New England Water Treatment Technology Assistance Center
University of New Hampshire ▪ Durham, New Hampshire
NE-WTTAC
PROJECT SUMMARY

Assessing Temperature Influences on Slow Sand Filtration Treatment Performance

During slow sand filtration (SSF) untreated water very slowly percolates through a bed of porous sand. Below the sand bed is a layer of gravel for support and also at the bottom an underdrain system collects the filtered water (Figure 1). As water passes through the filter, microorganisms colonize the sand grains. In addition to microorganisms, organic and inorganic material also accumulates and a sticky mat i.e. schmutzdecke forms on the surface of the filter bed. Removals achieved during SSF are generally associated with biological activity and biodegradation processes (predation, scavenging, natural death and inactivation, and metabolic breakdown, Haarhoff 1991) taking place at the schmutzdecke. Straining and bioadsorption also contribute to removals. The upper layers of a slow sand filter are the vast majority of the microorganisms and natural organic matter are removed from the influent raw water (Page 1996; Unger and Collins, 2006).

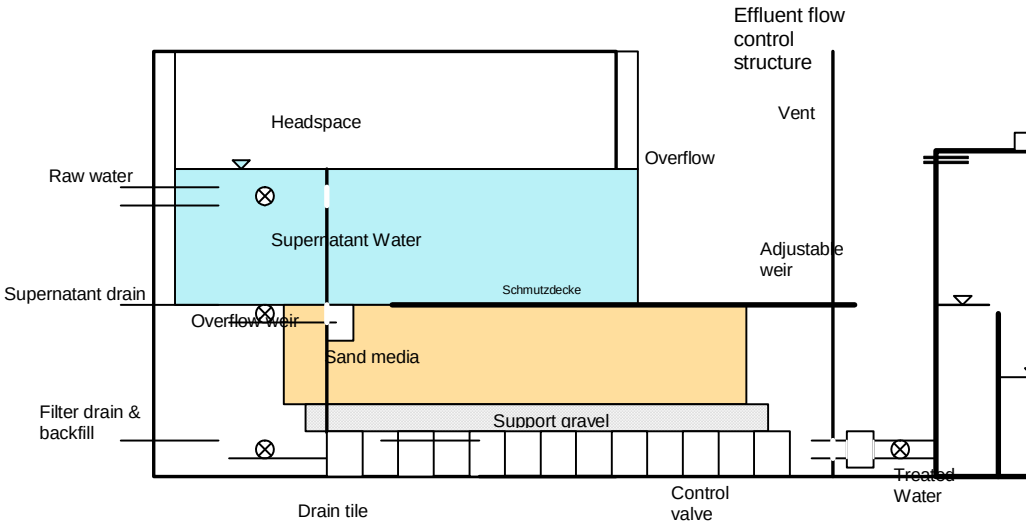

Figure 1. Typical Slow Sand Filter Schematic

Under appropriate circumstances, SSF may be the cheapest and simplest, but also the most efficient method of water treatment. According to the World Health Organization (Huisman and Wood, 1974), SSF is simple, inexpensive, and reliable and is still the chosen method of purifying water supplies for some of the major cities in the world. Other advantages include the fact that no chemicals need to be added to aid the filtration process, no backwashing and no automation are required. A comparative study between SSF and direct filtration (Cleasby et al., 1984) concluded that SSFs were superior especially where simple operation is important. More recently, SSF is making a dramatic comeback because of its inherent treatment simplicity. For example, in upper New England alone, over 24 new SSF facilities have been constructed over the past 13 years.

Unfortunately, there are several concerns that may limit SSF as a viable treatment option for many small communities. The most noted concerns include:

(ii) limited accessibility to raw waters containing moderate levels of abiotic or algal solids,
(iii) extensive filter downtimes and ripening periods,
(iv) necessity of lengthy pilot studies as it is difficult to predict filter runtimes,
(v) limited ability to remove organic precursor materials,
(vi) large footprint is required, and
(vii) reduced treatment performance during colder temperatures.

Many of these limitations have been evaluated and addressed over the past 15 years by research conducted at the University of New Hampshire, Thames Water Utilities and others (Collins et al., 1989; Eighmy et al., 1993; Bauer et al., 1996). As examples, roughing filters have extended the application of SSFs to marginal source waters, filter harrowing and faster methods of filter scraping have greatly reduced filter downtimes, and GAC addition have greatly enhanced organic precursor removals. Lower microbiological removal efficacy at very cold temperatures (Logsdon et al., 2002) appears to be an important limiting factor for SSF in North America as at cold temperatures; the biofilm may decrease significantly in certain SSFs and thus affect the filter's microbial removal efficiency. Unfortunately, few research or pilot studies have evaluated SSF performance during cold water temperatures. Any comparisons of SSF performance between winter and summer conditions are usually confounded by raw water quality variations between the winter and summer seasons. There have already been some personal communications from EPA and Canadian officials that SSF is not as effective in capturing source water microorganisms during cold temperatures (LeCraw, 2003). This issue has also been discussed by Logsdon et al., 2002; Bellamy et al., 1985, Pyper, 1985, and Poynter and Slade, 1977.

The gradual improvement in particle and pathogen removal that occurs in SSFs in the first days to months of filter operation has been associated to biological processes within the filter and is called the "ripening" (Gray and Osborn, 1995; Weber-Shirk, 2003). In this study, it was hypothesized that the presence of extracellular polymeric substances (EPS) produced by the SSF biofilm increased the attachment efficiency of particles and therefore removal efficiency. However, the biofilm may decrease significantly at cold temperatures reducing the EPS in the filter, which may explain the diminished microbial removal efficiency. Other substances such as metal ions have been hypothesized to help with microbial attachment and removal efficiencies. Nutrient deficiencies may also influence biofilm growth and activity in colder temperatures, which may in turn affect treatment performance.

The primary goal of this research is to elucidate the removal mechanisms of SSFs with special emphasis on the comparing of optimum summer conditions to more severe winter conditions as observed in the northern latitudes and mountainous regions. An effort was made to verify if the biological characteristics of the sand media are correlated to the microbial removal performance of the SSF at the different temperatures encountered in the New England area.

Methods and Materials

Pilot Filtration Apparatus. The pilot filtration studies were conducted on the Narrows Pond surface water supply for the town of Winthrop, ME. This site was chosen because according to the Winthrop Water Utilities the organic precursor content in the source water increased by roughly 10% from 2003 to 2004. Two pilot SSFs, Filter 1 (F1) and Filter 2 (F2), were operated simultaneously in the pipe gallery of the Winthrop, ME water treatment facility. The first microbial challenge took place in July of 2004 and was followed by 8 more filter challenges with the most recent event taking place in March 2006

(Table 1). A final challenge is planned for July 2006. Each of the filter challenges was followed a week later by a filter coring event where sand samples were collected. This week between the microbial challenge event and the coring event was necessary due to the distance of the sampling site to the laboratory and also due to the amount of samples collected from those two events. Both filters operated continuously for the duration of the study for approximately 600 days and were only taken off-line for sand sample collection or cleaning/scouring purposes. A low amount of ozone was continuously pumped into F1 and resulted in longer filter runs in F1 than those on F2. Ozone residuals in F1 ranged from below detection limit to 1.10 mg O3 mg/L.

Table 1. Filter Cleaning/Scouring Dates for Filter 1 and Filter 2

Filter challenge dates	Days between microbial challenges	F1 scraping date	F2 scraping date
7/28/04	92		2/19/04
10/26/2004	83	9/30/04	9/30/04
1/18/2005	56	10/22/04	10/22/04
3/15/2005	119	1/26/05	1/10/05
7/12/2005	63		3/22/05
9/13/2005	56		7/20/05
11/8/2005	70	8/31/05	8/31/05
1/17/2006	50		9/20/05
3/8/2006			11/5/05

The pilot scale filters were constructed from 43.2 cm diameter Schedule 40 PVC pipe (Figure 2). They were flanged and bolted 119 cm from the base to facilitate installation, cleaning, and sampling of the filter media. In order to be able to sample and clean the filter bed an opening with a gasketed, removable cover was installed on each filter. The cover of the opening was secured with stainless steel hose clamps encircling the column. A 13 mm by 13 mm PVC rod was welded to the column wall about 23 cm below the top of the sand to deter sidewall channeling. The filtration rates of the pilot-scale filters were controlled using a constant head constant flow device. Further details of the pilot filters may be found elsewhere (Page 1996).

The effective media size was 0.39 mm and the uniformity coefficient was 2.23. The media was obtained from Holliston Sand Co (Slatersville, RI). The media was thoroughly and repeatedly washed to remove fines prior to placement in the filters. The media was washed until the decanted water appeared to be visually clean.

Sample ports were provided along the column for profile sampling and to indicate headloss. The maximum head loss that could be measured by the piezometer tube for each column before the filters overflowed was 145 cm. Piezometers were made from clear acrylic tubing and headloss was measured by a meter-stick mounted on the side of each filter with the zero mark at the level of the effluent tailwater control. Water sample ports were located at different depths (5.8 cm, 21 cm, and 117 cm from the middle of the two flanged pieces of the filter). Sample ports were made out of 6 mm stainless-steel slotted tubes protruding inward about 5 cm from the column wall. During sampling, flowrates were low so as to avoid significant disruption of the filter flow. Media (core) sampling ports were used to obtain soil samples with depth. The openings of the media sampling ports were sealed with 6 mm NPT plugs during filter operation.

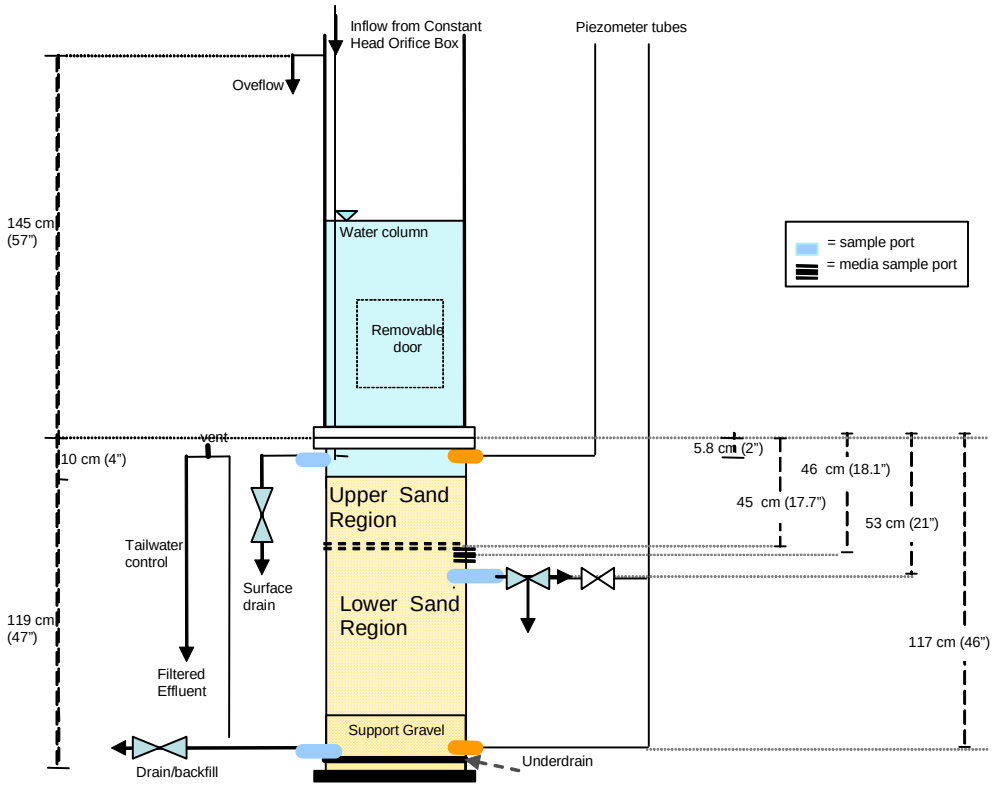

Figure 2. Schematic of Typical Pilot Slow Sand Filter Used in the Winthrop, ME Pilot Study

Filter Challenge Protocol. A 110 gallon tank was filled with a micro challenge solution, which contained untreated water from the Narrows Pond and approximately 106 colony forming units (CFU) per 100 mL of E.coli and *Bacillus atropheous* (formerly *Bacillus subtilis var. Niger*). Water from this tank was used to challenge the two filters. The difference in headloss in each filter was taken into consideration and thus the tank as well as each filter were dosed simultaneously to ensure that both filters were challenged with the same amount of microorganisms. Influent water samples were collected from the tank and from a port located directly above the level of the sand in each filter. Effluent samples were collected from the ports located approximately 46 cm, and 110 cm below the level of the sand in the filter after 3, 5 and 6 hours from the beginning of the challenge. Samples were also collected from the port located at 30 cm below the flange at a flowrate of 8 mL/min 4 hours after the beginning of the challenge till 6 hours. Temperature, pH, DO, chlorine residuals, and turbidity readings were taken on site. Water sample analysis took place at the Water Treatment Technology Assistance Center (WTTAC) laboratory at the University of New Hampshire (UNH). Samples were analyzed for *E. coli*, *Bacillus atropheous*, TOC, UV254 absorbance, BDOC, hardness, alkalinity, Aeromonas (analysis performed at the University of Tennessee by Dr. Kung-Hui Chu) and other water quality parameters.

Researchers returned to Winthrop, ME one week after the microbial challenge to collect filter media sand samples. In order to collect the sand samples the filters were partially drained to a level below the sampling depth. A 1.2 cm-diameter brass coring device was used to collect the core samples. Core samples were collected from 3 different locations in the filter and each core was approximately 13 cm long/deep. Cores were taken to the WTTAC laboratory at UNH for analysis. Three different samples (Figure 3) were compiled named Top, Middle and Bottom (based on depth from the top of the filter).

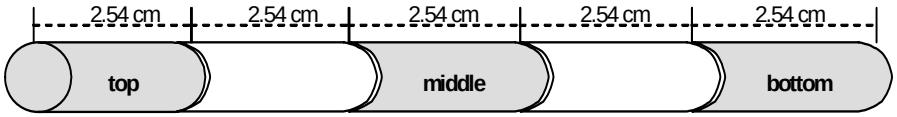

Figure 3. Typical core sample collected and divided

Once each core was divided in Top, Middle and Bottom, all 3 corresponding depth portions collected from each of the 3 cores were combined and mixed thoroughly to provide enough media for the various planned analyses. Sand samples were analyzed for biomass, extracellular polymeric substances (EPS) including carbohydrates and proteins, biological activity - respiration, chlorophyll, seston, and metal ions (aluminum, iron, and manganese). The above-mentioned parameters were chosen to aid in the identification of the specific aspects of the filter which may be affected and responsible for reduced microbial removals. This study looked into the presence of noticeable variations in biomass with temperature changes and their corresponding relationship, if any, to microbial removals.

Analytical Procedures. Sampling and preservation of samples (where required) was in accordance with the selected method (Table 2). All laboratory destined samples were immediately stored in a cooler, or stored in a refrigerator for later shipment to the laboratory.

Table 2. Sampling Parameters and Analytic Methods.

Microbial Analyses	**Analytical Methods Reference**
E. coli[a]	Partinoudi, 2004
Total Coliforms	Partinoudi, 2004
Bacillus sp.	Partinoudi, 2004
Aeromonas	EPA1605
Operational	**Analytical Methods Reference**
Flow Rate	NA[3]
Headloss	NA[3]
Water Quality	**Analytical Methods Reference**
pH[1]	4500-H^+B[2]
Temperature[1]	2550B[2]
Turbidity[1]	2130B[2]/Hach 8195
Particle count	2560C[2]
Conductivity[1]	2510B[2]
Dissolved Oxygen[1]	4500-O[2]
Ozone Residuals	Hach 8311
Hardness	Hach 8226
Alkalinity	Hach 8203
Cl_2 Demand (UFC)	5710B[2]
TOC	5310C[2]
BDOC	Mercier, 1998
UV	5910B[2]
Sand and Schmutzdecke	**Analytical Methods Reference**
Biomass (Phospholipids)	Mercier, 1998; Wang, 1995
Bio. Activity (Respirometry)	WTTAC QAPP, 2004
Polysaccharides	Dubois et al. 1956
Proteins	Lowry Method, Lowry et al. 1951
Aluminum (Al)	3111D/3113B/3120B[2]
Iron (Fe)	3111D/3113B/3120B[2]
Manganese (Mn)	3125[2]

[1] Parameters to be analyzed immediately
[2] APHA, 1998
[3] Not Applicable

Results and Discussion

Raw Water Quality. Raw water quality varied throughout the study. Figure 4 shows that the influent water turbidity remained low at approximately 1 NTU (0.07 NTU to1.04 NTU), pH ranged between 6.2 and 8.0 and temperature raged from 4.9o C to 22.4o C. These influent water quality values are within the range expected for lake water in New England. Natural organic matter as quantified by TOC and UV254 absorbance were slightly higher than many New England Surface waters averaging 4.99 m/L and 0.150 absorbance units/cm respectively. TOC readings in the influent water ranged between 4.40 and 6.09 mg/L whereas effluents ranged between 3.18 and 4.82 mg/L. Influent UV254 absorbance readings ranged from 0.127 to 0.192 cm-1 in the influent and 0.092 to 0154 cm-1 for the effluent water.

Selected Filter Operating Characteristics. Effluent turbidities ranged between 0.07 NTU and 0.016 NTU providing removals of approximately 98%.

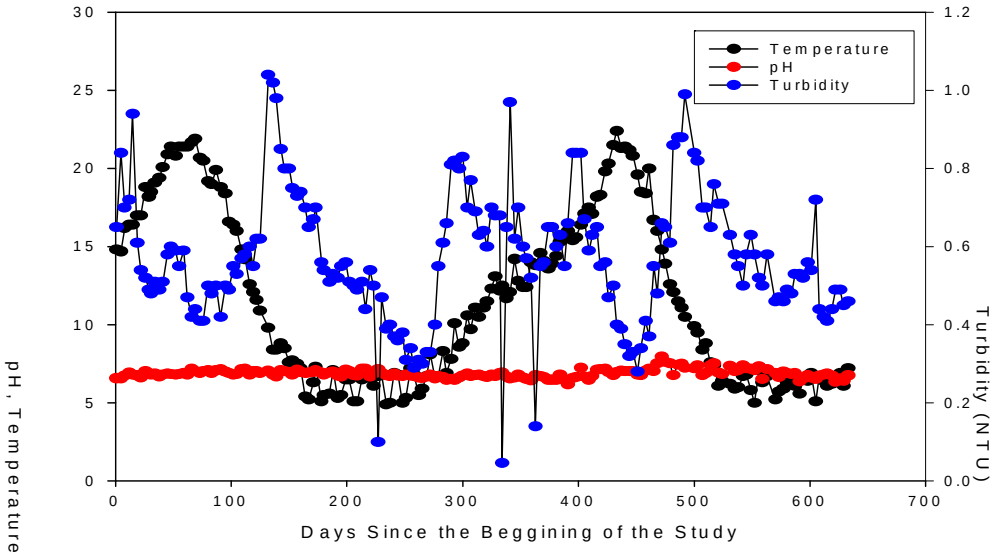

Figure 4. Selected Influent Water Characteristics for Winthrop, ME (July 2004-January 2006)

The cleaning/scouring times of each filter did not always take place at the same time due to the addition of ozone and a gravel roughing filter preceding F1 and thus the existence of longer filter runs compared to the more conventional F2. Figure 5 shows the typical relationship between run time and the increase in filter headloss.

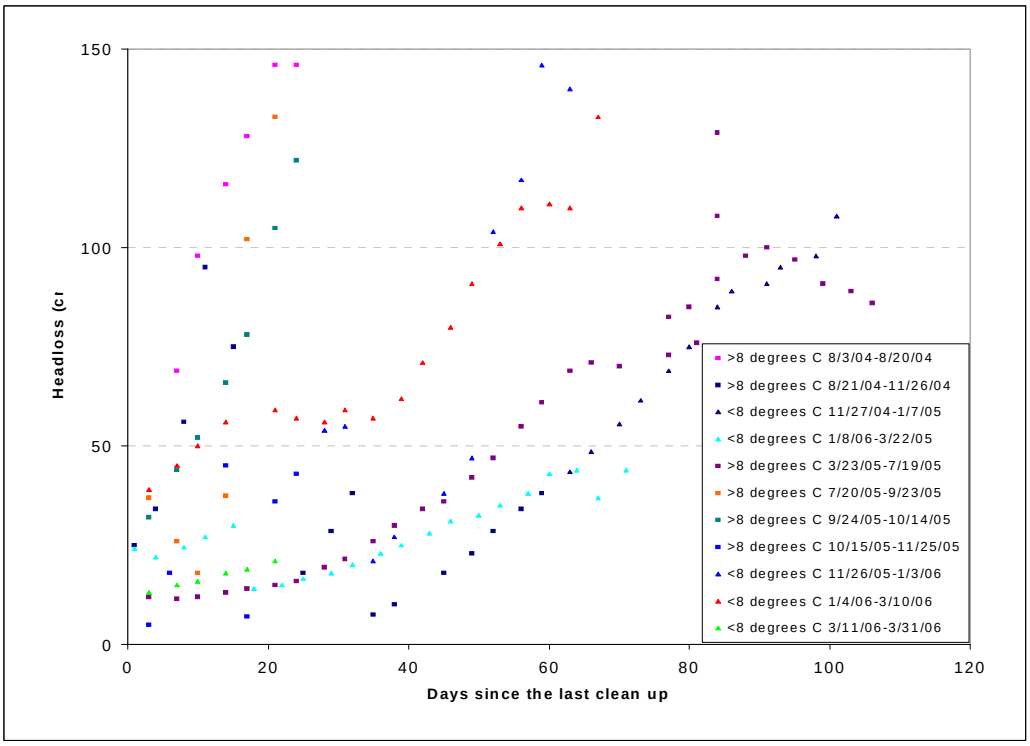

Figure 5. Filter Run Time versus Headloss Development in Pilot Filter 2

In general, longer filter run times were noted during the colder temperatures (<8oC). The one filter run exception was during spring runoff where influent turbidities and organic substrate levels were periodically diluted. The headloss trends also showed that although coring disturbed the filter/ schmutzdecke and thus the filter headloss, the filter recovered quickly and returned to its original headloss level trend in less than a month.

The TOC and UV254 absorbance removals averaged roughly 16-18% which is considered normal for conventional SSF (Collins et al., 1989). The pre-ozonated SSF did not significantly influence TOC or UV reductions confirming very low ozone dosing. Thus, the longer filter run lengths of F1 were mostly due to the pretreatment of the gravel roughing filter.

The SSF turbidity reductions were consistent throughout the study averaging close to 10-20% (data not shown). Temperature influences on either TOC or turbidity was difficult to ascertain.

Microbial Challenges. The target number of microorganisms in the challenge water was 106 colony forming units (CFU)/100 mL for both *E.coli* and *Bacillus atrophaeus* spores. Actual influent water levels confirmed that microbial numbers were typically within one-log unit of target value.

Overall *E.coli* and *Bacillus atrophaeus* removals by both filters throughout the study were 3.6±1.0 log and 2.9±0.7 log, respectively. There was a slight reduction in removal efficiencies during challenges with

colder temperatures (<8o C). Moreover, *E.coli* was easier to remove than *Bacillus Atrophaeus* suggesting preferential removals of selected microorganisms.

Prior to the microbial challenges, the presence of *Bacillus atrophaeus* was observed in the effluent samples collected from the filters (used as a control background sample) but was not observed in the influent control samples. Thusly, *Bacillus atrophaeus* could have colonized the filter or adsorbed to the sand grains and later become unattached and discharged in the filter effluent. In this study, it was possible to distinguish between laboratory grown spores used in this study and naturally-occurring spores due to the fact that laboratory spores formed a bright orange colored, round colony whereas naturally-occurring spores appeared to be transparent and more irregularly shaped. In other words the introduced *Bacillus atrophaeus* bled through the filter weeks after being introduced to the filters during the challenges.

Relationships between Filter Media Characteristics and Microbial Removals. Relationships between headloss, biomass as quantified by phospholipids, EPS as quantified by carbohydrates and proteins, and biological activity as quantified by respiration and *E.coli* and *Bacillus atrophaeus* removals were evaluated in this study. These filter media characterizations and log removals were generally subdivided into an upper region of the filter (0-45 cm below the sand surface), and a lower region of the filter (45-84 cm below the sand surface), and total filter (0-84 cm below the sand surface).

The influence of headloss development on microbial removals is depicted in Figure 6. There was a strong relationship between higher headloss development and log removals for both challenge microorganisms. Headloss development in an SSF can be due to the accumulation of small particles, i.e. clay particulates, and biofilm development especially in the schmutzdecke region. Under conventional SSF operation most of the headloss would be associated with the schmutzdecke, consequently most of the microbial removals in an SSF would also be expected in the schmutzdecke.

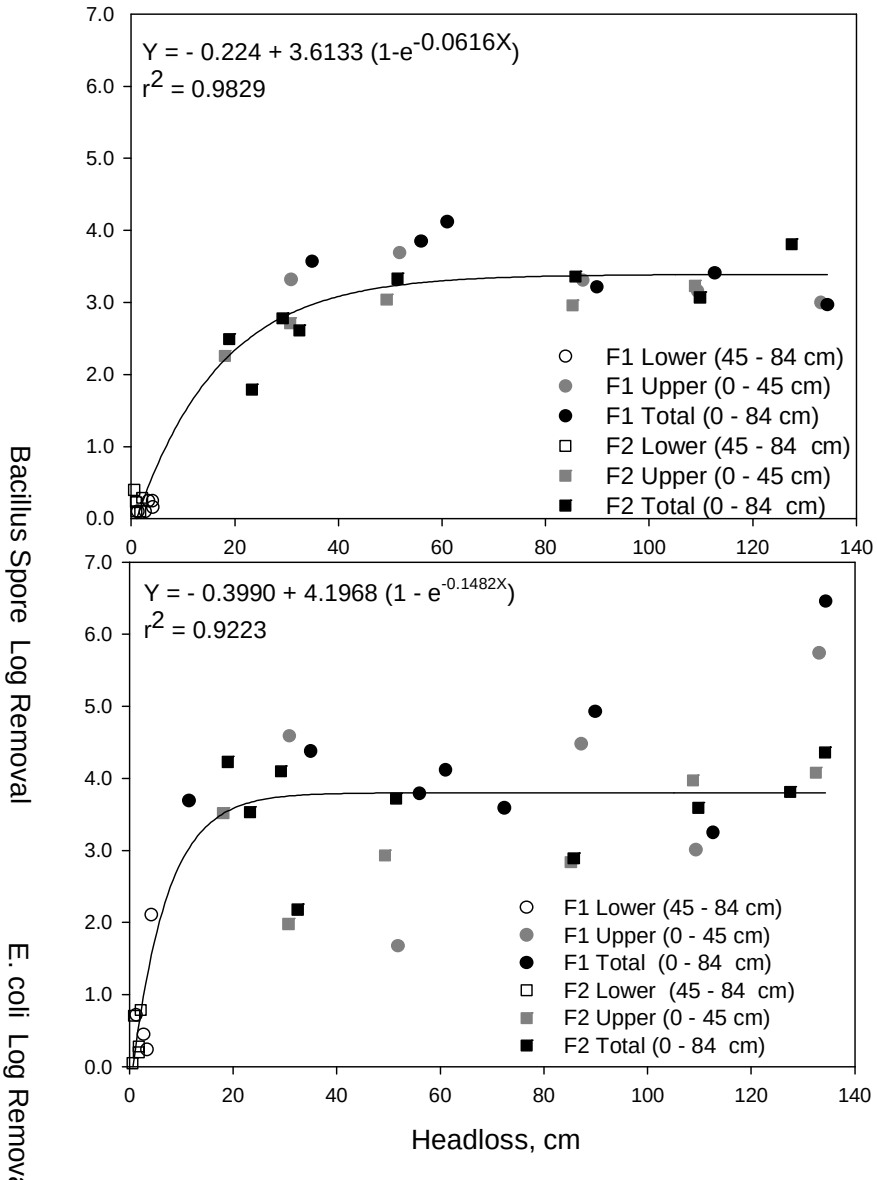

Figure 6. *Bacillus* Spores and *E. coli* Log Removal as a Function of Headloss in Pilot Slow Sand Filter 1 and 2 (Winthrop, ME)

An effort was made to relate filter media biomass as quantified by phospholipids to *E.coli* and *Bacillus* spore removal as influenced by temperature, i.e. >8o C vs. <8o C. These comparisons are shown in Figure 7 for both pilot filters. In general, higher removals were observed with increasing phospholipid biomass concentration. Again, most biomass was located in the upper region of the pilot SSFs. The highest microbial removals were obtained at the highest phospholipid biomass concentration during warmer temperatures while the lowest microbial removals were obtained during colder temperatures at lower phospholipid biomass concentration.

The different *Bacillus* spores and *E.coli* removal profiles between colder and warmer temperatures appeared to indicate that different removal processes are involved. Moreover profiles of phospholipid and *bacillus* spore removal suggested that short filter run time removals were similar to cold temperature profiles.

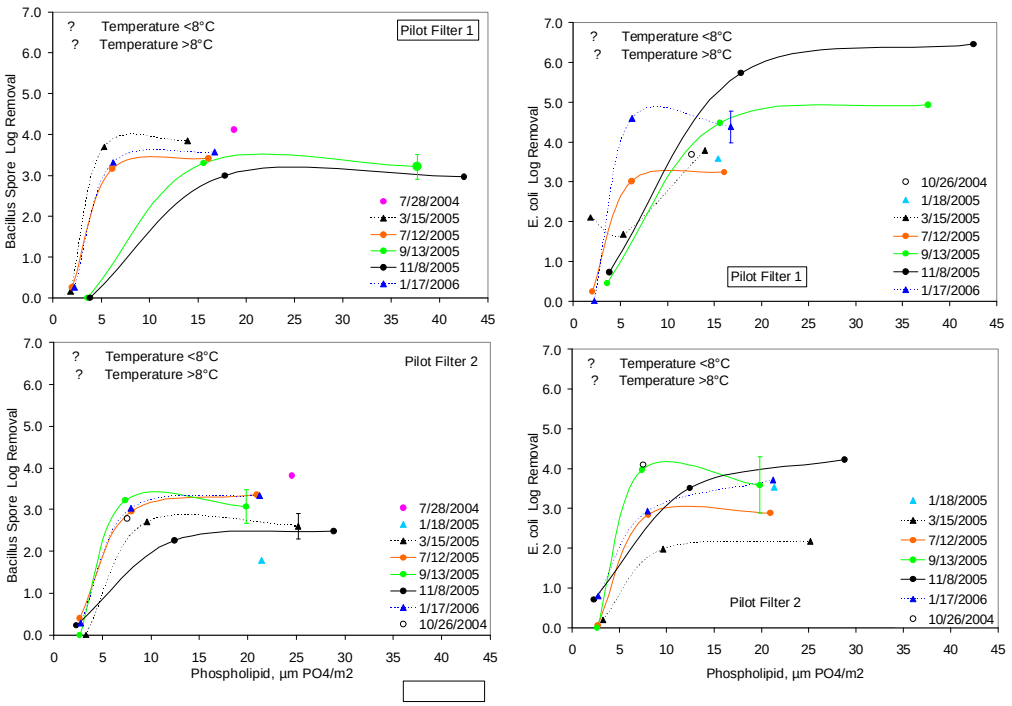

Figure 7. *Bacillus* Spore and *E.coli* Removal as a Function of Phospholipid Concentration in Pilot SSFs (Winthrop, ME)

The influence of biological activity as measured by respiration on microbial removals in the pilot SSFs is shown in Figure 8. As expected, most of the respiration took place in the upper regions of the pilot filters where the majority of the biomass was located. Both *Bacillus* spores and *E. coli* removals increased with increasing respiration.

Higher removal efficiencies of *Bacillus* spores and *E. coli* were observed in pilot Filter 1 over pilot Filter 2, which may have been due to: i) a low pre-ozone dose providing more readily available biological organic matter resulting in more organic mineralization and subsequent CO2 production (respiration) and/or ii) slightly warmer temperatures (1 - 2 °C) may also have increased metabolic activities.

Again, the respiration profiles associated with short filter run times or solder temperatures impacted removals similarly as noted for pilot Filter 2.

The influence of phospholipid concentration, respiration activity and temperature on *Bacillus* spores and *E. coli* log removals with depth is outlined in Figures 8 and 9, respectively, for the conventionally operated SSF (Pilot Filter 2). The challenge events of 3/15/2005 and 9/13/2005 were selected for comparison as they were not influenced by short filter run times.

Again, Figures 8 and 9 clearly showed the preferential microbial removal at the water-sand interface along with a greater rate of removal at warmer temperature. Removal profiles of *Bacillus* spore and *E. coli* were similar throughout the filter. There was also a strong correlation between increasing microbial removals and increasing phospholipid biomass as well as respiration activity. In all comparisons microbial removals were more efficient with warmer temperatures. For example, the microbial removal rates for biological respiration were roughly 2.5x more efficient in warm temperature (21°C) than in cold temperature (5.5 °C). Conversely, at warmer temperature, microbial removals increased more rapidly implicating the possibility that a more efficient type of biomass/biological activity was present.

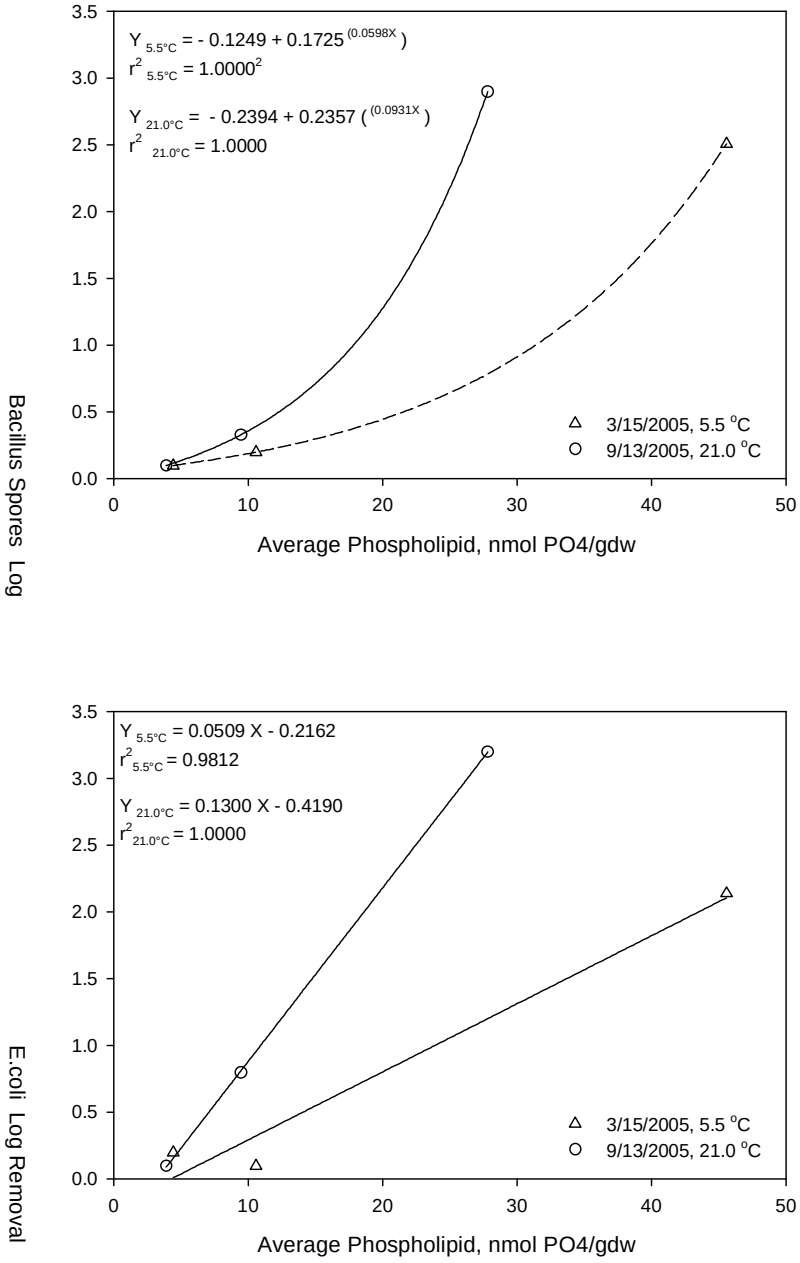

Figure 8. *Bacillus* Spores and *E. coli* Log Removal as a Function of Average Phospholipid Concentration at 5.5 and 21.0 °C in Pilot Slow Sand Filter 2 (Winthrop, ME).

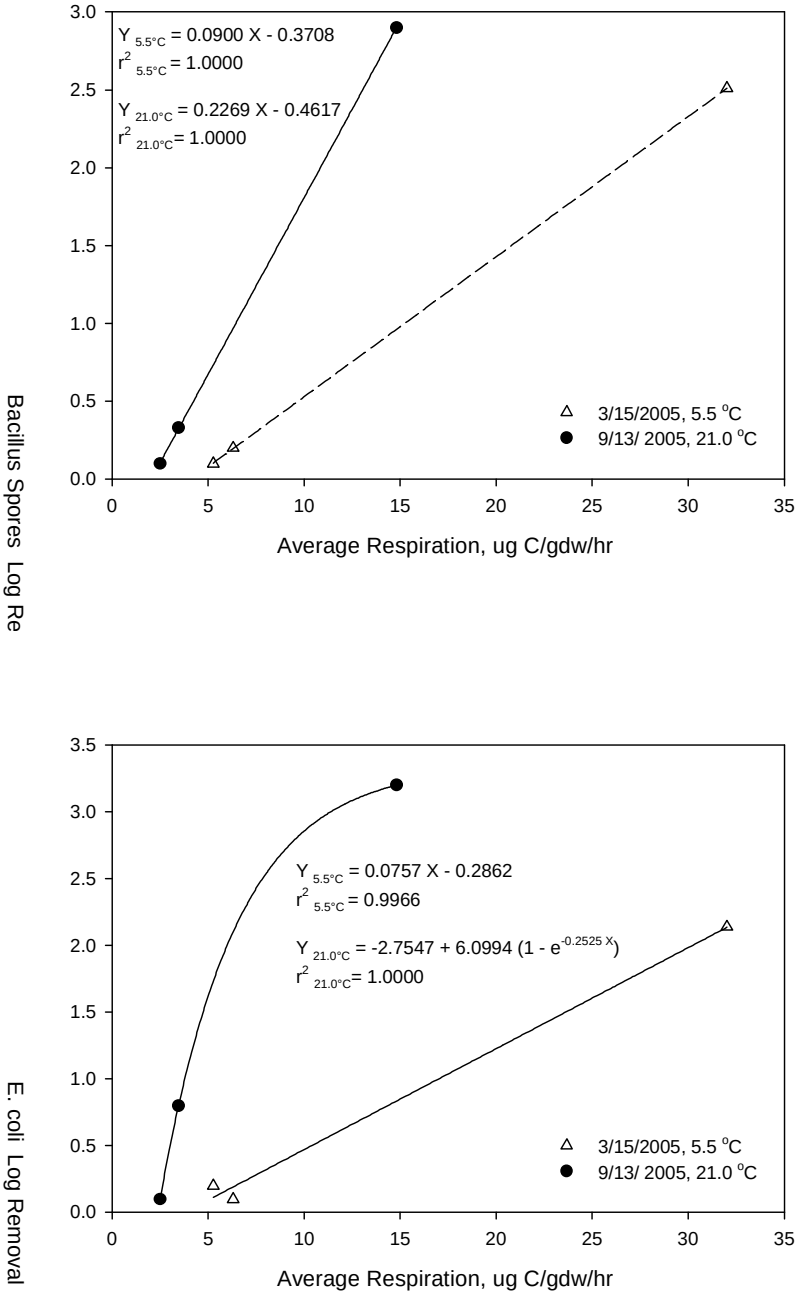

Figure 9. *Bacillus* Spores and *E. coli* Log Removal as a Function of Average Respiration Activity at 5.5 and 21.0 °C in Pilot Slow Sand Filter 2 (Winthrop, ME).

Conclusions

Several conclusions were drawn from the completion of the pilot study as listed below:

1. Longer SSF run time were noted during the colder temperatures (< 8°C).
2. Both *Bacillus* spore and *E. coli* removals by pilot SSFs were consistently greater than 2.5 logs under the conditions of the various challenges.
3. For reasons that are not presently ascertained, *Bacillus* spores used during the study became unattached from the filter media after the microbial challenges.
4. There was a strong relationship between higher headloss development and log removals for both microorganisms.
5. In general higher microbial removals were observed with increasing phospholipid biomass concentration and increasing respiration activity.
6. Most of the headloss development, biomass concentration, respiration activity and log removals were associated with the upper regions of the pilot SSFs.
7. No correlation was found between filter-media extrapolymeric substances content (carbohydrates and proteins) and microbial removals.

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