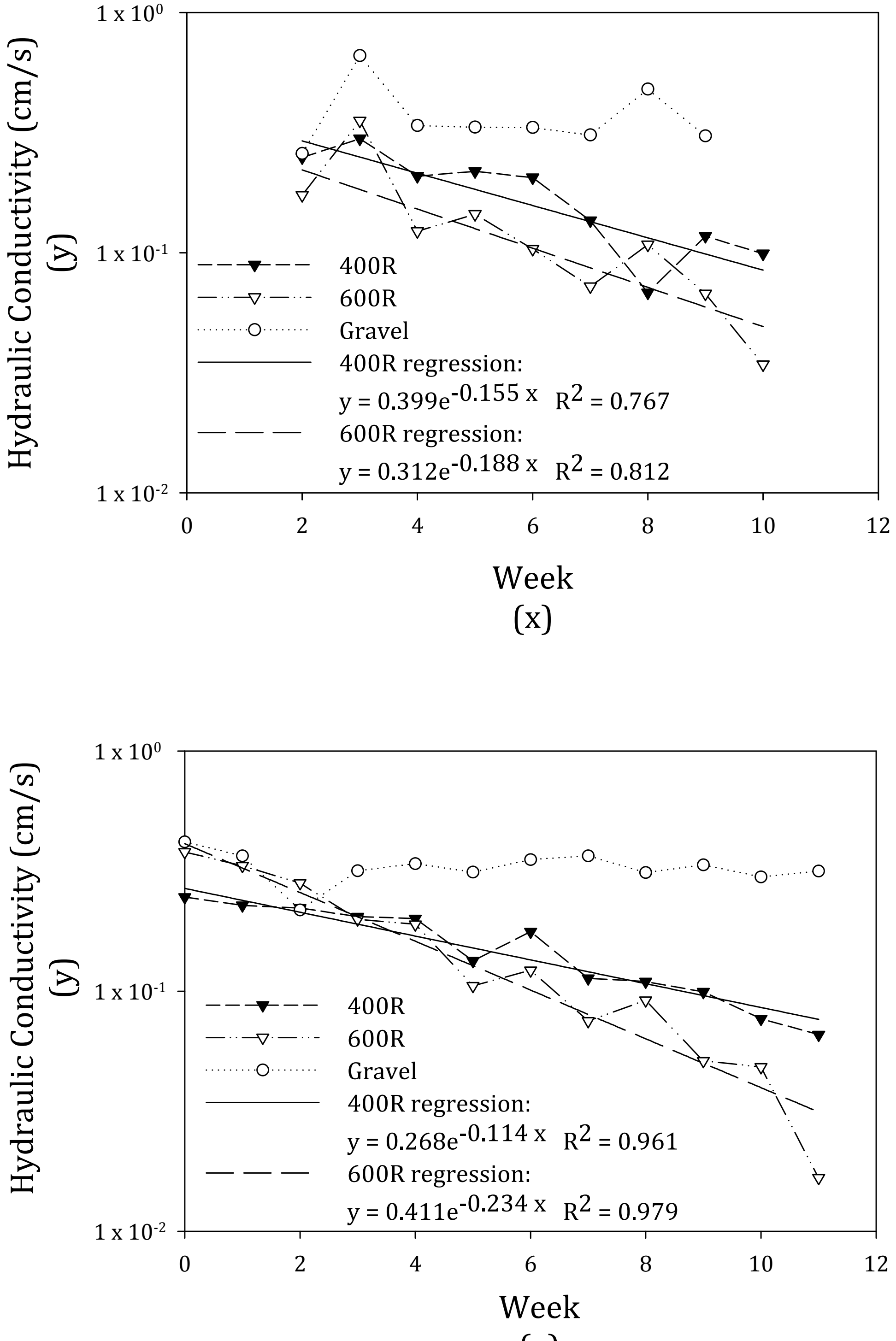

Figure 2. Results of hydraulic conductivity testing on the columns at 10°C (top) and 2°C (bottom).

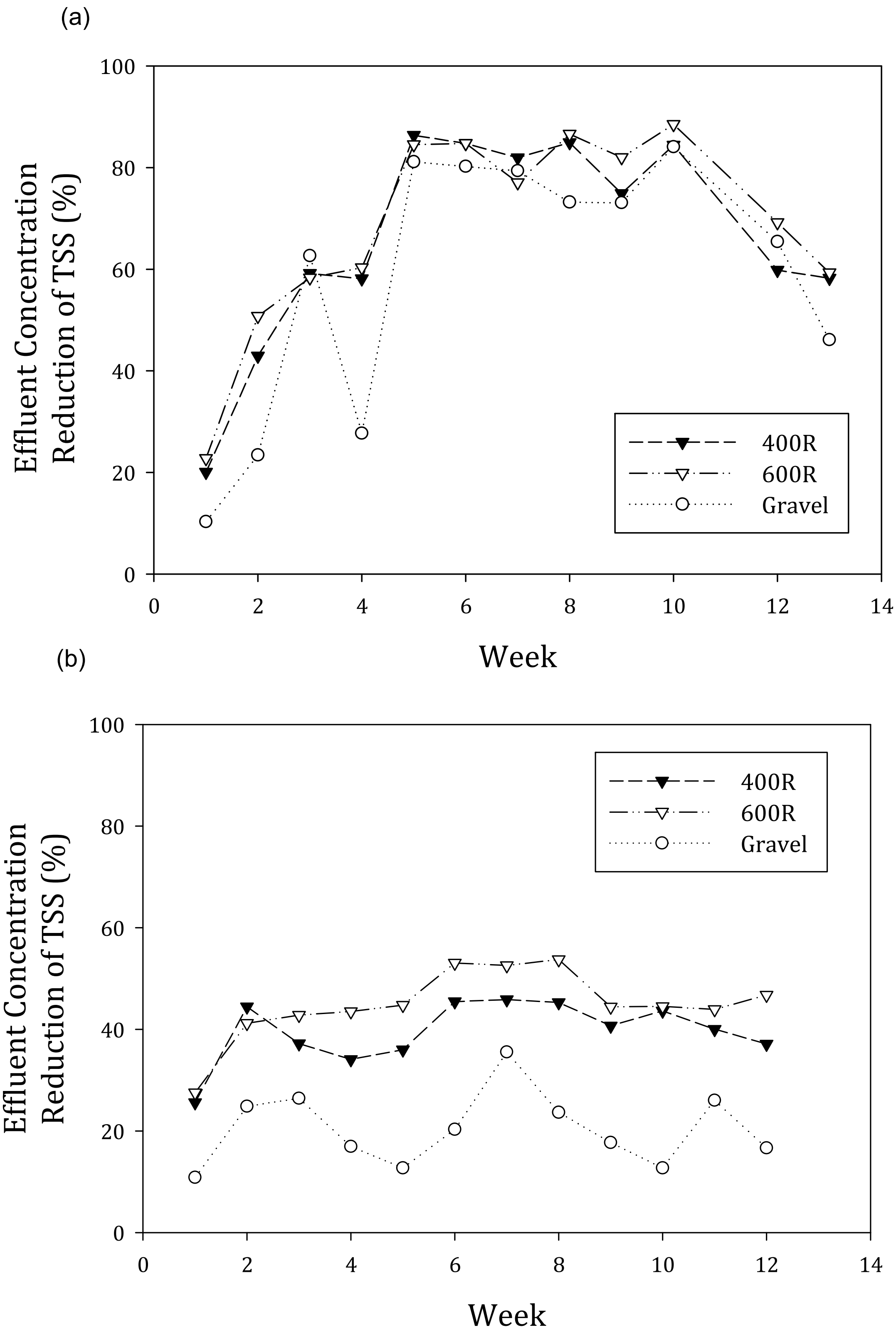

Figure 3. Effluent concentration percent reduction of TSS at 10 ºC (a) and 2 ºC (b)

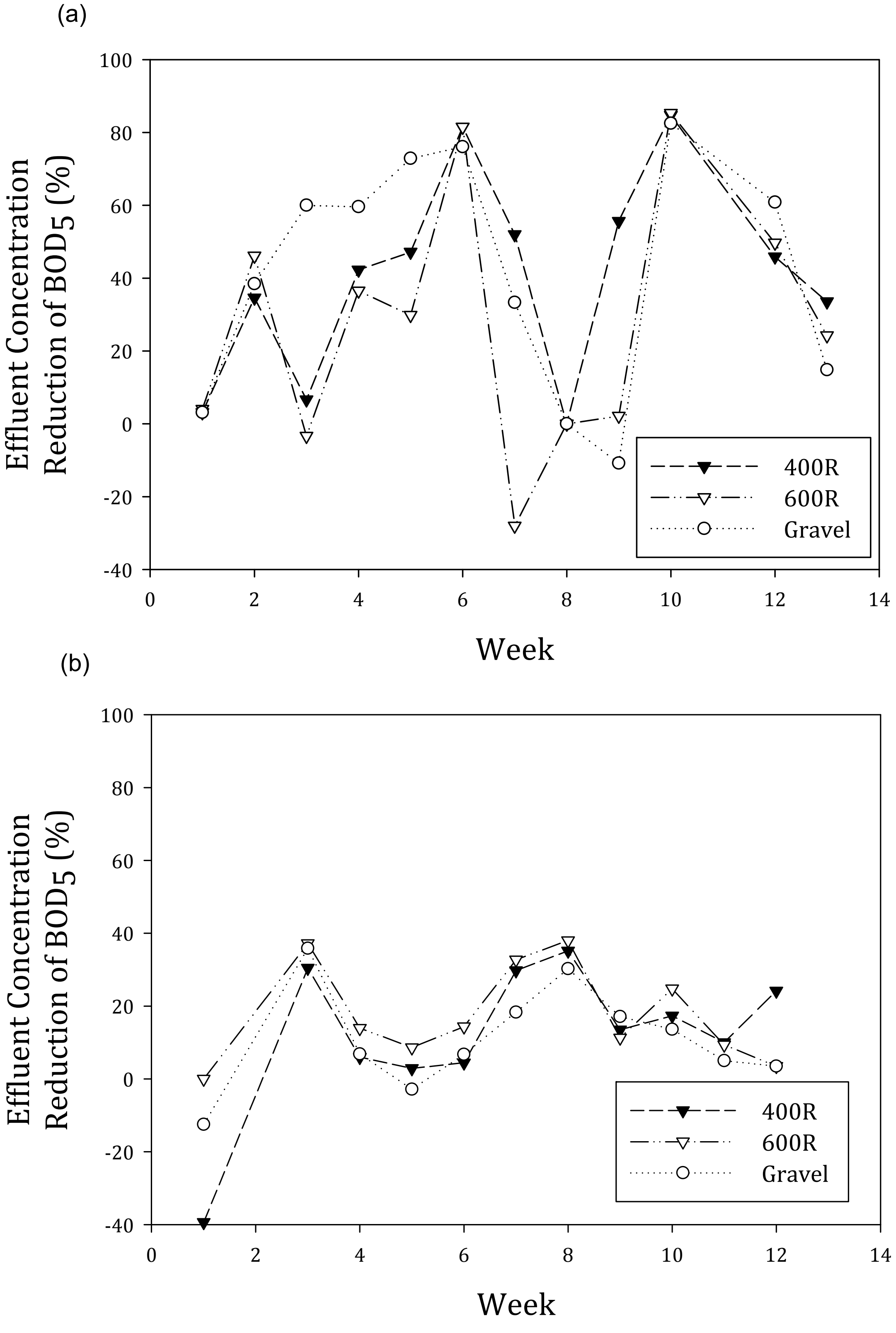

Figure 4. Effluent concentration percent reduction of BOD_5 at 10 ºC (a) and 2ºC (b)

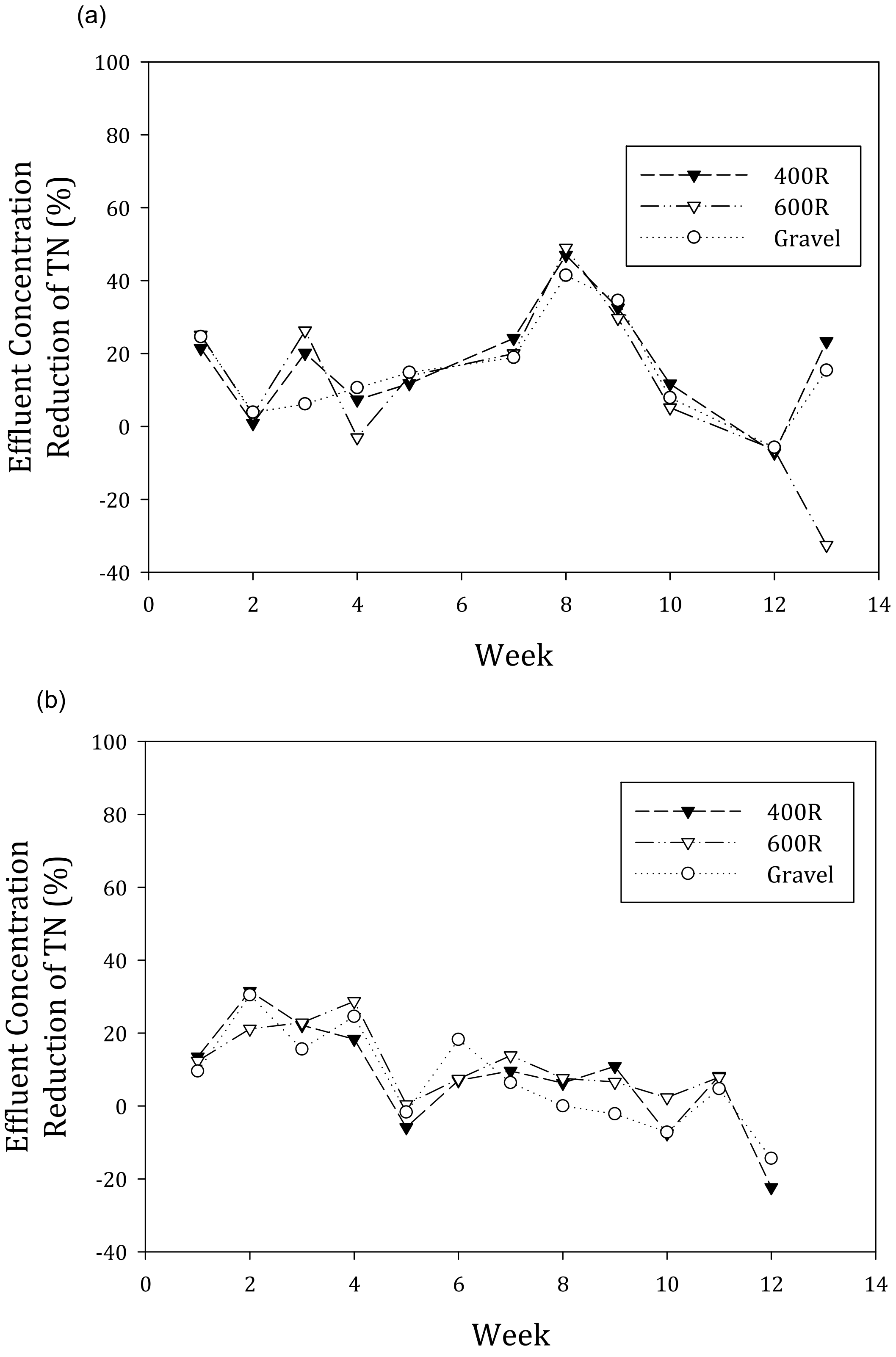

Figure 5. Effluent concentration percent reduction of TN at 10ºC (a) and 2 ºC (b)

Table 1: Characteristics of nonwoven geotextiles used

	400R	600R
Reported		
Apparent Opening Size (mm)	0.212	0.15
Mass (mg/cm^2)	23.7	33.9
Permittivity (sec^{-1})	1.5	1.2
Measured		
Thickness (mm)	2	3
Mass (mg/cm^2)	25.7	40.8
Hydraulic Conductivity (cm/s)	2.4 x 10^{-1}	2.5 x 10^{-1}

Source: (Terrafix, 2011)

Table 2: Dry mass of geotextile coupons before and after experiment

	10°C		2°C	
Dry Mass (mg/cm^2)	400R	600R	400R	600R
Initial	27.77	39.71	27.77	39.71
Average Final	38.59	50.31	33.67	48.70
Accumulated Biomass	10.82	10.60	5.90	8.99

Table 3: Statistical summary of water quality data at (a) 10 ºC and (b) 2ºC.

(a)

Parameter		Influent Concentration	400R	600R	Gravel
TSS (mg/L)	Mean	64.7	20.5	18.6	23.8
	Median	68.3	13.3	13.3	18.9
	Min	23.0	8.7	7.7	5.5
	Max	95.5	54.7	53.6	62.8
	St. Dev.	27.5	14.5	13.7	15.8
BOD$_5$ (mg/L)	Mean	47.9	29.3	31.6	27.5
	Median	43.1	20.0	19.6	16.7
	Min	9.4	4.5	6.0	3.8
	Max	111.0	109.0	107.0	109.0
	St. Dev.	29.1	28.5	28.3	28.9
E. coli (CFU/100mL)	Mean	1.7E+04	1.3E+04	6.6E+03	1.6E+04
	Median	2.7E+04	8.3E+03	6.0E+03	1.2E+04
	Min	7.8E+02	1.0E+03	1.1E+02	1.6E+03
	Max	1.9E+06	1.6E+06	1.6E+06	1.3E+06
	St. Dev.	2.1E+05	8.4E+04	6.5E+04	9.5E+04
NH$_4$-N (mg/L)	Mean	36.4	34.3	34.5	32.8
	Median	34.8	36.2	36.6	35.8
	Min	13.1	12.8	13.2	12.4
	Max	55.8	48.4	47.8	48.3
	St. Dev.	10.2	10.6	11.3	12.1
TN (mg/L)	Mean	38.3	32.0	33.9	32.0
	Median	42.2	34.5	32.4	33.6
	Min	19.0	13.8	13.6	14.0
	Max	56.8	39.6	76.8	48.8
	St. Dev.	11.5	8.1	14.0	9.6
TP (mg/L)	Mean	2.5	1.8	1.7	1.7
	Median	2.1	1.7	1.3	1.5
	Min	0.85	0.55	0.55	0.65
	Max	5.4	4.5	4.4	4.8
	St. Dev.	1.3	1.1	1.1	1.1
TOC (mg/L)	Mean	28.9	23.6	23.4	21.2
	Median	28.5	20.1	21.8	20.1
	Min	14.6	13.6	13.4	12.4
	Max	42.0	44.6	41.2	44.6
	St. Dev.	9.1	8.6	8.4	8.1

(b)

Parameter		Influent Concentration	400R	600R	Gravel
TSS (mg/L)	Mean	41.9	25.2	22.9	33.3
	Median	41.7	24.9	23.4	34.0
	Min	30.7	18.2	14.3	24.6
	Max	50.2	31.0	28.7	41.2
	St. Dev.	6.4	3.8	3.4	5.4
BOD_5 (mg/L)	Mean	46.0	39.0	36.6	40.1
	Median	44.6	38.1	36.0	42.3
	Min	21.8	14.4	18.0	20.4
	Max	70.0	57.5	45.9	53.0
	St. Dev.	12.4	10.8	7.4	9.1
E. coli (CFU/100mL)	Mean	4.2E+04	2.0E+04	1.6E+04	2.3E+04
	Median	3.9E+04	1.9E+04	1.6E+04	2.5E+04
	Min	3.6E+03	3.8E+03	1.3E+03	1.1E+03
	Max	6.4E+05	1.8E+05	1.9E+05	2.3E+05
	St. Dev.	1.6E+05	6.0E+04	5.2E+04	9.2E+04
NH_4-N (mg/L)	Mean	25.9	25.7	25.3	25.2
	Median	28.6	28.6	26.9	26.8
	Min	10.6	9.7	9.7	9.4
	Max	32.4	32.1	33.3	32.5
	St. Dev.	6.9	7.6	7.1	7.3
TN (mg/L)	Mean	26.7	24.6	24.5	24.8
	Median	27.9	25.5	24.1	24.7
	Min	17.8	13.0	13.6	13.0
	Max	33.8	34.0	36.8	33.2
	St. Dev.	5.6	5.6	5.6	6.2
TP (mg/L)	Mean	1.1	0.61	0.52	0.88
	Median	1.0	0.57	0.46	0.86
	Min	0.62	0.29	0.13	0.42
	Max	1.8	1.1	1.0	1.4
	St. Dev.	0.36	0.24	0.25	0.31
TOC (mg/L)	Mean	26.9	28.6	27.3	26.6
	Median	26.3	27.8	26.2	25.1
	Min	15.0	16.3	16.5	16.7
	Max	37.8	41.4	36.8	37.0
	St. Dev.	6.4	5.7	5.3	5.5

Table 4: Average water quality improvement as percent reduction, or log-reduction where indicated with “†”

	10°C			2°C		
Parameter	400R	600R	Gravel	400R	600R	Gravel
TSS	65.7%*	68.0%*	58.9%*	39.6%*	44.9%*	20.4%*
BOD_5	44.0%*	29.8%*	44.6%*	12.2%*	17.6%*	11.1%*
†E. coli	0.19	0.35	0.17	0.28	0.36	0.22
NH_4-N	7.72%	2.91%	9.59%	0.04%	1.71%	3.01%
TN	32.0%*	33.9%*	32.0%*	7.62%	6.47%	7.00%
TP	26.3%*	30.1%*	29.5%*	43.1%*	51.5%*	17.6%*
TOC	23.6%*	23.4%*	21.2%*	-8.42%	-2.92%	0.10%

* Average reduction in concentration was statistically significant ($p < 0.05$)