Investigating the Enhancement of Biological Filtration with Capping Material Designs and Nutrient Amendments

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Biologically active filters, or biological filters, remove particles and harness the metabolic capacity of bacteria attached to filtration media, in the form of a biofilm, to metabolize biodegradable organic matter (BOM). Pilot-scale biological filtration experiments were carried out at the Mannheim Water Treatment Plant in Kitchener, Ontario, Canada to evaluate the impact of capping material selection and nutrient amendments for granular activated carbon (GAC) filters, on both traditional and biological filtration performance parameters. Traditional filtration parameters included filter effluent turbidity, head loss development, and filter run time. Biological filtration performance was evaluated by total organic carbon (TOC), dissolved organic carbon (DOC), ammonia-nitrogen (NH_3-N), and soluble reactive phosphorus (SRP) removal. The top 20 cm layer of GAC (d_{10} = 1.3 mm) was replaced by a capping material with a larger effective size in three of the five pilot-scale filter columns—such use of capping layers in rapid biological filtration for drinking water treatment has not been reported previously. The capping materials that were investigated were an expanded clay (EC) aggregate (d_{10} = 1.7 mm) and a plastic “pinwheel” style medium (diameter = 2.5 cm). A stoichiometric carbon, nitrogen, and phosphorus (C:N:P) ratio of 100:10:1 is most commonly referenced in the drinking water industry as being ideal for microbial growth in distribution systems and biological filters. The nutrient amendment experiments studied the impact of amending the influent stoichiometric C:N:P ratio to 100:10:1 and 100:20:2, in a systematic and controlled manner. The monitoring and experimental program was conducted over 14 months to account for seasonal water quality and temperature effects. The results of this study have several implications for optimizing the design and operation of biological filters for drinking water treatment.

The capping materials delayed terminal head loss by 10-40 hours, compared to the control GAC filter, and significantly reduced the rate of head loss accumulation at all temperature ranges without negatively impacting filter effluent turbidity or BOM removal. There were no significant differences in filter run time at cold water conditions between each of the filter configurations; however, both capping layers extended filter run time at warm water conditions. Replacing a relatively small layer of media with one that has a larger effective size can lead to more robust filter operation.

At cold water conditions, amending the influent stoichiometric C:N:P ratio to 100:10:1 or 100:20:2 of the GAC or EC capped filters did not yield significant differences in either traditional or biological filtration performance. The observed reduction of SRP and no reduction in NH_3-N concentrations

suggest that the system was phosphorus limited but not nitrogen limited; however, the performance of the filters was not nutrient limited. The maximum stoichiometric C:N:P ratio of consumed nutrients by the biological filters was 100:0:10; thus, it was concluded that a C:N:P ratio of 100:10:1 was not optimal for performance enhancement at cold water conditions.

At warm water conditions, amending the influent stoichiometric C:N:P ratio of the GAC filter to either 100:10:1 or 100:20:2 did not yield any improvements in traditional or biological filtration performance. Reductions in the NH_3-N and SRP concentrations at the effluent of the nutrient-amended GAC filter suggests that it was both nitrogen and phosphorus limited, but not with respect to operational performance or BOM removal. Amending the influent stoichiometric C:N:P ratio to 100:10:1 of the EC capped filter led to a significant increase in its filter run time, while increasing the influent ratio to 100:20:2 improved both filter run time and rate of head loss accumulation; however, no improvements in BOM removal were observed. The long length of time required to observe improvements in filter performance at warm water conditions indicates that nutrient enhancement strategies may not be suitable for biological filters that operate in climates that experience short, or no periods of warm water conditions. Similar to the nutrient-amended GAC filter, reductions in the NH_3-N and SRP concentrations at the effluent of the nutrient-amended EC capped filter suggest that it was also nitrogen and phosphorus limited. The observed improvements in performance of the nutrient-amended EC capped filters, but not the GAC filter, suggests that nutrient enhancement strategies can be beneficial but at certain conditions only. The stoichiometric C:N:P ratio of consumed nutrients by the biological filters ranged between 100:67.3:6.0 to 100:153.3:7.4; thus, it was concluded that a C:N:P ratio of 100:10:1 was not optimal for performance enhancement at warm water conditions.

Residual amounts of SRP measured at the effluent of the nutrient-amended filters at all temperature ranges and nutrient dosing rates, suggests that there is a maximum amount of phosphorus can be metabolized by the biological filters. The plastic capped filter outperformed or matched the performance of the nutrient-amended filters in terms of the rate of head loss accumulation and filter run time, without any loss in performance in terms of turbidity trends or DOC removal at cold or warm water conditions. This suggests that using capping materials can be a cost effective way to improve biological filtration hydraulic performance, and is operationally less complicated than a nutrient addition system. However, adding capping layers to existing filters may require modifications to their operation.

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Table of Contents

Author's Declaration ii

Abstract.................... iii

Acknowledgments....................v

Table of Contents vi

List of Figures x

List of Tables xv

Chapter 1 Introduction....................1

1.1 Introduction 1

1.2 Research Objectives....................3

1.3 Research Approach....................4

1.4 Thesis Organization 4

Chapter 2 Literature Review 5

2.1 Granular Media Filtration....................5

2.1.1 Particle Removal During Physico-Chemical Filtration 5

2.2 Biological Filtration....................6

2.2.1 Biofilms....................7

2.2.2 Media Type....................9

2.2.3 Media Size and Uniformity Coefficient 13

2.3 Filter Capping Materials 15

2.4 Filter Backwash....................16

2.4.1 Collapsed Pulse Backwash 18

2.4.2 Extended Terminal Subfluidization Wash (ETSW)....................18

2.5 Nutrients....................20

2.5.1 Nitrogen....................20

2.5.2 Phosphorus 20

2.5.3 Nutrient Ratios (C:N:P)....................21

Chapter 3 Materials and Methods 27

3.1 Research Approach....................27

3.2 Mannheim Water Treatment Plant....................27

3.3 Pilot Plant....................28

3.3.1 Pilot Plant Equipment....................29

3.3.2 Filter Configuration and Media Selection ... 30
3.3.3 Pilot Filter Backwash ... 33
3.3.4 Operating Conditions ... 34
3.4 Experimental Design ... 34
3.4.1 Filter Run Time ... 36
3.4.2 Total and Dissolved Organic Carbon ... 36
3.4.3 Ammonia-Nitrogen ... 37
3.4.4 pH ... 38
3.4.5 Total Phosphorus (TP) ... 38
3.4.6 Soluble Reactive Phosphorus (SRP) ... 38
3.4.7 Total Suspended Solids (TSS) ... 38
3.4.8 Aluminum ... 39
3.5 Statistical Analyses ... 39
Chapter 4 Traditional Filter Performance Results ... 40
4.1 Overview ... 40
4.2 Filter Effluent Turbidity ... 42
4.2.1 Cold Temperature Range (T < 5°C) ... 42
4.2.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1 ... 44
4.2.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2 ... 45
4.2.4 Transitional Temperature Range (5°C ≤ T < 15°C) ... 46
4.2.5 Warm Temperature Range (≥ 15°C) ... 47
4.2.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1 ... 48
4.2.7 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:20:2 ... 49
4.3 Head Loss Accumulation ... 50
4.3.1 Cold Temperature Range (T < 5°C) ... 50
4.3.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1 ... 52
4.3.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2 ... 53
4.3.4 Transitional Temperature Range (5°C ≤ T < 15°C) ... 54
4.3.5 Warm Temperature Range (T ≥ 15°C) ... 54
4.3.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1 ... 56
4.3.7 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:20:2 ... 57
4.4 Filter Run Time ... 60

4.4.1 Cold Temperature Range (T < 5°C) 60
4.4.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1 63
4.4.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2 63
4.4.4 Transitional Temperature Range (5°C ≤ T < 15°C) 64
4.4.5 Warm Temperature Range (T ≥ 15°C) 64
4.4.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1 65
4.4.7 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:20:2 66
4.5 Head Loss Accumulation Temperature Dependence 68
4.6 Summary 69
Chapter 5 Biodegradable Organic Matter Removal 70
5.1 Overview 70
5.2 Total and Dissolved Organic Carbon 72
5.2.1 Cold Temperature Range (T < 5°C) 72
5.2.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1 74
5.2.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2 75
5.2.4 Transitional Temperature Range (5°C ≤ T < 15°C) 75
5.2.5 Warm Temperature Range (T ≥ 15°C) 77
5.2.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1 78
5.2.7 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:20:2 79
5.3 Ammonia-Nitrogen 79
5.3.1 Cold Temperature Range (< 5°C) 79
5.3.2 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:10:1 80
5.3.3 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:20:2 81
5.3.4 Transitional Temperature Range (5°C ≤ T < 15°C) 81
5.3.5 Warm Temperature Range (≥ 15°C) 82
5.3.6 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:10:1 83
5.3.7 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:20:2 84
5.4 Phosphorus 84
5.4.1 Cold Temperature Range (< 5°C) 85
5.4.2 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:10:1 86
5.4.3 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:20:2 88

5.4.4 Transitional Temperature Range (5°C ≤ T < 15°C) ... 89
5.4.5 Warm Temperature Range (T ≥ 15°C) ... 90
5.4.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1 ... 91
5.4.7 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:20:2 ... 93
5.5 DOC Removal Temperature Dependence ... 94
5.6 Consumed Nutrient Ratios ... 95
5.7 Summary ... 100
Chapter 6 Efficacy of Plastic Capping Material for Biological Filtration ... 102
6.1 Overview ... 102
6.2 Traditional Filtration Performance ... 102
6.2.1 Effluent Turbidity ... 102
6.2.2 Head Loss ... 104
6.2.3 Filter Run Time ... 106
6.3 Biodegradable Organic Matter Removal ... 107
6.3.1 DOC Removal ... 107
6.3.2 Consumed Nutrient Ratios ... 108
6.4 Material Accumulation ... 109
6.5 Summary ... 112
Chapter 7 Conclusions ... 113
Chapter 8 Implications and Recommendations ... 116
Bibliography ... 118
Appendix A Operational Data ... 129
Appendix B Nutrient Data ... 174
Appendix C Equations Used in Statistical Analyses ... 187
Appendix D Summary Data and Statistical Analysis ... 189
Appendix E Temperature Dependence Data Comparison ... 239
Appendix F Quality Control Data ... 242
Appendix G Filtration Media Specification Sheets ... 252

List of Figures

Figure 2.1: Conventional rapid granular filter (McSwain, 2013)..5

Figure 2.2: Generalized particle transport mechanisms for filtration (Ives, 1982) 6

Figure 2.3: Biofilm formation (Aalexopo, 2011) 8

Figure 2.4: Sample of common plastic filtration media (Snow Plastic Mesh Co., 2007)....................12

Figure 2.5: Filter ripening sequence (Amburgey et al., 2003; Amirtharajah and Wetstein, 1980) 17

Figure 2.6: The last nine filter runs in a series of 17 with nutrient enhancement (Lauderdale et al., 2012). The red box highlights the observable difference in terminal head loss at the end of the 12th filter cycle and persisting for the remaining filter cycles..24

Figure 2.7: The effect of ammonium chloride supplementation on head loss development (Lauderdale et al., 2012) 25

Figure 3.1: Process flow diagram of the MWTP..27

Figure 3.2: A simplified schematic of the Mannheim Water Treatment Plant pilot-scale filters (not to scale)...29

Figure 3.3: Filtrasorb® 816 granular activated carbon...32

Figure 3.4: Filtralite® NC 1,5-2,5 crushed expanded clay 32

Figure 3.5: BioFill® CT plastic media 32

Figure 4.1: Representative pilot plant effluent turbidity at cold water conditions (mean temperature = 3.5°C) from 25-28 November 2013...42

Figure 4.2: Representative pilot plant effluent turbidity data at cold water conditions (mean temperature = 1.5°C) from 1-4 December 2013. This figure demonstrates the rapid increased in effluent turbidity that was observed during the latter part of a filter cycle for all pilot filters. 43

Figure 4.3: Pilot plant effluent turbidity at cold water conditions (mean temperature = 1.0°C) from 8-11 February 2014 with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrates rapid increases in filter effluent turbidity in all of the pilot-scale filters after approximately 20-40 hours of filter operation during the first 3 filter cycles after nutrient amendment began, and subsided thereafter. 45

Figure 4.4: Pilot plant effluent turbidity at cold water conditions (mean temperature = 1.4°C) from 25-28 March 2014 with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrate the rapid increase in effluent turbidity during the latter part of the filter cycle that was observed by all but the EC capped pilot filter without nutrient amendment. 46

Figure 4.5: Pilot plant effluent turbidity data at warm water conditions (mean temperature = 16.9°C) from 12-15 May 2014. The red line illustrates the effluent turbidity operational cut-off of 0.2 NTU. This figure demonstrates an example of when a pilot filter had a filter run time of zero hours due to its inability to reach a stable turbidity below 0.2 NTU. 48
Figure 4.6: Pilot plant effluent turbidity at warm water conditions (mean temperature = 23.1°C) from 26-29 July 2014 with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1.. 49
Figure 4.7: Pilot plant head loss at cold water conditions (mean temperature = 1.1°C) from 9-12 January 2014. This figure demonstrates that the rate of head loss accumulation of the EC capped filters was slower than the uncapped GAC filters. 50
Figure 4.8: Mean rate of head loss accumulation± one standard deviation based on filter configuration at cold water conditions without nutrient amendments. This figure demonstrates that the EC capping layer reduced the rate of head loss accumulation as compared to the GAC pilot filter. 51
Figure 4.9: Mean rate of head loss accumulation± one standard deviation at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1. This figure demonstrates that amending the influent C:N:P ratio to 100:10:1 of the duplicate GAC and EC capped filters did not improve head loss performance. 52
Figure 4.10: Mean rate of head loss accumulation ± one standard deviation at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates that amending the influent C:N:P ratio to 100:20:2 of the duplicate GAC and EC capped filters did not improve head loss performance. 53
Figure 4.11: Mean rate of head loss accumulation ± one standard deviation categorized by filter configuration at transitional water temperatures without nutrient amendments. This figure demonstrates statistical significance between the two filter configurations. 54
Figure 4.12: Mean rate of head loss accumulation± one standard deviation categorized by filter configuration at warm water conditions without nutrient amendments. This figure demonstrates statistical significance between the two filter configurations. 56
Figure 4.13: Mean rate of head loss accumulation ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrates no statistical significance with nutrient amendment. 57
Figure 4.14: Pilot plant head loss data at warm water conditions (mean temperature = 19.5°C) of the EC capped filters with (Filter 4) and without nutrient addition (Filter 1) from 15-18 September 2014 .

This figure demonstrates an improvement in head loss performance in the EC capped filter with nutrient amendment. 58

Figure 4.15: Mean rate of head loss accumulation ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates statistical significance between the two GAC filter configurations, but a statistical significance between the two EC capped filter configurations. 59

Figure 4.16: Summary of experimental pilot-scale filter run time and water temperature. The red vertical lines represent the periods when the influents of Filters 2 and 4 were nutrient-amended. 61

Figure 4.17: Mean filter run time ± one standard deviation categorized by filter configuration at cold water conditions, without nutrient amendments. This figure demonstrates no statistical significance between the GAC and EC capped pilot filters. 62

Figure 4.18: Mean filter run time ± one standard deviation at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrations no statistical signifiance between the different filter configurations. 62

Figure 4.19: Mean filter run time ± one standard deviation at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates no statistical significance between the filter configurations. 63

Figure 4.20: Mean pilot plant filter run time ± one standard deviation categorized by filter configuration at transitional water temperatures without nutrient amendments. This figure demonstrates no statistical significance between the GAC and EC capped pilot filters. 64

Figure 4.21: Mean pilot plant filter run time data ± one standard deviation categorized by filter configuration at warm water conditions without nutrient amendments. This figure demonstrates a statistical significance between the GAC and EC capped pilot filters. 65

Figure 4.22: Mean pilot plant filter run time ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrated no statistical significance in the GAC filters, but a statistical significance in the EC capped filters. 66

Figure 4.23: Mean pilot plant filter run time ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates no statistical significance between the GAC filters, but a statistical significance between the EC capped filters. 67

Figure 4.24: Pilot-scale filter mean rate of head loss accumulation ± one standard deviation vs cold and warm temperature ranges without nutrient amendments. 68
Figure 5.1: Influent stoichiometric C:N:P ratios just prior to nutrient amendment (error bars indicate ± one standard deviation) 71
Figure 5.2: Mean percent of TOC and DOC removed ± one standard deviation at the effluent at cold water conditions with and without nutrient amendments. This figure demonstrates no statistical significance between the nutrient-amended and non-nutrient amended filters. 73
Figure 5.3: Mean percent of TOC and DOC removed ± one standard deviation at the effluent at transitional water temperatures without nutrient amendments. This figure demonstrates no significant difference between the GAC and EC capped filters. 76
Figure 5.4: Mean concentration of TOC and DOC removed ± one standard deviation at the effluent at warm water conditions with and without nutrient amendments. This figure demonstrates no significant differences between the nutrient and non-nutrient-amended filters. 77
Figure 5.5: Mean NH_3-N concentration ± one standard deviation at the effluent at cold water conditions with and without nutrient amendments. 80
Figure 5.6: Mean NH_3-N concentration ± one standard deviation at the effluent categorized by filter configuration at transitional water temperatures without nutrient amendments. This figure demonstrates no statistical significance between the two configurations. 82
Figure 5.7: Mean NH_3-N concentration ± one standard deviation at the influent and effluent at warm water conditions with and without nutrient amendments 83
Figure 5.8: Mean concentration of SRP ± one standard deviation at the influent and effluent at cold water conditions with and without nutrient amendments 85
Figure 5.9: Summary of potential metabolic pathways of heterotrophic bacteria adapted from Blanch & Clark (1997) 87
Figure 5.10: Mean concentration of SRP± one standard deviation at the effluent at transitional water temperatures without nutrient amendments. This figure demonstrates no statistical significance between the two configurations. 90
Figure 5.11: Mean SRP concentration ± one standard deviation at the influent and effluent at warm water conditions with and without nutrient amendments 91
Figure 5.12: Pilot-scale filter mean percent DOC removal ± one standard deviation vs cold and warm temperature ranges without nutrient amendments 94

Figure 5.13: Normalized molar N (■) and P (▲) concentrations removed with respect to C at a) cold water conditions without nutrients, b) cold water conditions with nutrients, c) warm water conditions without nutrients, and d) warm water conditions with nutrients 97
Figure 5.14: Consumed nutrient ratios during experiments by Lauderdale et al. (2011) 100
Figure 6.1: Pilot plant effluent turbidity data at cold water conditions (mean temperature =1.5°C) from 1-4 December 2013. This figure demonstrates that similar turbidity trends were observed by all filter configurations at cold water conditions. 103
Figure 6.2: Pilot plant effluent turbidity data at warm water conditions (mean temperature = 21.3°C) from 14-17 August 2013. This figure demonstrates that similar turbidity trends were observed by all filter configurations at warm water conditions. 103
Figure 6.3: Mean rate of head loss accumulation based on filter configuration at cold and warm water conditions without nutrient amendments ± one standard deviation. This figure demonstrates that both capping materials improved the rate of head loss accumulation at cold and warm water conditions. 105
Figure 6.4: Mean rate of head loss accumulation ± one standard deviation at warm water conditions while Filters 2 and 4 were nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates that the plastic capped filter performed the best at warm water conditions. 105
Figure 6.5: Mean filter run time± one standard deviation at cold and warm water conditions without nutrient amendments. This figure demonstrates that at cold water conditions they were not different, but longer run times were achieved with capping layers at warm water conditions. 106
Figure 6.6: Mean filter run time± one standard deviation of the EC capped filter with nutrient amendments and the plastic capped filter without nutrient amendments at warm water conditions. This figure demonstrates that longer filter run times can be achieved with the plastic capping material than all the other filter configurations tested, with or without nutrient enhancement. 107
Figure 6.7: Pilot-scale filter mean effluent percent DOC removal vs cold and warm temperature ranges without nutrient amendments 108
Figure 6.8: Normalized molar N (■) and P (▲) concentrations removed with respect to C at a) cold water conditions without nutrients, b) warm water conditions without nutrients 109
Figure 6.9: Material accumulation at the top of Filter 2 containing GAC media only 110
Figure 6.10: Material accumulation at the top of Filter 3 capped with BioFill® media 110
Figure 6.11: Material accumulation around an individual BioFill® plastic element 110

List of Tables

Table 2.1: Studies investigating the suitability of EC aggregates for biological filtration 11
Table 2.2: Typical Reynold's numbers defining the flow regime through a packed bed..................... 13
Table 2.3: Filter ripening sequence stages adapted from Amburgey et al. (2003).............................. 17
Table 2.4: Ratios by mass of carbon, nitrogen, and phosphorus in various plankton samples (Redfield, 1934) 22
Table 3.1: Mannheim Water Treatment Plant full-scale filter configurations 28
Table 3.2: Pilot plant filter configurations.. 30
Table 3.3: Pilot filter backwash parameters.. 33
Table 3.4: Pilot plant influent water conditions across all observed temperature ranges 34
Table 4.1: Traditional filter performance data (mean ± standard deviation) at cold and transitional water temperatures with and without nutrient amendments 41
Table 4.2: Traditional filter performance data (mean ± standard deviation) at warm water temperatures with and without nutrient amendments.. 41
Table 4.3: Summary the mean Filter 2 and 5 rate of head loss accumulation at warm water conditions without nutrient amendments from 9 May 2014 to 5 July 2014 55
Table 5.1: Summary of the mean fraction of the total TOC and DOC removed at sample port S2 at cold water conditions without nutrient amendments.. 73
Table 5.2: Mean fraction of the total TOC and DOC removed at sample port S2 at transitional water temperatures... 76
Table 5.3: Mean fraction of the total TOC and DOC removed at sample port S2 at warm water conditions without nutrient amendments.. 78
Table 6.1: Summary of TSS and aluminum analyses of material collected from the Filter 3 BioFill® capping layer... 111

Chapter 1
Introduction

1.1 Introduction

While physico-chemical filtration is a process that removes fine particles from water, biologically active filtration, or biological filtration, has the additional potential to oxidize and remove biodegradable organic matter (BOM) by employing the metabolic capacity of heterotrophic bacteria. The bacteria are attached to filtration media surfaces in the form of a biofilm; thus, the filtration media act as a support matrix for biological activity. Here, BOM is used as an energy and a carbon source by bacteria that form active biofilms and are predominantly naturally occurring (Urfer et al., 1997). Common implementations of biological filtration include slow sand filtration, river bank filtration, and ground passage (Urfer et al., 1997).

In a drinking water treatment plant setting, a filter is considered biologically active when no residual disinfectant is measured in its effluent (Evans, 2010). There are many potential benefits to using biological filtration, such as: improving the biological stability of finished water, and the removal of various compounds of aesthetic and health concern, like disinfection by-product precursors, taste and odour compounds, pharmaceuticals and personal care products, as well as iron, manganese, nitrogen species, and perchlorate (Dussert and Tramposch, 1997; Evans, 2010; Urfer et al., 1997). The use of biological filtration for drinking water treatment is increasingly widespread in North America and around the world (Evans, 2010). In some cases it is actively implemented, while in others it is unintentional. In other facilities it is not implemented due to design constraints, or an active decision is made to not use it. Regardless of how or why biological filtration is implemented, one of the biggest challenges with its use is its impact on water production rates. Specifically, head loss develops quickly in biological filters due to biomass growth and biofilm development; as a result, filter operational efficiency decreases because of reduced filter run time.

The operation and performance of biological filters can be optimized using several approaches. These include implementing or making appropriate modifications to preceding treatment processes (e.g., chemical coagulation, flocculation, and clarification). In particular, dosing ozone upstream of a filter can promote biological activity, as it increases the biodegradable fraction of organic matter in the water (Carlson and Amy, 1998; Ødegaard, 1996). Quantifying the extent of this increase is difficult due to the variety of methods that can used to measure and describe the biodegradability of aquatic organic matter. For example, it has been suggested that higher bacterial densities on the surface of slow sand filter media generally correspond to higher levels of biodegradable dissolved organic carbon (BDOC) (Graham, 1999). Similarly, it has been widely reported that ozone application prior to rapid filtration can increase attached biomass densities and improve biological filter performance during drinking water treatment (Camel and Bermond, 1998; Carlson and Silverstein, 1997; Carlson and Amy, 1998; Hozalski et al., 1999; Melin and Ødegaard, 1999; Servais et al., 1991; Speitel et al., 1993).

Filter design is another factor that is critical to optimizing biological filtration performance. Filter media selection, effective size, and configuration are important design parameters because they have cost, performance, and operational implications (Amirtharajah and Wetstein, 1980; Boller and Kavanaugh, 1995; Carlson and Amy, 1998; Emelko et al., 2006; Jin et al., 2015; Liu et al., 2001; Stevenson, 1997; Urfer et al., 1997). The most common granular media types used in drinking water filters include anthracite, sand, and granular activated carbon (GAC). Some studies have demonstrated that adsorptive media, like GAC, can provide better BOM removal than non-adsorptive media, like anthracite and sand; in contrast, other investigations have shown no differences in BOM removal performance between different filtration media types (Emelko et al., 2006; Persson et al., 2007, 2006; Wang et al., 1995). In addition to media composition, granular media effective size (d_{10}) also has a significant impact on the performance and operation of a filter. Smaller effective grain size results in greater differential pressure, or head loss, across a filter; thereby often leading to higher operational energy costs and a reduced production rate because a higher backwash frequency is required. Accordingly, granular media filters used in the drinking water production are often configured as dual-media filters with a layer of larger-sized anthracite or GAC above a layer of smaller-sized sand; filters with three or more media types are not very common. The addition of a small layer of media on top of an existing filter, a “capping layer”, to achieve a specific operational target is not a new idea; however, its use in rapid biological filtration for drinking water treatment has not been reported.

Similar to traditional filters, biological filters must be backwashed as part of their regular operation and maintenance. Backwashing allows filters to maintain good particle/turbidity removal and reduces differential pressure across the filters. To be effective, a backwash must yield sufficient particle removal to reduce differential pressure across the filter depth and/or prevent turbidity breakthrough during the subsequent filter cycle. Additionally, some biomass must be retained on the filtration media for continued BOM removal after the backwash. A number of backwash techniques have been developed; however, an optimal backwashing strategy for use with biological filters has not been demonstrated. The "collapsed pulse" backwash, which requires a combination of sub-fluidized air and water, has been demonstrated to be effective for traditional filters relative to other approaches such as water alone or an air scour followed by a water backwash (Ahmad and Amirtharajah, 1998; Amirtharajah, 1993, 1989, 1978; Amirtharajah et al., 1991). The extended terminal sub-fluidization wash (ETSW), which extends the duration of a backwash at a sub-fluidization flow rate, is a strategy developed to reduce the impact of filter ripening by preventing the detachment of additional particles from the filter media. Optimization of the filter backwash procedure is important to achieving robust and efficient biological filtration performance.

Recently, the concept of amending aqueous nutrient concentrations in biological filter influent water to achieve nutrient ratios optimal for biological growth has garnered significant interest as a potential process optimization technique. There are a number of different carbon, nitrogen, and phosphorus (C:N:P) stoichiometric ratios that have been suggested as ideal for biological treatment processes; notably, a C:N:P ratio of 100:10:1 is often cited for enhancing biological filtration performance in drinking water treatment applications (Lauderdale et al., 2012; LeChevallier et al., 1991). To date, the universality of the 100:10:1 C:N:P ratio for biological filter performance enhancement has not been demonstrated. Moreover, the potential applicability and utility of other C:N:P ratios for optimizing biological filtration during drinking water treatment has not been systematically investigated.

1.2 Research Objectives

The overall goal of this research was to investigate filter media selection and operational strategies for improving rapid biological filtration performance during drinking water treatment. Filtration performance was evaluated using both BOM and traditional particle removal-related parameters. The research objectives in support of improving biological filtration performance were to evaluate the:

- Impact of capping materials on filtration performance;
- Impact of nutrient amendments at typically recommended ratios (i.e., C:N:P of 100:10:1) on filtration performance; and
- Applicability and utility of different C:N:P ratios for optimizing biological filtration performance.

1.3 Research Approach

A series of pilot-scale experiments were conducted to investigate the research objectives described above. These experiments were carried out at the Region of Waterloo's pilot plant, located at the Mannheim Water Treatment Plant (MWTP) in Kitchener, Ontario, Canada. The pilot-scale experiments were designed to investigate capping material selection, nutrient amendments, and their interaction on biological and traditional filtration performance. To investigate the use and selection of capping materials for GAC filters, two different capping filtration media with larger effective sizes than the GAC used at the MWTP pilot plant were selected. The top 20 cm of GAC were replaced with the larger capping medium in three of the five pilot-scale filters. Further investigation of nutrient amendments involved the addition of nutrients at two different stoichiometric nutrient ratios in two of the five filter columns, for the purposes of creating more favourable environments for indigenous microbial utilization (and removal) of BOM in the filters. Biological filtration performance was assessed by total organic carbon (TOC), dissolved organic carbon (DOC), ammonia-nitrogen (NH_3-N), and soluble reactive phosphorus (SRP) removal. Traditional filtration performance was assessed by turbidity removal, head loss accumulation, and filter run time.

Pilot plant operations began at the end of the summer of 2013 and progressed through a series of phases. The first experimental phase involved monitoring biological filter performance during the acclimation period at both warm and cold water conditions. As BOM removal by biological filtration processes can diminish at colder water conditions, the impact of nutrient amendments at two different stoichiometric nutrient ratios was examined at cold water conditions during the second experimental phase. These experiments were repeated at warm water conditions to assess seasonality impacts of nutrient amendments during the third experimental phase.

1.4 Thesis Organization

A review of relevant information regarding traditional and biological filtration, nutrient amendments, and characterization techniques relevant to this research is presented in Chapter 2. Chapter 3 outlines the details of the experimental procedures, equipment, and analytical methods used in this research. The results of the pilot-scale experiments are presented in Chapters 4, 5, and 6. Chapter 7 contains the conclusions drawn from these investigations, and Chapter 8 contains implications of this work and recommendations for future investigations of biological filtration.

Chapter 2
Literature Review

2.1 Granular Media Filtration

In water and wastewater treatment, filtration is a unit operation used to remove suspended solids from water using a filter bed typically comprised of granular media; this reduction of solids often helps to facilitate effective downstream disinfection. Slow sand filtration was likely the first filtration process developed for the treatment of water, with typical loading rates of 0.03-0.06 m/d (Metcalf & Eddy, 2003). Rapid filtration processes were developed to treat larger water volumes with a smaller footprint, at loading rates of 4.8-12.0 m/h (Metcalf & Eddy, 2003). A typical conventional rapid filter in which water enters through an inlet channel, passes through a filter bed, collects in an underdrain system, and is conveyed for disinfection is illustrated in Figure 2.1.

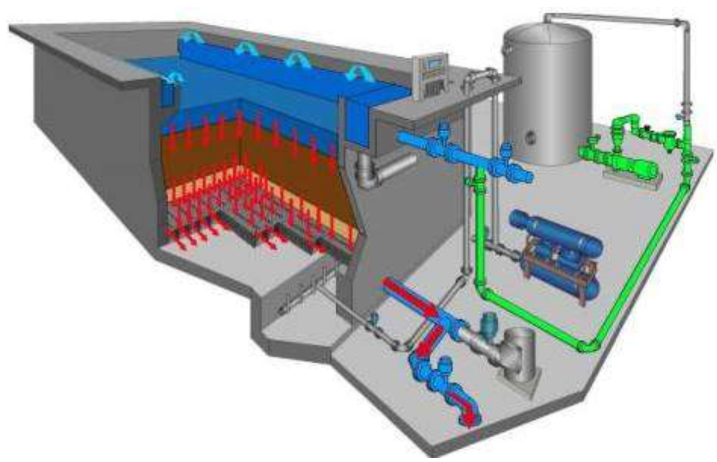

Figure 2.1: Conventional rapid granular filter (McSwain, 2013)

2.1.1 Particle Removal During Physico-Chemical Filtration

Removal of particles within a filter bed involves two steps: transport and attachment. Transport refers to the movement of suspended particles toward filter media grains (Figure 2.2), whereas attachment refers to collisions between destabilized particles and filter grains, resulting in particle deposition on filter grain surfaces. An additional step may be included when considering filtration performance over time: the detachment of particles from collector surfaces.

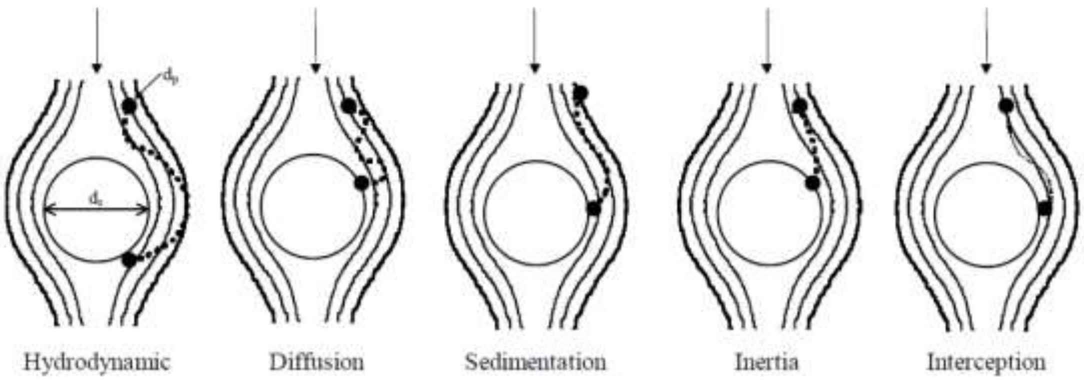

Figure 2.2: Generalized particle transport mechanisms for filtration (Ives, 1982)

Several particle transport mechanisms relevant to granular media filtration have been identified (Amirtharajah, 1988; Ives, 1982). Particle transport by hydrodynamics refers to the additional force between the particles and media grain, which is caused by non-uniform shear distributions (i.e., wall effect (Brenner, 1961; Goldman et al., 1967a, 1967b; O'Neill, 1968)) and complex flow patterns in the streamlines (i.e., particle rolling (Greenberg and Hammer, 2001)). Particle transport by diffusion involves particles crossing streamlines due to random Brownian motion. Sedimentation refers to particle movement along fluid streamlines toward the surface of filter grains as a result of higher densities compared to the fluid. In contrast, in inertial action, particle density is much greater than that of the fluid; consequently, particles move across streamlines. Interception occurs when particles move along streamlines that are sufficiently close to filter grain surfaces so that attachment occurs. It is generally accepted that diffusion and sedimentation are the dominant particle transport mechanisms during physico-chemical filtration (Amirtharajah, 1988).

2.2 Biological Filtration

Biological treatment processes that are used in the water and wastewater treatment industries employ communities of microorganisms to degrade various contaminants, which are metabolized through oxidation-reduction reactions (Zhu et al., 2010). The earliest applications of biological drinking water treatment include slow sand filtration and riverbank filtration. Both of these are examples of fixed-film biological processes in which biofilms are formed on support media surfaces (Zhu et al., 2010). While particles are removed during biological filtration, it has the added benefit of having the potential to remove significant amounts of natural organic matter (NOM) relative to traditional (non-biological) filtration. Specifically, biological filtration achieves oxidization and BOM removal by utilization of the metabolic capacity of heterotrophic bacteria in the form of a biofilm attached to a support medium (Bouwer and Crowe, 1988; Evans, 2010; Hozalski et al., 1999; Urfer et al., 1997). The benefits of removing these dissolved organic compounds (i.e., BOM) include reducing 1) regrowth potential in the distribution system, 2) formation of regulated and emerging disinfection by-products of health concern, and 3) chlorine demand (Emelko et al., 2006; Krasner et al., 1993; Moll et al., 1998; Urfer et al., 1997).

Ozone is a powerful oxidizing agent and an effective disinfectant (Melin and Ødegaard, 1999). It is capable of removing metallic ions, micropollutants, and compounds that cause taste and odour issues (Camel and Bermond, 1998). Ozone's ability to oxidize NOM, breaking it into smaller and simpler compounds increases the NOM biodegradability in water; of course, this depends on source water quality and applied ozone dosage (Carlson and Amy, 1998; Glaze et al., 1989). Increases in the biodegradable fraction of NOM (i.e., BOM) are undesirable as they may result in bacterial growth in the downstream distribution system (Carlson and Amy, 1998; Zhang et al., 2002). The smaller molecular weight organic compounds produced by ozonation, which are relatively more biodegradable, typically include aldehydes, ketones, ketoacids, and carboxylic acids (Carlson and Amy, 1998; Glaze et al., 1989; Kuo et al., 1996) — their removal is important to the provision of safe-drinking water. For example, due to their high biodegradability, they can lead to bacterial regrowth in the distribution system (Carlson and Amy, 1998). Other consequences include: pathogen shielding (Percival and Walker, 1999), pathogen harbouring (Camper et al., 1991; Rice et al., 1991), and taste and odour complaints (Bruchet, 1985). Some of these compounds are precursors to compounds that have been identified as potential human health concerns; specifically, they can be precursors of chlorinated disinfection by-products (DBPs), some of which are non-regulated and more toxic than some of the DBPs that are currently regulated (Krasner, 2009; Shah et al., 2012; Speitel et al., 1993). Notably, ozonation by-products are often removed well through biological filtration; moreover, the associated increases in NOM biodegradability promote biological filtration (Krasner, 2009; Melin and Ødegaard, 2000).

2.2.1 Biofilms

Regardless of its function and composition, biofilm formation generally follows a four-step process (Boland et al., 2000). First, a conditioning film forms on the surface of a support medium. It is composed of a thin layer of organic molecules, proteins, and salts (step 1). Once the conditioning film is present, individual or aggregates of microbes will reversibly attach to it (step 2), eventually forming a biofilm. The strength of this initial biofilm depends on the structure of the conditioning film. The microorganisms that have attached reversibly to the conditioning film will eventually attach irreversibly once sufficient extracellular polymeric substances (EPS) are produced to provide the structural matrix required to create the biofilm (step 3). Finally, microorganisms will accumulate within the biofilm through *in situ* cell growth (step 4).

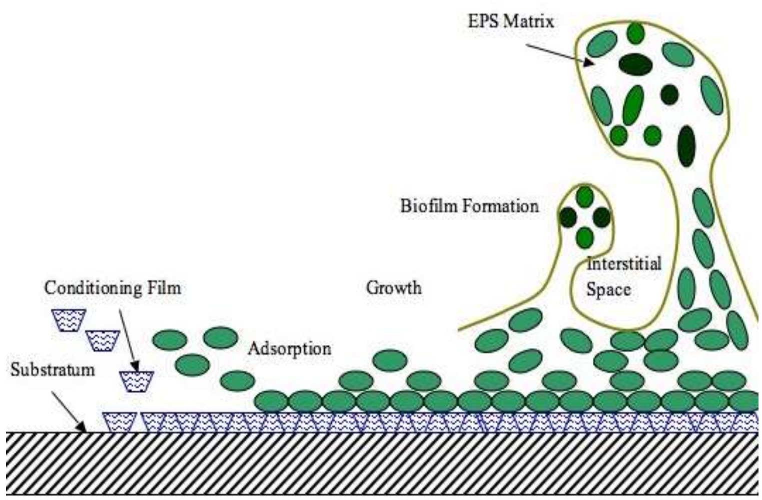

Figure 2.3: Biofilm formation (Aalexopo, 2011)

The removal of organic compounds from water by biofilms occurs via two mechanisms, singly or in combination: physical adsorption onto or into the biofilm, and biodegradation (Carlson and Silverstein, 1998). EPS comprises a significant portion of a biofilm, and in turn affects the interactions between the biofilm and dissolved compounds found in the water (Carlson and Silverstein, 1998). The EPS matrix has many chemically active sites that interact with inorganic cations and organic molecules (Characklis and Marshall, 1990). The dominant functional groups of the sugar-acid residues in the EPS are carboxyl and hydroxyl groups, which release protons under neutral or alkaline conditions resulting in a negative charge on surfaces found in most environments where biofilm is present (Horan and Eccles, 1986; Morgan et al., 1990). The net negative charge of most biofilms affects the transport of charged compounds such as negatively charged aquatic NOM, towards its surface; thus, affecting their removal from water.

An inversely proportional relationship between NOM molecular size and removal by biological filtration was reported by Carlson and Silverstein (1998). Using various compounds as NOM surrogates, they also demonstrated that the charge of the molecule affected its removal; accordingly, the removal of anionic sorbates was lower removals than that of uncharged molecules. As might be expected, ozonation of aquatic NOM has been found to decrease NOM characteristic molecular weight; however, in one study significant concurrent increases (>50%) in NOM acidity were also observed (Carlson and Silverstein, 1997). As a likely result of the competing effects of decreased molecular weight and increased anionic character of the NOM, significant changes in aqueous NOM concentrations after ozonation were not observed during that investigation (Carlson and Silverstein, 1997).

2.2.2 Media Type

Filter media type is a particularly important biological filtration design parameter because it has cost, performance, and operational implications (Amirtharajah and Wetstein, 1980; Boller and Kavanaugh, 1995; Carlson and Amy, 1998; Emelko et al., 2006; Jin et al., 2015; Liu et al., 2001; Stevenson, 1997; Urfer et al., 1997). From a drinking water utility's perspective, filtered water must meet regulatory criteria and targets (e.g., 0.3 NTU 95th percentile from combined filter effluent requirement and 0.1 NTU individual filter effluent turbidity target (USEPA, 2007, O.Reg 170/03)) while meeting plant-specific capital and operational cost constraints. The most common granular materials installed in biological filters include: anthracite, GAC, and sand. Other filtration media such as garnet, and expanded and crushed clays have also been used successfully in drinking water filtration applications (Crittenden et al., 2012a; LeChevallier et al., 1992; Urfer et al., 1997).

GAC can be made from a variety of materials including nutshells, coconut husks, wood, lignite, coal, and petroleum pitch (Metcalf & Eddy, 2003). The raw material is carbonized using a pyrolysis process at low oxygen levels. The carbonized material, or char, is activated by exposure to steam and carbon dioxide at high temperatures developing a porous structure and a large internal surface area (Metcalf & Eddy, 2003). GAC is often an optimal choice as a support medium for biological filtration because when it is used, BOM is removed at both ideal and non-ideal operational conditions for biological filtration (e.g., low temperatures, chlorinated backwash utilization, collapse pulsing backwash utilization, and relatively higher proportion of NOM compounds that are not readily biodegraded in filter influent (Dussert and Tramposch, 1997; Emelko et al., 2006; Liu et al., 2001; Wang et al., 1995). It has been suggested that the adsorptive properties of GAC allow substrates, nutrients, and oxygen to be adsorbed to its surface extending their effective contact time with biofilm and allowing microbial activity to be sustained when filter influent BOM concentrations are too low to support growth (Dussert and Tramposch, 1997). Biologically toxic compounds also can adsorb to GAC, reducing their concentration in local microbial environments (Dussert and Tramposch, 1997).

As well, bacteria readily attach to GAC (Ahmad and Amirtharajah, 1998; Billen et al., 1992; Stewart et al., 1990) and oxidants/disinfectant (e.g., ozone, chlorine) residuals are reduced by it (Dussert and Tramposch, 1997; Krasner et al., 1993), potentially protecting attached microorganisms. GAC is often cited as being a suitable support medium for biological filtration due to its high porosity and surface area, providing more sites for microbial attachment and potentially higher removals of BOM (Emelko et al., 2006; Nkwonta et al., 2010; Spanjers and Emelko, 2012; Urfer et al., 1997)

Expanded clay (EC) aggregates have been used successfully as filtration media for both drinking water and wastewater treatment. Typically, EC media are produced by heating clay beads at high temperatures (1100-1200°C) causing the liquids and gases contained within them to expand and escape creating micropores (Eikebrokk and Saltnes, 2002; Melin and Ødegaard, 1999). The resulting beads are then crushed and sieved to achieve a target effective size and uniformity coefficient. Crushing the beads increases the surface area by creating a rough and angular surface, as well as exposing the internal microporous structure (Melin and Ødegaard, 1999). EC aggregates have good abrasion resistance and are less friable than GAC, but do not have any adsorptive capacity. The manufacturing process of EC aggregates can be adjusted to yield media with different levels of porosity, or dry density. EC media can be produced with an inverse relationship between grain size and density (Eikebrokk and Saltnes, 2002), which is beneficial for the design and operation of downflow filters. As filters are operated, the media stratify with smaller grains of media of the same density accumulating at the top of filters. This may lead to excessive head loss, as well as the removal of most suspended solids within the first few centimeters of bed depth, thus resulting in inefficient use of the filter bed (Crittenden et al., 2012).

The suitability of EC aggregates for biological filtration applications has been extensively investigated (Table 2.1). Melin and Ødegaard (1999) investigated the suitability of using an EC medium in a biological filtration application using two EC media of different densities in pilot-scale upflow filters receiving ozonated water. They found that the filters were able to achieve 18-37% TOC removal, as well as an 80% minimum removal efficiency of readily biodegradable ozonation by-products. Eikebrokk and Saltnes (2002) concluded that EC media can be used as a substitute for anthracite media during biological filtration because no significant differences in colour or TOC removal were observed; moreover, the EC filter had a lower initial head loss and rate of head loss accumulation. The use of different sized media and different support material confounds the comparison of the two filtration media investigated in that study, however. In another investigation, similar DOC, BDOC, and assimilable organic carbon (AOC) removals, and oxygen consumption rates (OCR) by GAC and EC filters were reported; additionally, biomass development on comparably sized GAC and EC media was not significantly different (Persson et al., 2006). Persson et al. (2007) also compared biological GAC and EC filtration; in this case, for the removal of geosmin and 2-methylisoborneol (MIB), which are taste and odour causing compounds. Geosmin and MIB were similarly removed by the filters at higher water temperatures; however, the GAC filters achieved higher removals of these compounds at colder temperatures when the filter biomass concentrations were relatively lower. Lower initial head loss and rates of head loss accumulation, as well as greater resilience to algae laden stored water, also have been reported in EC filters, as compared to anthracite filters (Mikol et al., 2007). Despite similar media grain sizes, the use of a different EC medium instead of sand as a supporting medium may have confounded this comparison of anthracite and EC media, however. Moreover, although EC media are suitable for supporting biological growth during biological filtration, their use as a capping material in combination with other filtration media in a biological filtration application has not been reported.

Table 2.1: Studies investigating the suitability of EC aggregates for biological filtration

Study	**Media (ES mm)**	**Design Influences**
Melin & Ødegaard (1999)	Low density EC (0.5) & Gravel High density EC (0.5) & Gravel	
Eikebrokk & Saltnes (2002)	Anthracite (0.82) & Sand (0.5) EC (1.65) & EC (0.82)	Different media sizes and type of support material
Persson et al. (2006)	GAC (0.9) & Gravel EC (0.9) & Gravel EC (2.45) & Gravel	
Mikol et al. (2007)	Anthracite (1.7) & Sand (0.6) EC (1.5) & EC (0.8)	Different media sizes and type of support material
Persson et al. (2007)	GAC (0.9) EC (0.9)	

With the exception of membrane technologies, plastic media have seen very limited use in drinking water treatment and are more commonly found in wastewater treatment and aquaculture operations. Plastic media in the form of floating beads have been used to enhance contact-flocculation (Chiemchaisri et al., 2003) and deep bed roughing filtration (Sokolovic et al., 2009). They have also been woven into sheets to enhance slow sand filtration (Clarke et al., 1996). The "pinwheel" is the most commonly utilized shape of plastic filtration media; examples are provided in Figure 2.4. Numerous variations on the “pinwheel” have been developed and patented.

Figure 2.4: Sample of common plastic filtration media (Snow Plastic Mesh Co., 2007)

Plastic media are typically used as a biofilm carrier in trickling filters (Rehman et al., 2012), fixed and packed bed bioreactors (Min et al., 2004), and moving-bed biofilm reactors (MBBR) (Ødegaard, 2006). Min et al. (2004) demonstrated that plastic media can be used as biofilm carriers for the biological removal of perchlorate from contaminated ground water and compared its performance with a traditional sand filter. They found that the sand filter was able to operate at loading rates approximately twice as high as the plastic media bioreactor, but was more susceptible to short circuiting requiring more frequent and rigorous backwashing. In contrast, more consistent perchlorate removal and lower differential pressure were observed with the plastic media, which were also significantly easier to backwash.

Compared to conventional activated sludge systems, MBBRs containing plastic biofilm carrier elements are robust and compact reactors; they have been implemented at many wastewater treatment facilities across the world (Ødegaard, 2006). MBBRs combine the activated sludge process with biological filtration—eliminating the need for a sludge recycle line—and can be used at aerobic, anoxic, or anaerobic conditions (Ødegaard, 2000). These types of plastic media also have been successfully used as fixed film biological carriers for the biological removal of organic matter, nitrogen, and phosphorus at both warm and cold water conditions (Di Trapani et al., 2013; Helness and Ødegaard, 2001; Ødegaard, 2006). They have consistently yielded low head loss, prevented channelling, and required infrequent backwashing (Di Trapani et al., 2013). Notably, Ødegaard

(1996) used plastic Kaldnes® media in a bioreactor, as part of a multistage process including both slow and rapid sand filtration during drinking water treatment, yielding substantial reductions in chemical oxygen demand (COD) and TOC. Clearly plastic media are suitable materials for supporting biofilm growth in both wastewater and drinking water applications. Their generally consistent performance yielding low head loss, preventing channelling, and requiring relatively minimal backwashing efforts suggests that they could be effectively used as filter capping materials in rapid biological filtration processes; however, their use in this application has not been reported to date.

2.2.3 Media Size and Uniformity Coefficient

Granular media used for filtration are characterized by their effective size (ES) and uniformity coefficient (UC). Evaluation of EC and UC requires measurement of media grain size distributions, typically by sieve analysis, in which a sample of dry aggregate of known mass is separated through a series of sieves of progressively smaller openings (ASTM Standard C136M-14, 2014). The ES is defined as the diameter of the granular media where 10% of the sample by weight is smaller (d_{10}). The UC is used to represent the grain size distribution, and is the ratio of the 60^{th} percentile grain diameter (d_{60}) to the 10^{th} percentile grain diameter (d_{10}), as given by Equation 2.1.

$$UC = \frac{d_{60}}{d_{10}}$$ **Equation 2.1**

Many equations have been developed to predict clean bed head loss through packed beds, based on the flow regime of the system. The flow of a fluid through a packed bed may be laminar, transitional, or turbulent, and is defined by the Reynold’s number (Re). Typical values for Re at different flow regimes are summarized in Table 2.2; these are calculated using Equation 2.2

Table 2.2: Typical Reynold's numbers defining the flow regime through a packed bed

Flow Regime	Reynold’s Number (Re)
Laminar	$Re < 10$
Transitional	$10 \leq Re \leq 2000$
Turbulent	$2000 < Re$

$$Re = \frac{2D_pV_s\rho}{3\mu(1-\varepsilon)}$$ **Equation 2.2**

where D_p is the diameter of the media grain, V_s is the superficial velocity of the fluid, ρ is the density of the fluid, μ is the viscosity of the fluid, and ε is the porosity or void space of the packed bed. The equation developed by Ergun (1952) to predict the clean bed head loss through a packed bed, valid for all flow regimes, is a combination of the *Kozeny-Carman* and *Burke-Plummer equations* and is presented in Equation 2.3

$$h_l = K_t \frac{V_s^2}{g\,D_p}\frac{(1-\varepsilon)\,\Delta z}{\varepsilon^3} + K_l \frac{V_s\,\mu\,(1-\varepsilon)^2\,\Delta z}{D_p^2\,\varepsilon^3\,g\,\rho} \qquad \textbf{Equation 2.3}$$

where K_t is the head loss coefficient at turbulent flow conditions, K_l is the head loss coefficient at laminar flow conditions, Δz is the depth of the media in the filter, and g is the acceleration due to gravity. As evidenced by *Ergun equation*, as filter media grain size increases, head loss decreases; accordingly, shorter run times have been commonly reported as a result of the use of smaller sized filtration media (Crittenden et al., 2012a; Scott, 2008; Van der Hoek et al., 1996). Larger sized media are typically used to decrease the rate of head loss accumulation across filters, decreasing the energy requirements associated with passing water through filters and potentially extending filter run times. Notably, it has been demonstrated that use of media with larger effective size does not *necessarily* deleteriously impact turbidity, assimilable organic carbon (AOC), or heterotrophic plate count (HPC) reductions by filtration (Crittenden et al., 2012a; Van der Hoek et al., 1996).

BOM removal by biological filters has been correlated with a dimensionless contact time (X^*), which is defined as

$$X^* = \frac{\theta\,\alpha\,D_f}{\tau} \qquad \textbf{Equation 2.4}$$

where, θ is the empty bed contact time (EBCT), α is the specific surface area, D_f is the diffusivity of the substrate into the biofilm, and τ is the biodegradation rate of the substrate (Zhang and Huck, 1996). EBCT is equal to the volume of the empty bed divided by the volumetric flow rate. EBCT and hydraulic loading rate are critical operational parameters that also enable comparison of performance results between filtration investigations. The specific surface area of the medium (α), which is a function of grain size, provides a general indication of the amount of available surface area for biofilm growth; it is calculated by

$$\alpha = \frac{\xi(1-\varepsilon)}{d_{10}} \qquad \textbf{Equation 2.5}$$

where ξ is the dimensionless shape factor of the media. Although filtration media effective size and available surface area have not been rigorously correlated with either biofilm coverage or BOM removal by filtration, it is reasonable to anticipate some relationship between BOM removal and the ES of granular media in a biological filter, because the smaller the ES the greater the surface area. The UC of a granular filtration medium (coupled with its density) affects how it stratifies after it is backwashed. As a filter is operated and backwashed periodically, the finest media grains will collect at the top of the bed (in absence of significant differences in density). These fine grains can reduce the porosity (i.e., void space) of the top few centimeters of a filter bed, thus causing significant head loss, and reducing the overall efficiency of the filtration process (Crittenden et al., 2012a). Similarly, larger media grains will settle near the bottom of filter beds (in absence of significant differences in density) and may be difficult to fluidize. As would be expected, these effects are increasingly evident at larger UCs.

2.3 Filter Capping Materials

"Filter capping" is the addition of a shallow layer of media on top of an existing filter to achieve a specific operational target. The use of filter capping materials is not a new concept. The premise is to combine the elements of multistage filtration in one filter; in effect, integrating roughing filters that remove larger solids and prevent premature clogging with conventional "polishing" filters that remove fine particles. For example, Adin (2003) found that the addition of a 20 cm layer of volcanic material (ES = 0.6 mm or 0.5 mm) on top of a 50 cm deep slow sand (ES = 0.25 mm) filter significantly extended the filter run time without any change in effluent water quality during the treatment of secondary wastewater effluent. Similarly, Mälzer and Gimbel (2002) investigated the use of permeable synthetic collectors (PSC), made of reticulated foam, as a protection layer on top of a slow sand filter during secondary wastewater treatment. The rate of head loss accumulation decreased with the addition of the PSC because larger suspended solids accumulated on its surface and throughout the capping layer, rather than on and within the top few centimeters of the smaller sized sand medium. As would be expected, filter run times increased significantly; notably, without deteriorating effluent water quality. Filter caps have also been used in drinking water treatment, though less frequently. One example of a capped filter design during drinking water treatment is the GAC Sandwich™, which involves a layer of GAC between two layers of sand to enable adsorption of non-biodegradable NOM during slow sand filtration (Bauer et al., 1996). Page et al. (1996) found that the addition of this GAC layer did not significantly impact head loss development, and led to significantly higher NOM removals; although the mechanism(s) associated with that benefit are not completely clear because the GAC became biologically active over time (Steele et al., 2006). While the performance benefits of capping layers have been demonstrated for slow sand filtration processes, their application to, and potential utility in rapid biological filtration during drinking water treatment has not been reported.

2.4 Filter Backwash

Filters are backwashed when the effluent water quality has degraded to an unacceptable level, when the differential pressure across the filter reaches a predetermined level (Hozalski and Bouwer, 1998), or when a specific amount of time has elapsed. Backwashing of a conventional rapid filter refers to the reverse flow of clean water, with or without air, through a filter bed to expand the bed and remove particles that have accumulated on the filtration medium. In the case of biological filtration, some of the biomass that has grown on the medium during the course of the filter cycle will also be removed during the backwash. Some removal of biomass from biological filters can be important for reducing filter head loss and achieving flow rate and production volume targets during the subsequent filter cycle. Some biomass should be retained on filtration media to maintain biological treatment/degradation capacity when biological filtration is employed–Hozalski and Bouwer (1998) demonstrated that incomplete biomass removal during a backwash is beneficial for the removal of biodegradable TOC when it is returned to service.

Filter ripening is a period of degraded effluent water quality due to increased particle passage when a filter is returned to service after a backwash. Approximately 90% of the particles that pass through a well-operated filter occurs during the filter ripening sequence (FRS) (Amirtharajah, 1988; Amburgey, 2005), which has been described to occur in five stages summarized in Figure 2.5 and Table 2.3. The severity and duration of the FRS depends on a number of factors, including but not limited to: the backwash procedure, the influent water chemistry, the backwash water chemistry, the coagulants used, and the coagulation efficiency (Amburgey, 2005). Utilities may filter-to-waste following a backwash to help mitigate filter ripening; however, if the filter-to-waste procedure is not optimized, significant losses in treated water volume and downtime may result. In addition, not all water treatment facilities have filter-to-waste capabilities, which may lead to the release of pathogens into the distribution system.

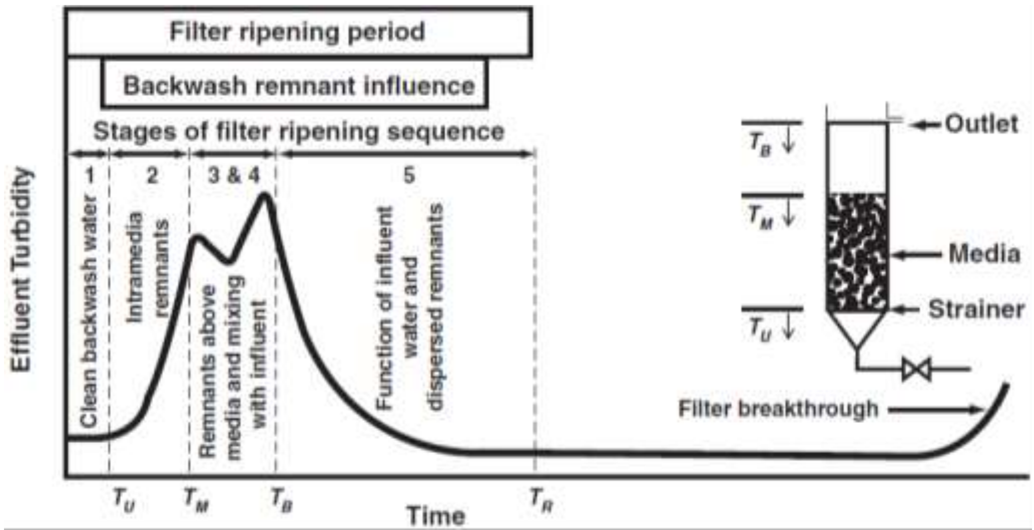

Figure 2.5: Filter ripening sequence (Amburgey et al., 2003; Amirtharajah and Wetstein, 1980)

Table 2.3: Filter ripening sequence stages adapted from Amburgey et al. (2003)

1. Lag Phase	- Clean water remaining in the underdrain region of the filter yielding low turbidity
2. Media disturbance and intra-media remnant stage	- Particles dislodged from the media during the backwash sequence and settling remaining in the pore water, resulting in the increase in turbidity
3. Upper filter remnant stage	- Particles dislodged during the backwash sequence remaining in the filter box suspended in the water above the filter media
4. Influent mixing and particle stabilization	- Influent water enters the filter box mixing with the backwash remnant water above the filter media - Stages three and four are separate processes, but often occur simultaneously if there is significant intermixing in the volume above the filter media
5. Dispersed remnant and filter media conditioning	- Newly attached particles become collectors for other incoming particles

The passage of remnant particles during the FRS is related to their surface charge, or zeta potential. As the backwash procedure progresses, the zeta potential of the remnant particles becomes more negative, reverting back to their original charge (Amburgey et al., 2003). The exact cause for this change in the zeta potential is unknown, but it has been speculated that it may be due to the partitioning of soluble organic matter onto retained particles in the filter bed, the aging of metal hydroxide floc particles, and new biological growth (Amburgey and Amirtharajah, 2005).

2.4.1 Collapsed Pulse Backwash

A combination of air and water at a subfluidization flow rate is used in a collapsed pulse backwash. This backwashing technique has been found to achieve the best removal of particles that have accumulated in conventional, non-biological filters by maximizing the scouring action between the media grains (Amirtharajah, 1993). In a water only backwash, collisions and abrasion between the media grains are limited because nearly all of the energy that is introduced to the filter is used to fluidize the filtration media (Amirtharajah, 1978). In addition, increasing the duration of a high rate water backwash does not significantly impact the effluent turbidity of a filter when returned to service (Amburgey et al., 2003). Collapsed pulse backwashing is generally understood to be the most effective backwashing process for preventing the formation of preferential flow pathways, mudballs, and media clumping in conventional filters (Amirtharajah, 1978).

The impact of collapsed pulse backwashing on biological filtration performance has been extensively studied At warm water conditions, collapsed pulse backwash did not affect the removal of ozonation by-products such as acetate, formate, and formaldehyde; however, higher glyoxal removal was achieved without the addition of air while backwashing with chlorinated water (Liu et al., 2001). Additionally, carboxylic acid and aldehyde removal decreased while using the collapsed pulse backwash in anthracite filters, but only at low temperatures (Liu et al., 2001). In a different study, it was found that the collapsed pulse backwash did not negatively impact non-purgeable organic carbon (NPOC) or AOC removal in anthracite filters (Ahmad and Amirtharajah, 1998); however, the introduction of air in the backwash process did yield higher effluent turbidity peaks during filter ripening and higher initial head loss levels (Ahmad et al., 1998). A full-scale investigation of biological demonstrated that the collapsed pulse backwash did not diminish BOM removal in either GAC or anthracite filters, but did lead to a significant decrease in filter run time due to turbidity breakthrough (Emelko et al., 2006). Clearly, there are contradictory observations related to the impact and applicability of the collapsed pulse backwash during biological filtration. Notably, these observations do not indicate that it cannot be used successfully for maintaining biological filter operation, but rather that its implementation requires confirmation and potential optimization.

2.4.2 Extended Terminal Subfluidization Wash (ETSW)

ETSW is a filter backwash technique that extends the duration of a normal backwash by applying subfluidizing flow rates for a period that allows the movement one theoretical filter volume through the filter box (Amburgey, 2005). Lower flow rates are used during this period to produce relatively lower shear forces at the media surfaces, thereby preventing the removal of remaining attached particles from the media, while removing already detached particles within and above the filtration media (Amburgey et al., 2003). In some cases, ETSW has been able to significantly shorten or eliminate the FRS, and has been demonstrated to be effective for both anthracite and GAC media (Amburgey et al., 2003; Snider et al., 2014).

ETSW is optimized with respect to flow rate. A flow rate that is too high results in shear forces that can detach attached particles from the filter media, while a flow rate that is too low may leave a significant amount of detached particles in the pore spaces between media grains. These particles (i.e., turbidity) will then pass into effluent streams when filters are returned to service, thereby extending filter downtime (Amburgey, 2005). The optimal ETSW flow rate depends on water temperature, floc strength, particle density, and the size of detached particles (Amburgey, 2005). Accordingly, ETSW duration is also an important operational consideration. The filter ripening turbidity peak can be gradually reduced and shifted to a point later in the FRS with each increment of the ETSW duration, by flushing out more remnant particles from the filter (Amburgey et al., 2003). At subfluidization flow rates, low shear forces may allow dislodged particles to reattach to the filtration media (Amburgey et al., 2003). This mechanism may have positive or negative impacts on filter performance, depending on the amount of particles flushed out of the filter box and whether they will detach later during the filter cycle (Amburgey et al., 2003).

While the ETSW is effective at removing remnant particles, relative to other backwash protocols, it does not allow for better control over the fluidization step or backwash cycle for the purposes of removing a target number of remnant particles from a filter (Amburgey et al., 2003). Reduced water usage may or may not be realized upon the implementation of the ETSW, but it may eliminate the need for a filter-to-waste procedure (Amburgey et al., 2003). The ETSW was successfully implemented at full-scale at the MWTP in Kitchener, Canada—it reduced peak turbidity during the FRS from ~0.3 NTU to ~0.05 NTU, increased the plant's annual net production volume by 236,000 m^3 (~62 million gallons), and reduced their annual coagulant and polymer demand by 6,600 kg and 76.6 kg, respectively. In addition, the annual amount of energy consumed by the ozone system was reduced by 82,000 kWh (Snider et al., 2014).

2.5 Nutrients

It is accepted that carbon (C), nitrogen (N), oxygen (O), hydrogen (H), and phosphorus (P) are the critical building blocks of life on Earth. Nitrogen and phosphorus, along with carbon, are considered macronutrients and are essential for the growth of microorganisms, plants, and animals. The identification of minimal or optimal ratios for biomass growth in various environments has been the focus of numerous investigations; nonetheless, no universal ratios have been identified, as discussed below.

2.5.1 Nitrogen

Nitrogen is used by microorganisms to build proteins, cell wall components, and nucleic acids (Lengeler et al., 1999). The most common forms of nitrogen in water include: organic nitrogen, nitrite (NO_2^-), nitrate (NO_3^-), ammonia (NH_3), ammonium (NH_4^+), and nitrogen gas (N_2) (Metcalf & Eddy, 2003). Organic nitrogen can be found in either a soluble or particulate form, and is a complex mixture of amino acids, amino sugars, and proteins. NO_2^- is toxic but unstable, and is easily oxidized to NO_3^-. NO_3^- is the most oxidized form of nitrogen and can lead to serious health effects if consumed. In water, NH_3 and NH_4^+ exists in equilibrium, the fraction of each species is dependent on pH. Within typical operating ranges of water treatment plants (pH 6.0 to 8.5), NH_4^+ is typically the dominant aquatic species of nitrogen. This is ideal for biological filters because NH_4^+ is the preferred form of nitrogen for microorganisms (Lengeler et al., 1999). NH_3 and NH_4^+ can be taken up by microorganisms and converted to NO_3^- through nitrification, or assimilated within the cell (Metcalf & Eddy, 2003).

2.5.2 Phosphorus

Phosphorus is critical to the generation of ATP energy, nucleic acids, organic acids, and lipids (Thompson et al., 2006). Phosphorus can exist as organic phosphates, polyphosphates, and orthophosphate in nature (Metcalf & Eddy, 2003). Organic phosphate consists of a phosphate molecule associated with a carbon-based molecule (USEPA, 2012). Polyphosphates can be produced by polyphosphate accumulating bacteria (PAOs) at anaerobic conditions, and are used in wastewater treatment for biological phosphorus removal (Metcalf & Eddy, 2003). Polyphosphates can undergo hydrolysis into orthophosphate forms, but this is a slow process (Metcalf & Eddy, 2003). Orthophosphate can exist in a variety of species depending on pH (PO_4^{3-}, HPO_4^{2-}, $H_2PO_4^-$, H_3PO_4).

For microorganisms, orthophosphate is the most readily assimilable form of phosphorus and is often referred to as soluble reactive phosphorus (SRP).

2.5.3 Nutrient Ratios (C:N:P)

The relative ratios of carbon, nitrogen, and phosphorus that are required to sustain various microorganisms can vary substantially. One of the most recognized nutrient ratios is the Redfield ratio, which is based on a postulate that the chemical composition of the ocean water would depend on, or be closely related to, the composition of the material that decomposes in it, and *vice versa* (Redfield, 1934). Water samples from different open water locations and depths of the Atlantic, Pacific, and Indian Oceans were collected and nutrient concentrations were measured. A stoichiometric N:P ratio of 20:1 persisted across all sampling locations and depths; based on these data, this ratio was expanded to include carbon yielding a stoichiometric C:N:P ratio of 140:20:1 (Redfield, 1934). While the relative C:N:P ratios of various plankton vary, it was found that the mean C:N:P ratio of the plankton samples was similar to that of the mean of ocean water (Table 2.4) (Redfield, 1934). These results gave rise to the concept of the biochemical cycle and the theory that the environment determines the conditions under which life exists, but the organisms influence the prevailing conditions in the environment (Redfield, 1958).

The Redfield ratio was further refined to a stoichiometric C:N:P ratio of 106:16:1, which is commonly recognized today (Redfield, 1958). Notably, this ratio only applies to open water, marine environments; for example, the stoichiometric nutrient ratios relevant to coastal waters vary considerably because of local plants and animals (Redfield, 1958), as well as anthropogenic activities.

While the 106:16:1 ratio is often referred to as being "canonical," its relevance to non-marine environments and across large temporal and spatial scales remains poorly understood. For most microbes, the majority of consumed nitrogen is used in protein production, while phosphorus is largely used in the production of ribosomal RNA (Geider and La Roche, 2002). Optimal production of both protein and RNA depends on microbe growth rate and availability of limiting nutrients in its environment. Some theoretical models have suggested that the optimal production ratio of protein to RNA depends on environmental conditions, and not the Redfield ratio (Klausmeier et al., 2004) and build on demonstrations of individual phytoplankton, which exhibit N:P ratios that differ widely and in a manner that depends on environmental conditions (Klausmeier et al., 2004; Weber and Deutsch, 2010). Accordingly, these models show how an N:P ratio of 16:1 is due to a combination of environmental conditions and taxonomically fixed N:P ratios that are not dependent on the environment, which suggests that C:N:P ratios that differ from the Redfield ratio are equally plausible and also likely (Klausmeier et al., 2004; Weber and Deutsch, 2010). For example, using a model that included the mean nitrogen content of the twenty amino acids and the mean nitrogen and phosphorus content of four ribonucleotides, it was demonstrated that a stable rate of protein and RNA production at nutrient abundant conditions would require an N:P ratio of 16±3:1 (Loladze and Elser, 2011). However, it is important to recognize that at nitrogen limited conditions the protein and RNA production rates would require ratios below the Redfield value, while phosphorus limited conditions would require ratios above the Redfield value (Loladze and Elser, 2011).

Table 2.4: Ratios by mass of carbon, nitrogen, and phosphorus in various plankton samples (Redfield, 1934)

Sample	Carbon	Nitrogen	Phosphorous
Mixed copepods from Buzzards Bay	100	21	1.98
Centropages typicus, Gulf of Maine	100	25.6	1.06
Calanus finmacrchicus, Gulf of Maine	100	13.4	2.04
Calanus finmacrchicus, Gulf of Maine	100	15.8	2.26
Diatoms – Bay of Fundy, almost entirely *Thalassiosira nordenskioldi*	100	18.2	1.36
Diatoms – off Nova Scotia coast – 17 species of somewhat the same abundance	100	15.6	2.26
Peridinians – Meyer (1914)	100	13.2	2.2
Chiefly peridinians – mean of samples 1, 2, 3, 4, Brandt (1898)	100	8.1	-
Chiefly diatoms – mean of samples 6 and 7, Brandt (1898)	100	12.4	-
Chiefly copepods – mean of samples 8 and 9, Brandt (1898)	100	15.3	-
Mixed plankton- sample 10, Brandt (1898)	100	11.3	-
Mean of all samples	**100**	**15.4**	**1.88**
Estimated from analyses of sea water	**100**	**16.7**	**1.85**

Hoover and Porges (1952) developed a general chemical formula representing biomass as $C_5H_7O_2N$. When phosphorus is included, the chemical equation becomes $C_{60}H_{87}O_{23}N_{12}P$ (Metcalf & Eddy, 2003). These equations were meant to be approximations and may vary with time, environmental conditions, and species; nonetheless, they are often used for estimation and simple modeling. For example, Droste (1997) modified this general chemical expression of biomass to

$C_5H_7O_2NP_{0.074}$ for use in wastewater applications; thus, the associated literature often cites a C:N:P ratio of 100:5:1 as ideal for aerobic digestion, by mass (Henze et al., 2001; Metcalf & Eddy, 2003). On a molar basis, this C:N:P ratio becomes 100:4.3:0.4. This ratio is based on several assumptions: 1) 100% of the carbon in the system (as COD) is removed, 2) the biological process has a yield coefficient of 0.41, and 3) the microbial phosphorus requirement is 20% of the nitrogen requirement (Ammary, 2004). Some of these assumptions may be considered arbitrary.

The relationship between biological activity, nutrient ratios, and abundance is still poorly understood. Thompson et al. (2006) studied the impact of varying C:N:P ratios on the formation of *Enterobacter cloacae* and *Citrobacter freundii* biofilms on GAC media. Relative to the Endo formulation (Endo et al., 1982), they found that lower carbon and nitrogen nutrient formulations led to higher counts of attached bacteria, consistent with the results of Allan et al. (2002). General nutrient limitation may stimulate quorum-sensing molecules that are known to be involved in the attachment of bacteria to surfaces (Lazazzera, 2000; Withers et al., 2001), while nutrient abundance may favour suspended cells (Thompson et al., 2006). Low nutrient environments have also been reported to promote the production of EPS, which may be the primary contributor to clogging in biological filters (Fang et al., 2009; Liu et al., 2006; Mauclaire et al., 2004; Sutherland, 2001).

It has been suggested that heterotrophic bacteria require a stoichiometric C:N:P ratio of 100:10:1 (LeChevallier et al., 1991); however, the basis for this ratio has not been presented. Nonetheless, this is the most commonly cited nutrient ratio that is applied to discussion of biological treatment processes in the drinking water industry. Notably, water entering a distribution system in that investigation actually had molar C:N:P ratios of 100:0.4:2.1 and 100:4.0:23.6, based on the reported TOC and AOC concentrations, respectively. Based on the prescribed 100:10:1 ratio, the system was deficient in nitrogen, but had an excess of phosphorus. When water was sampled from the distribution system at locations 1.1 km, 1.6 km, and 10 km from the water treatment plant, it was reported that AOC concentrations decreased, while other parameters (NO_2^-, NO_3^-, NH_4^+, SRP, TP, TOC) remained unchanged (LeChevallier et al., 1991); thus, the prescribed 100:10:1 nutrient ratio appears ill-suited for that system because carbon was consumed while at nutrient deficient conditions. Further, the lack of nitrogen or phosphorus removal suggests that the system was not limited by those nutrients.

Lauderdale et al. (2012) stated that a stoichiometric C:N:P ratio of 100:10:1 was ideal for microbial growth in a biological filters, based on LeChevallier et al. (1991) and USEPA (1991), though this ratio was not specified in the latter document. In their study, biological filter influent water amendment with nutrients was investigated at warm water conditions only; the mean water temperature during their five month study was 26.0 ± 4.8°C (Lauderdale et al., 2011). The mean influent DOC concentration entering the pilot-scale biological filters was 3.6 ± 0.1 mg/L and a C:N:P ratio was developed based on the mean DOC concentration (0.4 mg/L) removed by a control pilot-scale filter; they also concluded that the system was not nitrogen limited because of this observed DOC removal (Lauderdale et al., 2012). Notably, the phosphorous dosage rate in that system was 100% greater than the target concentration that would be prescribed by a 100:10:1 ratio. Accordingly, while the work suggests that nutrient amendment may enhance certain aspects of biological filtration performance, the validity and optimality of a 100:10:1 ratio for biological filtration performance enhancement cannot be reasonably assessed based on Lauderdale et al., (2012, 2011).

Lauderdale et al. (2012) demonstrated a decrease in the terminal head loss during the last nine of 17 consecutive 18-hour filter runs with nutrient amendment in the influent (Figure 2.6). Specifically, there was an observable difference in the terminal head loss between the control and nutrient amended filters at the end of the 12th filter cycle. While no improvements in turbidity breakthrough were observed with the addition of nutrients in the filter influent, DOC removal increased from 0.4 mg/L to 0.7 mg/L (Lauderdale et al., 2012).

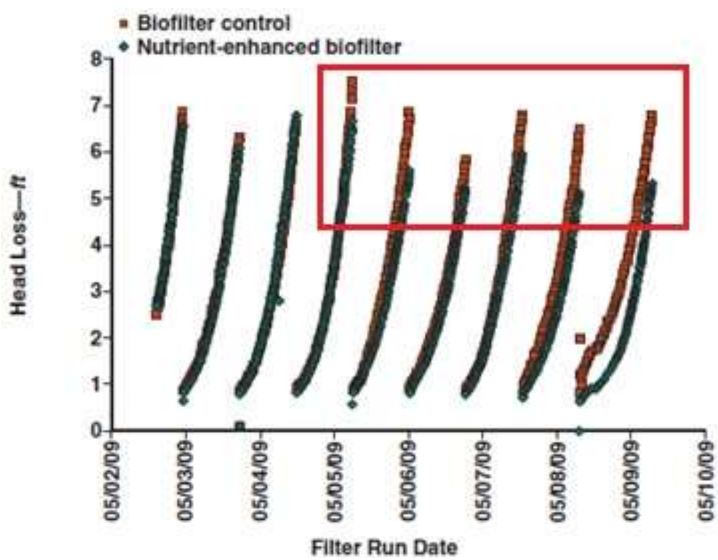

Figure 2.6: The last nine filter runs in a series of 17 with nutrient enhancement (Lauderdale et al., 2012). The red box highlights the observable difference in terminal head loss at the end of the 12th filter cycle and persisting for the remaining filter cycles.

The impact of nitrogen limitation on biological filtration performance was also investigated by Lauderdale et al. (2012), as demonstrated in Figure 2.7. Here, nitrogen was artificially limited by increasing the influent carbon concentration by dosing ethanol for a seven week period. The NH_4^+ concentration was then increased to achieve a stoichiometric C:N:P ratio of 100:10:2. Ethanol may not be representative of the actual carbon character of the filter effluent, since dissolved NOM in surface water is typically made up of a mixture of both simple and complex organic compounds, not limited to ethanol. However, a significant improvement in terminal head loss was observed when the nitrogen limitation, based on the prescribed ratio, was eliminated. This suggests that a nitrogen limitation may be as deleterious to the hydraulic performance of biological filters as a phosphorus limitation (Lauderdale et al., 2012).

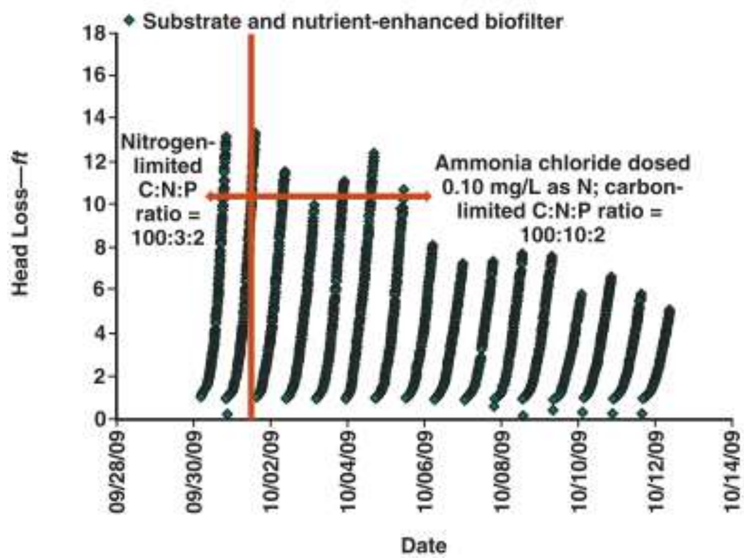

Figure 2.7: The effect of ammonium chloride supplementation on head loss development (Lauderdale et al., 2012)

Although it is widely accepted that the concentrations of carbon, nitrogen, and phosphorus are important to sustain microorganisms, the recommended relative concentrations of these macronutrients for the optimization of microbiological processes vary widely with scientific discipline and application. Generalized nutrient ratios should be regarded as rules of thumb, and not over-interpreted as ultimately prescriptive. Given this, it is not surprising that despite several pilot- and full-scale attempts, the biological filtration performance benefits reported by Lauderdale et al., (2012) have not been reproduced (Azzeh et al., 2015; McKie et al., 2015; Pharand, 2014; Vahala et al., 1998). Notably, the validity of the 100:10:1 ratio has not been investigated on a systematic basis and requires further exploration. Although reports suggest that nutrient amendment can enhance biological treatment performance (Chu et al., 2005; Fang et al., 2009; Lehtola et al., 2002; Thompson et al., 2006; Yu et al., 2003) and thus can be optimized, it is likely that the optimal relative macronutrient concentrations may vary by geography and environmental conditions, and may require experimentation on a site specific basis.

Chapter 3
Materials and Methods

3.1 Research Approach

To investigate the research needs identified above, biological filtration experiments were conducted at the Region of Waterloo's pilot-scale drinking water treatment plant, at the Mannheim Water Treatment Plant (MWTP) in Kitchener, Ontario, Canada. The overall goal of this research was to investigate the impact of capping media, nutrient addition, and their interaction on biological filtration performance. Filtration performance was evaluated by both biological and traditional filtration parameters. The pilot-scale study enabled filter operational parameters to be manipulated without affecting potable water production and quality from the full-scale plant.

3.2 Mannheim Water Treatment Plant

The MWTP utilizes a conventional chemically-assisted filtration process, and has a rated capacity of 72.6 MLD (Region of Waterloo, 2011). The raw water that feeds the MWTP comes from the Grand River and is stored in a four cell reservoir, with a capacity of 142 ML, before entering the plant (Walton, 2014). Once raw water enters the plant, it is split into two treatment trains and undergoes chemical coagulation, flocculation, settling, ozonation, and granular filtration, followed by UV irradiation and chloramination. Both treatment trains were operated and optimized in the same way. A simplified process flow diagram (PFD) of the MWTP is presented in Figure 3.1.

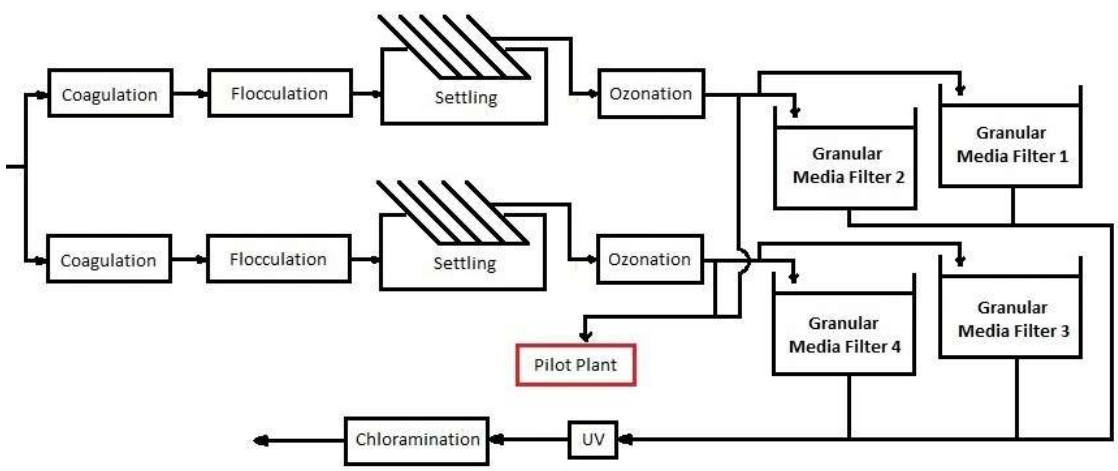

Figure 3.1: Process flow diagram of the MWTP

Poly-aluminum chloride (PACl) is the primary coagulant used at the MWTP. A polyelectrolyte (Catfloc LT-22S) is also added as a flocculant aid. All of the dual media, gravity-fed full-scale filters at the MWTP were upgraded with new underdrains and GAC media within the last two years; during the 2013-14 period. Each filter contained a 0.3 m layer of support sand overlain by approximately 1.3 m of GAC, yielding an overall media depth of 1.6 m. A summary of the full-scale filter configurations is presented in Table 3.1. Each of the full scale filters has a rated capacity of 756 m^3/h (3329 gpm), which corresponds to a hydraulic loading rate of 11.2 m/h (4.6 $gal/min \cdot ft^2$).

Table 3.1: Mannheim Water Treatment Plant full-scale filter configurations

	Filter 1	Filter 2	Filter 3	Filter 4
Media Type	GAC	GAC	GAC	GAC
Effective Size (mm) (d_{10})	1.3	1.3	1.3	1.3
Depth (m)	1.3	1.3	1.3	1.3
Upgrade Completion Date	April 2013	Nov. 2013	April 2014	Nov. 2014

3.3 Pilot Plant

The pilot plant enabled the investigation of different capping materials and nutrient addition rates without affecting full-scale operations at the MWTP. Experiments were conducted at both cold and warm water conditions to account for seasonal water quality and temperature effects. The pilot-scale filters received ozonated water (typical applied ozone dose of 1-6 mg/L) from the full-scale MWTP, as illustrated in Figure 3.1. Valves were installed on each of these lines to allow water from either treatment train 1 or 2 to enter the pilot plant, or to use water from both treatment trains simultaneously. The pilot plant was fed with water from both treatment trains simultaneously for the full duration of this project. Each of the filter columns was constructed from 8” Schedule 80 clear PVC pipe, with an overall height of approximately 4.2 m. A simplified schematic of the pilot plant is presented in Figure 3.2.

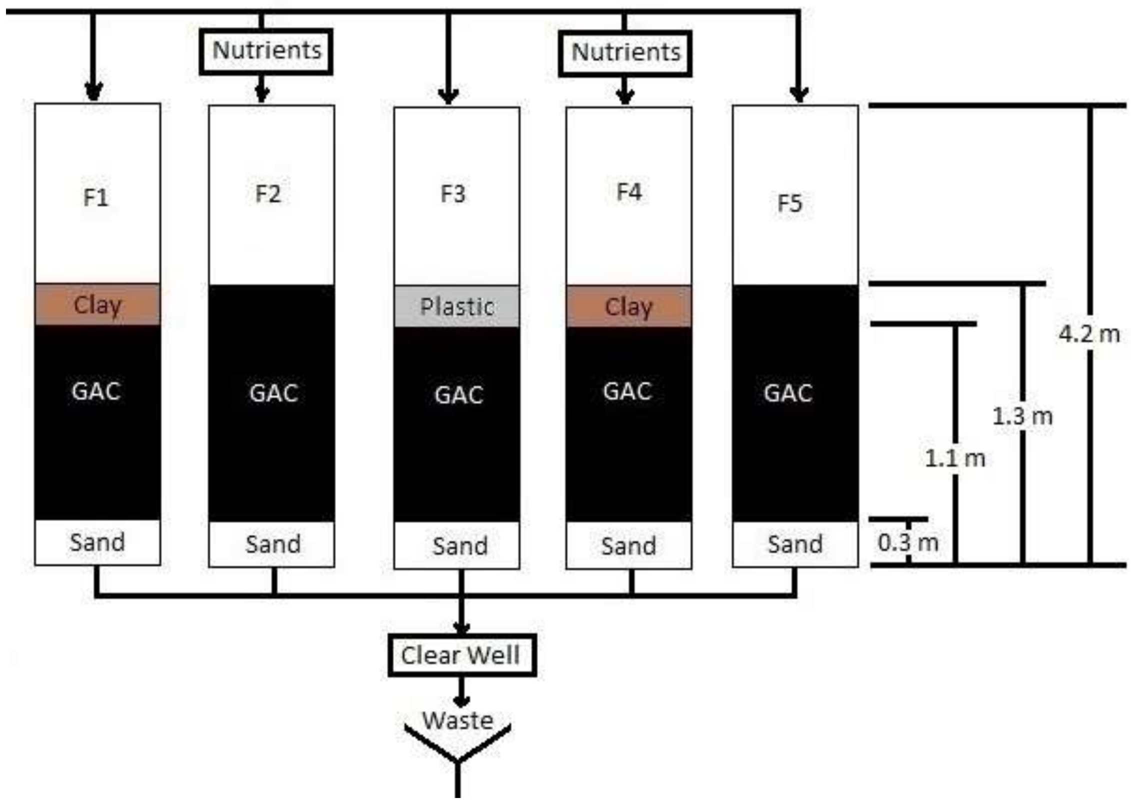

Figure 3.2: A simplified schematic of the Mannheim Water Treatment Plant pilot-scale filters (not to scale)

The effluent water from the pilot-scale filters flowed to a clear well reservoir where it was collected and used to backwash the filters. The water from the clear well reservoir was pumped to the plant's waste stream. Originally, the pilot plant consisted of four filter columns; Filter 5 was subsequently constructed. Accordingly, the clear well reservoir has four separate chambers for collecting the effluent from Filters 1, 2, 3, and 4. To minimize costs and conserve space, the effluent of Filter 5 was plumbed into the clear well chamber of Filter 1. Because each clear well chamber cannot hold enough water to backwash two filters, Filter 5 was operated while the other filters were backwashed.

3.3.1 Pilot Plant Equipment

Head loss, filter effluent turbidity, and filter effluent flow rate data were collected by an Allen-Bradley supervisory control and data acquisition (SCADA) system (Rockwell Automation, Inc., Milwaukee, WI). Differential pressure across each filter was measured using Foxboro IDP10-T differential pressure transmitters (Invensys Foxboro, Foxboro, MA). Filter effluent turbidity was measured using Hach sc100™ 1720E Low Range Turbidimeters (Hach Company, Loveland, CO).

The SCADA system was programmed to control the pilot-scale filter effluent flow rates using Chemline Q Series electric valve actuators (Chemline Inc., Cranford, NJ). ABB ProcessMaster FEP300 (ABB Inc., Zürich, Switzerland) electromagnetic flow meters reported flow rate data to the SCADA system. A Porter-Cable Pancake compressor (Pentair, Inc., Arden Hills, MN) was used to supply air to the filter columns during the backwash. The air flow rate for the backwash was controlled using a King Instruments 7530 Series acrylic tube flow meter (King Instruments Company, Garden Grove, CA). A Grundfos CRNI vertical multi-stage centrifugal pump (Grundfos Pumps Corp., Bjerringbro, Denmark) was used to backwash the filters. A Grundfos MQ3-45 pump (Grundfos Pumps Corp., Bjerringbro, Denmark) was used to pump the pilot-scale filter effluent from the clear well to MWTP's waste stream. An LMI P121-358TI solenoid diaphragm chemical metering pump (Flomotion Systems, Inc., Buffalo, NY) was plumbed into the wall of the Filters 2 and 4, 1.4 m above the filter media surface, and 1.2 m below the filter inlet.

3.3.2 Filter Configuration and Media Selection

A summary of the pilot plant filter configuration is presented in Table 3.2. The overall media depth of each pilot filter was 1.3 m. It was originally planned to have an overall media depth of 1.6 m to match the configuration of the full-scale filters at the MWTP; however, the valves used to drain the filters prior to backwashing are installed 1.5 m from the bottom of each filter column. To maximize the filter media depth and to allow for sufficient separation between the filter media surface and the drain valve, an overall media depth of 1.3 m was accordingly selected.

Table 3.2: Pilot plant filter configurations

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Capping Material	Filtralite®	N/A	BioFill®	Filtralite®	N/A
Capping Material depth (m)	0.2	N/A	0.2	0.2	N/A
Bulk Filter Medium	GAC	GAC	GAC	GAC	GAC
Bulk Filter Medium Depth (m)	0.8	1.0	0.8	0.8	1.0
Support Sand Depth (m)	0.3	0.3	0.3	0.3	0.3
Overall Media Depth (m)	1.3	1.3	1.3	1.3	1.3
Nutrient Dosing Pumps	No	Yes	No	Yes	No

The experiments were designed so that each pilot-scale filter would have the same EBCT. To achieve this while maintaining the same flow rate, the overall filter media depth in each filter must be the same. The amount of GAC that was installed in Filters 1, 3, and 4 was reduced to accommodate the layer of capping material and maintain the same EBCT in each filter. Reducing the amount of GAC and replacing it with a medium with a larger effective size and no adsorptive capacity reduces the available surface area for adsorption and biofilm attachment; however, using a medium with a larger grain size can help reduce the differential pressure across the filter—this relationship was a key question in this investigation. Given this hypothesis, it was recognized that capping material depth could be an important design parameter for the optimization of biological filtration performance; however, that optimization study was beyond the scope of the present proof-of-concept investigation.

Nutrient amendment was tested using only two of the three filter configurations (because the pilot system has only five filter columns). The fifth filter column served as a critical experimental control because it allowed performance reproducibility between filters to be evaluated, albeit to a limited extent. The duplicate filter was used to test the reproducibility of nutrient amendment impacts on a GAC filter because that configuration was most similar to the full-scale filters at the MWTP. The EC capped filter was duplicated, instead of the plastic capped filter, as this filter configuration would be more likely to be found in a municipal drinking water treatment application.

GAC was installed in each of the pilot-scale filter columns as the bulk, or main, filtration medium. During the pilot-scale investigations, GAC media from MWTP full-scale Filter 3 were utilized; specifically, FILTRASORB® 816 (Calgon Carbon Corporation, Pittsburgh, PA) with an effective size of 1.3 mm. Fairmount Minerals Best Sand silica sand (Fairmount Santrol, Chardon, OH), with an effective size of 0.79 mm, was installed at the bottom of each filter as the support medium. One of the capping materials was Filtralite® NC 1,5-2,5 (Saint-Gobain Weber, Oslo, Norway), with an effective size of 1.7 mm. Filtralite® products are crushed expanded clay designed for water and wastewater treatment applications. Expanded clay (EC) media are less brittle than GAC, but have no adsorptive capacity. This particular Filtralite® was selected due to its larger effective size, compared to the FILTRASORB® 816. Additionally, among the available EC products, this one had the largest effective size with the lowest density. Density was an important consideration for media selection as the larger the difference in density between the two media, the lower the probability of the layers of media mixing after a backwash. Initially, the GAC and Filtralite® media existed in the Filters 1 and 4 as two distinct layers; however, after approximately one month of operations, the EC and GAC media became somewhat intermixed.

The second capping material was the BioFill® CT plastic media (Biologìa y Filtraciòn (Bio-Fil), Barcelona, Spain) with a diameter of 2.5 cm. This plastic medium is made by injection molding using a mixture of polypropylene and polyethylene. It is less dense than the GAC, but has a specific gravity greater than one allowing it to settle in water. This type of plastic medium is typically used in wastewater applications for trickling filters, fixed bed bioreactors, and moving bed biofilm reactors. While its use in a rapid granular filter is unconventional, the plastic medium was selected to test an extreme capping medium size.

All of the media described above were hydraulically loaded into each filter column according to ANSI/AWWA standards B100 and B604 (AWWA Standard, 2002), however, the scraping step was omitted. The GAC medium that was collected from full-scale Filter 3, which was fully wetted, was installed in the pilot-scale filter columns on the same day. The other media were soaked in water for several days to become saturated before being hydraulically loaded into the appropriate filter column. Any grains of media that were not fully saturated were discarded before installation.

Figure 3.3: Filtrasorb® 816 granular activated carbon

Figure 3.4: Filtralite® NC 1,5-2,5 crushed expanded clay

Figure 3.5: BioFill® CT plastic media

3.3.3 Pilot Filter Backwash

The pilot plant filters were manually backwashed every three days. The period between filter backwashes was selected to allow enough time for the filters to reach the end of their filter cycle based on head loss, as well as being near the maximum number of days of data that could be collected by the SCADA system before overwriting itself. To maintain pilot-scale filter operation, each filter was subjected to a collapsed pulse (CP) backwash, followed by a settling period and a high rate wash to expand the filter bed by 30%. The CP backwash was selected, as it is understood to achieve the greatest extent of particle removal by maximizing inter-particle scouring (Amirtharajah, 1993). Because the pilot filter columns are constructed from clear PVC pipe, it was possible to observe each backwash. The CP backwash parameters were calculated according to Amirtharajah (1993), and then visually optimized by adjusting the water and air flow rates. The CP water and air flow rates were kept the same for each filter. A summary of the backwash parameters is presented in
Table 3.3.

Table 3.3: Pilot filter backwash parameters

	Warm Water Conditions			**Cold Water Conditions**		
Parameter	Water (m/h)	Air (scfm/ft^2)	Duration (min)	Water (m/h)	Air (scfm/ft^2)	Duration (min)
Collapsed Pulse Backwash	14.6	252	6	13.8	252	6
Media Settling	0	0	2	0	0	2
High Rate Backwash	50.8	0	8	46.8	0	8
Filter 3 ETSW	25.4	0	16	13.4	0	16

The CP backwash was carried out until the water level reached approximately 30 cm below the filter influent, which occurred after six minutes. After the CP backwash was complete, the media were allowed to settle before the high rate wash. The time required for the media to settle was based on visual inspection. The duration of the high rate wash was also based on visual inspection; the high rate wash was terminated when the backwash water leaving the filter was clear. Turbidimeters were not installed on the backwash waste stream. As the project progressed, it was observed that the plastic media in Filter 3 would sink into the GAC during the high rate wash. To mitigate the intermixing of media, an extended terminal subfluidization wash (ETSW) was used instead of a high rate wash. After the CP backwash and settling period, the media in Filter 3 were expanded to 30% to allow the filter bed to stratify. Once the media stratified into its layers, the velocity was reduced by half. To keep the backwashes of all the pilot filters as similar as possible, the number of bed volumes used in the high rate backwash and ETSW was kept the same by doubling the duration of the ETSW.

As temperature decreases, the density of water increases reaching its maximum at 4°C. To account for this change in density, the velocity of the water required during both the CP and high rate backwashes were decreased at cold water conditions. The duration of the backwashes was kept constant at all water temperature conditions.

3.3.4 Operating Conditions

Pilot plant monitoring operations began on 5 August 2013 and ended 21 September 2014. During this period, the temperature fluctuated between 0.5°C and 26.5°C. The length of the monitoring period enabled the assessment of seasonal changes in water temperature and quality. A summary of pilot plant influent water quality during the study period is presented in
Table 3.4.

Table 3.4: Pilot plant influent water conditions across all observed temperature ranges

Parameter	**T < 5°C**	**5°C ≥ T < 15°C**	**T ≥ 15°C**
Loading Rate, m/h	8.5	8.5	8.5 and 2.6
Water Temperature, °C	Mean: 1.5 Range: 0.5-4.5	Mean: 9.2 Range: 5.6-14.5	Mean: 20.8 Range: 15.4-26.5
Influent DOC, mg/L	Mean: 3.364 Range: 2.476-4.123	Mean: 3.886 Range: 2.532-4.907	Mean: 4.018 Range: 3.420-5.330
pH	Mean: 7.63 Range: 7.27-8.07	Mean: 7.71 Range: 7.45-7.95	Mean: 7.54 Range: 7.35-7.73
Total Ammonia (NH_3-N), mg/L	Mean: 0.377 Range: 0.082-0.461	Mean: 0.094 Range: 0.062-0.144	Mean: 0.034 Range: 0.008-0.095
Soluble Reactive Phosphorus (SRP), mg/L	Mean: 0.0030 Range: 0.0010-0.0057	Mean: 0.0053 Range: 0.0039-0.0074	Mean: 0.0036 Range: 0.0011-0.0054
Total Phosphorus (TP), mg/L	Mean: 0.0102 Range: 0.0013-0.0193	Mean: 0.0050 Range: 0.0016-0.0092	Mean: 0.0011 Range: 0-0.0088

3.4 Experimental Design

The pilot plant experiments were designed to assess the impacts of capping material selection and nutrient amendments on both traditional and biological filtration parameters. The configuration of the pilot scale filters allowed for continuous monitoring of traditional filtration performance parameters including effluent turbidity, flow rate, and differential pressure. From the start of pilot plant operations on 5 August 2013 until 3 January 2014, operational data were collected from Filters 1, 2, 3, and 4 but not Filter 5, because it was not connected to the SCADA system. Filters 1-4 were connected to the SCADA system and were operated on a constant flow rate declining head mode, while Filter 5 was operated in a constant head declining flow rate mode (and thus only provided limited replication information initially). On 3 January 2014, Filter 5 was connected to the SCADA system for data collection and operated in the same fashion as the other filters.

Traditional filtration performance parameters including effluent turbidity, head loss, and flow rate were used to determine the run time of each pilot-scale filter. For each sampling event, grab samples were collected from the influent and effluent of each pilot-scale filter. Samples were collected at these locations to assess the impact of capping material selection and nutrient amendments on the removal of carbon, nitrogen, and phosphorus. The concentrations of these elements were evaluated as total organic carbon (TOC), dissolved organic carbon (DOC), ammonia-nitrogen (NH_3-N), total phosphorus (TP), and soluble reactive phosphorus (SRP).

Nutrient amendment experiments were conducted at both cold and warm water conditions. The molar carbon, nitrogen, and phosphorus (C:N:P) ratio was adjusted to 100:10:1 and 100:20:2 by dosing a solution of ammonia and phosphate directly into Filters 2 and 4, at both target influent nutrient ratios. A 99.5% reagent grade granular ammonium chloride (NH_4Cl) (EMD Chemicals, Billerica, MA) was used for ammonia supplementation. A ≥85% reagent grade phosphoric acid (Sigma-Aldrich Company, St. Louis, MO) was used for the phosphate supplementation. Lauderdale et al. (2012) conducted their nutrient enhancement experiments for 17 consecutive filter runs each lasting 18 hours. On the 12th day of experiments, there was an observed decrease in the differential pressure across the nutrient enhanced filter compared to the control. To ensure that signs of performance enhancement were not missed during the nutrient amendment experiments, each experiment herein was conducted for approximately 30-40 consecutive days.

In determining the appropriate nutrient dosage rates for their nutrient enhancement experiments, Lauderdale et al. (2012) amended filter influent nutrient concentrations based on the mean DOC that was removed by their control biological pilot-scale filters. Using the mean DOC removed by the control biological filters, instead of the total influent DOC, inherently assumes that only the mean amount of DOC removed (0.4 mg/L in the case of Lauderdale et al. (2012)) is biodegradable. Any observed changes in the DOC removed with the addition of nutrients would affect the effective C:N:P ratio. Based on a stoichiometric C:N:P ratio of 100:10:1 and a mean DOC removal of 0.4 mg/L, concentrations of 0.047 mg NH_3-N/L and 0.010 mg PO_4-P/L were required. Lauderdale et al. (2012) conducted their phosphorus enhancement experiments by doubling their PO_4-P dosage to 0.020 mg/L. This was done to "provide consistent delivery and overcome PO_4-P adsorption to aluminum hydroxide [precipitate] carryover." Conducting the nutrient enhancement experiments in this manner confounded their observations and precluded clear identification of a causal relationship; thus, the validity and applicability of the 100:10:1 C:N:P ratio was not evaluated in their experiments.

In the present investigation, the nitrogen and phosphorus dosage rates for the nutrient amendment experiments at the stoichiometric C:N:P ratios of 100:10:1 and 100:20:2 were based upon the pilot plant's total influent DOC concentration. This approach enabled mechanistic conclusions regarding nutrient ratios and uptake during biological filtration. Water samples were collected just above the filter media surface, and were analyzed for both NH_3-N and SRP to confirm that 1) the nutrient solution was formulated correctly and 2) the nutrient dosing pumps were operating properly, during the nutrient amendment experiments.

3.4.1 Filter Run Time

The start of a filter cycle occurs at the point when the effluent turbidity falls below 0.2 NTU and stabilizes, signifying the end of filter ripening. The end of the filter cycle was based on one of the following criteria being met for a period of ten consecutive minutes: the flow rate was <4 L/min, the differential pressure across the filter was ≥120 inches of water, or the filter effluent turbidity was ≥0.2 NTU. The end of the filter cycle could have also occurred after 60-72 hours when the filters were backwashed. This final criterion introduces a limitation to this investigation, as it could have led to underestimations of (maximum achievable) filter run time. Notably, at "optimal" conditions the full-scale filters at the MWTP can be operated up to 75 hours before a backwash is required. Of course, it is also common practice that filters operated at water and wastewater treatment plants are backwashed after a specified period of time for operational ease, even if backwash triggers based on flow rate, head loss, or effluent turbidity are not met.

3.4.2 Total and Dissolved Organic Carbon

Water samples from the pilot plant were collected in 1 L amber glass bottles that were prepared according to Standard Methods (APHA et al., 1998). Bottles were washed, submerged in 10% hydrochloric (HCl) acid bath for at least one day, triple rinsed with ultra-pure water, and dried.

Bottles were rinsed three times with sample water prior to sample collection. Samples were acidified to pH 2 with reagent grade concentrated HCl acid (Sigma-Aldrich Company, St. Louis, MO). Samples were filtered with a 0.45 µm nylon ZapCap® filter (Maine Manufacturing, Sanford, ME) for DOC analysis. The ZapCap® filters were rinsed with 750 mL of ultrapure water to prevent DOC contamination of the filtered samples. Samples utilized for TOC analysis were not filtered. The samples were stored at 4°C when not being analyzed.

The carbon content of the TOC and DOC samples was analyzed using a Shimadzu TOC-Vcph total organic carbon analyzer with the Shimadzu ASI-V auto sampler (Shimadzu Scientific Instruments, Inc., Kyoto, Japan). This instrument employs combustion catalytic oxidation. The NPOC method was used to measure the organic carbon content in the samples (Method 5310 D; APHA et al., 2012). The method detection limit (MDL) for both DOC and TOC was 0.1 mg C/L.

DOC removal was one of the parameters used to assess biological filtration performance. The amount of DOC removed was calculated by subtracting the concentration of DOC measured in the filter effluent from the concentration of DOC measured in the influent sample. DOC was chosen as a monitoring parameter as it is a nutrient for microorganisms, as well as a key design parameter for coagulation and disinfection processes(Crittenden et al., 2012b).

3.4.3 Ammonia-Nitrogen

There are a variety of forms of nitrogen available for uptake by microorganisms, including: ammonia (NH_3-N), nitrate (NO_3-N), nitrite (NO_2-N), nitrogen gas ($N_{2\ (g)}$), and organic nitrogen. Heterotrophic bacteria most readily utilize NH_3-N (Ebeling et al., 2006), however.

NH_3-N was measured in grab samples collected from the pilot plant in the prepared 1 L amber glass bottles. Samples that could not be measured immediately were preserved with reagent grade 95-98% sulfuric acid (Sigma-Aldrich Company, St. Louis, MO) to a pH 2, and kept at 4°C. NH_3-N was measured using an Orion™ high performance ion-selective electrode (Thermo Fischer Scientific Inc., Waltham, MA). The electrode uses a hydrophobic gas-permeable membrane that allows $NH_{3\ (aq)}$ to diffuse through it (Method 4500-NH_3 D; APHA et al., 2012). The MDL was 0.01 mg NH_3-N/L. All of the dissolved ammonia ($NH_{3\ (aq)}$ and NH_4^+) is converted to $NH_{3\ (aq)}$ with the addition of a strong base to adjust the pH to above 11. A 10 N sodium hydroxide (NaOH) solution, made with reagent grade granular NaOH (EMD Chemicals, Billerica, MA), was used to raise the pH of the sample.

3.4.4 pH

The pH of grab samples from the pilot plant was measured using an Orion™ economy series pH electrode (Method 4500-H^+, APHA et al., 2012).

3.4.5 Total Phosphorus (TP)

To measure TP, grab samples were collected from the pilot plant in prepared 1 L amber glass bottles. The samples were acidified with reagent grade concentrated sulfuric acid to a pH of 2, and kept at 4°C. The samples underwent an acid hydrolysis digestion. The persulfate digestion method, described in Standard Methods (Method 4500-P D; APHA et al., 2012) was used. The MDL was 3 µg P/L. The resulting sample was filtered using Whatman™ 0.45 µm Puradisc nylon membrane syringe filters (General Electric, Fairfield, CT). The syringe filters were not rinsed before filtering samples. The filtered samples were analyzed using the stannous chloride method as outlined in Standard Methods (APHA Method 4500-P D, 2012). All samples were analyzed colorimetrically using a Technicon AutoAnalyzer II colorimeter (Technicon Instruments Corp., Tarrytown, NY). The wash/carrier liquid used for the AutoAnalyzer was a 0.2% H_2SO_4 solution.

3.4.6 Soluble Reactive Phosphorus (SRP)

SRP is the most microbiologically accessible form of phosphorus(Guhathakurta et al., 2007). Grab samples were collected from the pilot plant in prepared 1 L amber glass bottles. The samples underwent filtration using Whatman™ 0.45 µm Puradisc nylon membrane syringe filters (General Electric, Fairfield, CT), and were stored at 4°C.The syringe filters were not rinsed before filtering samples. The filtered samples were analyzed using the stannous chloride method as outlined in Standard Methods (Method 4500-P D; APHA et al., 2012). The MDL was 3 µg P/L. All samples were analyzed colorimetrically using a Technicon AutoAnalyzer II Colorimeter (Technicon Instruments Corp., Tarrytown, NY). Type I water was used as wash/carrier liquid for the AutoAnalyzer.

3.4.7 Total Suspended Solids (TSS)

TSS measurements are most commonly used in wastewater treatment facilities to assess the performance of a various physical unit operations, and biochemical processes. To aid in identifying the source of solids above the filter, a sample of material that accumulated within the plastic media in pilot-scale Filter 3 was collected for TSS analysis according to Standard Method (Method 2540 B; APHA et al., 2012).

3.4.8 Aluminum

To aid in identifying the source of solids above the filter, the aluminum content of the material accumulated within the BioFill® plastic media in pilot-scale Filter 3 was measured. Hach Method 8012 was used (Hach Company, 2014), which was adapted from Standard Methods (Method 3500-Al B; APHA et al., 2012). The MDL was 0.01 mg Al^{3+}/L. The sample was mixed thoroughly and then diluted before analysis.

3.5 Statistical Analyses

Filter performance was assessed by the parameters described above. The differences in the performance parameters between the pilot-scale filters were assessed quantitatively to determine if there were any differences in filter performance. They were evaluated statistically by hypothesis testing using an analysis of variance (ANOVA) and a paired t-test. A 5% significance level was considered statistically indicative of significant effects. The test statistic used in the ANOVA is the F-test, which is used to quantitatively compare the variances of two data sets ($\alpha = 0.0500$). The paired two-tailed t-test was used to quantitatively compare the means of the data sets collected ($\alpha = 0.0250$). The equations used in the ANOVA and t-test analyses are detailed in Appendix C.

Some data points were omitted from the statistical analyses of both operational and nutrient data sets. Operational data, such as effluent turbidity, flow rate, or head loss, were omitted from analyses when the pilot plant encountered certain operational issues. These issues included: full-scale plant shut downs for maintenance, unbalanced influent flow rate to the pilot filters, and breaks in communication between instruments and SCADA system. Nutrient data were omitted from statistical analyses when clear signs of contamination were identified, or when sample bottles were broken during transport.

Chapter 4
Traditional Filter Performance Results

4.1 Overview

The MWTP pilot-scale filters were configured to evaluate the effect of replacing the top layer of granular media in a filter with a capping material with a larger effective size, as well as amending the influent stoichiometric nutrient ratio, on both traditional and biological filtration performance during drinking water treatment. This chapter examines the impact the capping materials and nutrient amendments had on the traditional filter performance parameters, including: filter effluent turbidity, rate of head loss accumulation, and filter run time.

The pilot-scale filters were operated from 8 August 2013 until 21 September 2014 to account for any seasonal effects in operation. The data were analyzed across three water temperature ranges: less than 5°C (cold), greater than or equal to 5°C and less than 15°C (transitional), and greater than or equal to 15°C (warm). The pilot-scale filters were operated at cold water conditions from 22 November 2013 until 18 April 2014. The influent water of pilot-scale Filters 2 and 4 was nutrient-amended to an influent stoichiometric carbon, nitrogen, and phosphorus (C:N:P) ratio of 100:10:1 and 100:20:2 from 8 February 2014 to 16 March 2014 and 16 March to 18 April 2014, respectively. The pilot-scale filters were operated within the transitional temperature range from 17 October 2013 until 22 November 2013, and from 15 April 2014 until 9 May 2014. Both periods of transitional temperature operation lasted for approximately one month with the temperature steadily decreasing and increasing, respectively. Nutrient amendment was not investigated during these periods because their relatively short duration precluded the filters from reaching pseudo-steady state conditions (e.g., head loss accumulation, turbidity removal, BOM removal). The pilot-scale filters were operated at warm water conditions from 5 August 2013 until 17 October 2013, and from 9 May 2014 until 21 September 2014. The influent water of pilot-scale Filters 2 and 4 was nutrient-amended to a stoichiometric C:N:P ratio of 100:10:1 and then 100:20:2, from 5 July 2014 to 16 August 2014 and 16 August 2014 to 21 September 2014, respectively. During the nutrient amendment experiments, the relative stoichiometric nitrogen and phosphorus concentrations were adjusted with respect to the influent DOC concentration. No operational data were collected for pilot Filter 5 from 8 August 2013 until 3 January 2014 because its connection to the SCADA system was not available until 3 January 2014.

Table 4.1: Traditional filter performance data (mean ± standard deviation) at cold and transitional water temperatures with and without nutrient amendments

	Cold Water Conditions							Transition Temperature Range		
	No Nutrients Added			100:10:1		100:20:2		No Nutrients Added		
	GAC	EC Capped	Plastic Capped	GAC	EC Capped	GAC	EC Capped	GAC	EC Capped	Plastic Capped
Temperature (°C)	1.5 ± 0.8			1.4 ± 0.4		1.6 ± 1.0		9.2 ± 2.1		
Number of Filter Cycles	55	63	43	12	12	10	10	27	37	19
Filter Run Time (h)	47 ± 18	49 ± 18	48± 21	54 ± 19	52 ± 20	62 ± 10	60 ± 11	51 ± 19	53 ± 18	52 ± 18
Rate of Head Loss Accumulation (in H_2O/day)	44 ± 10	37 ± 6	29 ± 5	32 ± 4	28 ± 4	38 ± 4	29 ± 5	40 ± 15	32 ± 9	22 ± 6

Table 4.2: Traditional filter performance data (mean ± standard deviation) at warm water temperatures with and without nutrient amendments

	Warm Water Conditions						
	No Nutrients Added			100:10:1		100:20:2	
	GAC	EC Capped	Plastic Capped	GAC	EC Capped	GAC	GAC
Temperature (°C)	20.7 ± 2.6			22.2 ± 0.9		20.9 ± 2.2	
Number of Filter Cycles	76	99	61	14	14	11	11
Filter Run Time (h)	34 ± 12	44 ± 20	56 ± 17	35 ± 6	52 ± 11	35 ± 7	52 ± 8
Rate of Head Loss Accumulation (in H_2O/day)	73 ± 13	54 ± 10	37 ± 7	85± 11	59 ± 6	83 ± 9	57 ± 7

4.2 Filter Effluent Turbidity

Turbidity is an aggregate measure of light scattering, and is a key parameter for assessing water quality and designing water treatment processes. It is often used at critical control points in determining whether process units within water treatment plants are operating adequately. Additionally, effluent turbidity limits are often used as a process control criterion to determine if filters require backwashing. Detailed turbidity data obtained during the course of this project are provided in Appendix A.

4.2.1 Cold Temperature Range (T < 5°C)

At cold water conditions, the pilot filters were able to consistently achieve excellent (≤0.1 NTU) effluent turbidities after filter ripening. As temperature decreased below 5°C, the effluent turbidities from each pilot filter did not substantially fluctuate. Representative trends in filter effluent performance when T <5°C during the period from 25-28 November 2013 are presented in Figure 4.1.

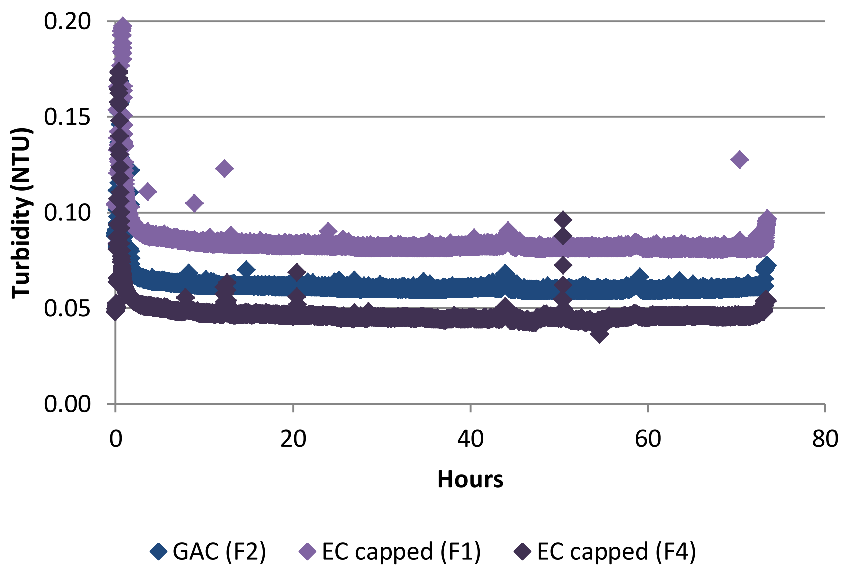

Figure 4.1: Representative pilot plant effluent turbidity at cold water conditions (mean temperature = 3.5°C) from 25-28 November 2013

Excellent filter effluent turbidities (≤0.1 NTU) still were achieved as water temperature further decreased to approximately 1°C; however, there were more fluctuations in the individual effluent turbidities. Moreover, a rapid increase in the effluent turbidity 20-50 hours after filter ripening was initially observed (i.e., during the first several filter cycles) for all filter configurations, as presented in Figure 4.2.

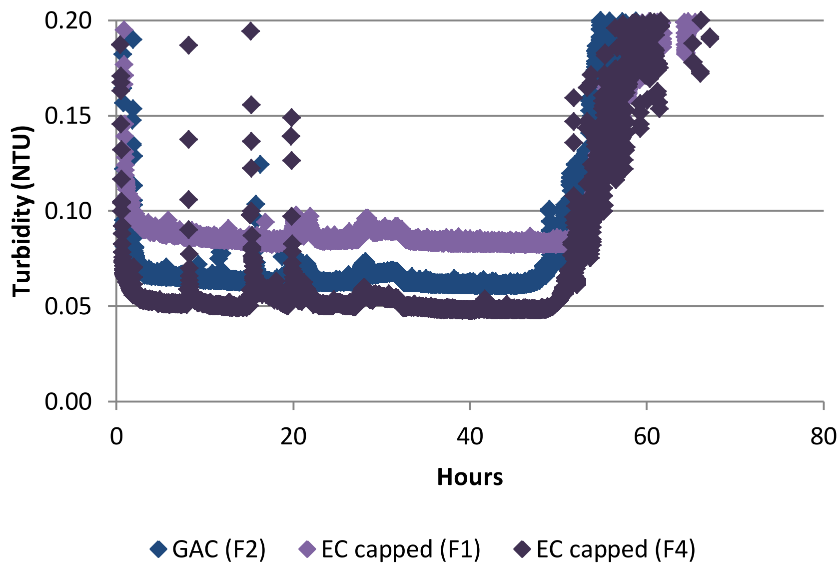

Figure 4.2: Representative pilot plant effluent turbidity data at cold water conditions (mean temperature = 1.5°C) from 1-4 December 2013. This figure demonstrates the rapid increased in effluent turbidity that was observed during the latter part of a filter cycle for all pilot filters.

As pilot plant operations continued at temperatures ≤1°C, the fluctuations in filter effluent turbidity and the rapid increase in the effluent turbidity in the latter part of the filter cycle subsided in each filter. The rapid increase in the effluent turbidity of the pilot-scale filters, presented in Figure 4.2, did not subside until the middle of February 2014 (i.e., after approximately 19 filter cycles), but when it did, filter effluent turbidity trends were similar to those presented in Figure 4.1.The small turbidity spikes that were observed in all turbidity data sets, in Figure 4.2 approximately 10, 15 and 20 hours, typically coincided with the closing of the full-scale filter isolation valves for backwashing.

Overall, the pilot-scale filters behaved similarly to one another at any given operational condition. Notably, when the trends in filter effluent water quality changed, they were observed for each filter; all of the filters demonstrated fluctuations and a rapid increase in the effluent turbidity on the same day (1 December 2013). Additionally, subsequent improvements in effluent turbidity performance during the latter part of the filter cycle also occurred on the same day (23 February 2014) for each of the filters.

The cause of the fluctuations in performance and the rapid increase in the effluent turbidity during the latter part of the filter cycles is unknown. It may have been temperature dependent, as it is commonly recognized that coagulation efficiency is temperature dependent—the optimum pH for coagulation increases with decreasing temperature (Maulding and Harris, 1968). As temperature changes, jar testing is required to optimize coagulant dose. Additionally, as the temperature decreases the density of water increases, which slows the rate of the settling of flocs during clarification (Camp et al., 1940). This will lead to material carryover from the clarification process onto the downstream filters increasing the probability of breakthrough. Further, turbidity removal by filtration is often diminished at lower temperatures due to the reduction in floc strength, or mean particle size (AWWA, 2011). It is possible that any or several of these factors contributed to the observations described above in Figures 4.1 and 4.2.

At lower temperatures, microbial activity decreases and response to environmental changes may be slower. Preliminary work by Spanjers and Emelko (2012) suggests that biomass and retained particles may contribute positively towards turbidity dampening. The decreased rate of biological activity reduces the amount of biomass that could be produced after a backwash, decreasing a filter's capacity for turbidity removal. Accordingly, the observed recovery in filter effluent turbidity performance of each filter also could have been the result of attached microorganisms within the filter becoming acclimated to the cold water conditions.

4.2.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1

When nutrient amendment to a stoichiometric C:N:P ratio of 100:10:1 in the influent stream of Filters 2 (GAC) and 4 (EC capped) commenced, excellent (≤0.1 NTU) filter effluent turbidities were achieved during the first 20 to 40 hours after filter ripening; however, filter effluent turbidity in all of the pilot-scale filter increased rapidly thereafter; notably, this type of performance was also observed in identical filters without nutrient amendment. An example of this performance is presented in Figure 4.3, in which filter effluent turbidity data from 8-11 February 2014 are presented.

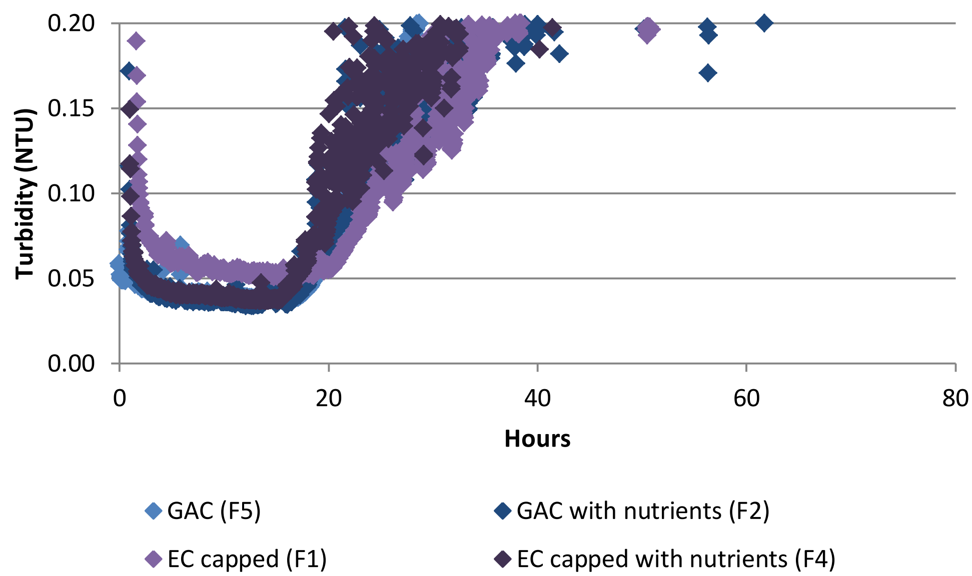

Figure 4.3: Pilot plant effluent turbidity at cold water conditions (mean temperature = 1.0°C) from 8-11 February 2014 with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrates rapid increases in filter effluent turbidity in all of the pilot-scale filters after approximately 20-40 hours of filter operation during the first 3 filter cycles after nutrient amendment began, and subsided thereafter.

As nutrient amendment in the influent of Filters 2 and 4 continued, the effluent turbidity performance improved and the rapid increase in effluent turbidity subsided (after approximately 3 filter cycles). Notably, the effluent turbidity performance of the non-nutrient amended filters also improved at the same time; the effluent turbidity performance with and without nutrient addition were not different. Accordingly, amending the influent nutrient C:N:P ratio to 100:10:1 to either the GAC or EC capped filters did not provide any advantages in effluent turbidity performance or mitigation of the rapid increases in filter effluent turbidity observed at the start of the 100:10:1 nutrient enhancement experiment at cold water conditions.

4.2.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2

The effluent turbidity of Filters 2, 4, and 5 increased rapidly, approximately 50 hours after filter ripening, when the nutrient dosage in the influent streams of Filters 2 and 4 was increased to a ratio of 100:20:2. In contrast, the effluent turbidity of Filter 1 remained stable (Figure 4.4; data from 25-28 March 2014). During this period of approximately 50 hours, excellent (≤ 0.1 NTU) effluent turbidities were achieved by each filter.

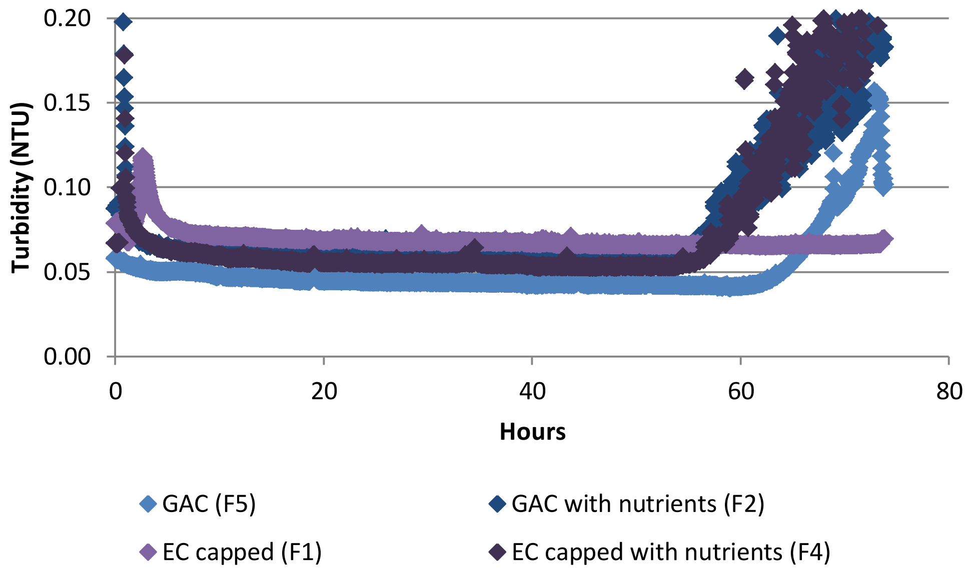

Figure 4.4: Pilot plant effluent turbidity at cold water conditions (mean temperature = 1.4°C) from 25-28 March 2014 with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrate the rapid increase in effluent turbidity during the latter part of the filter cycle that was observed by all but the EC capped pilot filter without nutrient amendment.

The effluent turbidity trends of Filters 2, 4 and 5 improved (after 6 filter cycles) as the nutrient dosing experiment continued, and the rapid increase in effluent turbidity subsided in all of the filters, with or without nutrient addition. Like with the previous experiment, nutrient addition (this time at a C:N:P ratio of 100:20:2) to Filters 2 and 4 did not provide any advantages in mitigating the rapid increase in effluent turbidity observed at the start of the nutrient enhancement experiment at cold water conditions. Notably, Filter 1, which contained the 20 cm layer EC cap, initially outperformed all of the other filter configurations, regardless of nutrient addition.

4.2.4 Transitional Temperature Range (5°C ≤ T < 15°C)

The pilot filters were still able to achieve excellent (≤ 0.1 NTU) effluent turbidities after filter ripening during the period when water temperature decreased from 15°C to 5°C, at the start of Winter 2013. From 23 October 2013 to 8 November 2013, water temperature was between 8.9°C and 12.1°C and filter effluent turbidity increased during the latter part of the filter cycle in each of the pilot scale filters, in a manner similar to the trends presented in Figure 4.2. Notably, at temperatures above and below this range, filter effluent turbidities were stable for the full duration of the filter cycle, consistent with the trends presented in Figure 4.1. Although excellent filter effluent turbidities ≤0.1 NTU were observed after ripening, rapid increases in effluent turbidity during the latter part of the filter cycle were observed again from all of the filters during the period of 5-9 May 2014, when water temperature increased from 9.9°C to 12.5°C. Accordingly, these observations collectively suggest that temperatures between ~8°C and 13°C may represent a critical operational period for biological filtration during which microorganisms within the filters begin to acclimate, or shift their behaviour in response to water temperature shifts from cold to warm, and *vice versa*. It is commonly recognized that there is a temperature transition zone for biological filtration performance that is not well understood (Huck et al., 2000). The recovery in performance of the filters as the temperature stabilized suggests microorganism acclimation to the new environmental conditions.

4.2.5 Warm Temperature Range (≥ 15°C)

The pilot-scale filters were able to achieve excellent (≤ 0.1 NTU) effluent turbidities after filter ripening at warm water conditions (Figure 4.1). During this period of warm water operations (8-17 September 2013), a rapid increase in the effluent turbidity 24-40 hours after filter ripening was consistently observed from each pilot-scale filter over three consecutive filter cycles. No operational changes or changes in temperature occurred during that period, and could not explain the ephemeral, but significant change in filter effluent turbidity performance during that period of time. This filter performance was similar to the rapid increases in effluent turbidity that were observed 12-40 hours after filter ripening from all of the pilot filters after 9 May 2014, during the transitional water temperature period. During the present operational period, the effluent turbidity of some filters did not improve to below 0.2 NTU, thus resulting in filter run times of zero hours (e.g., Filter 4 in Figure 4.5). As warm water operations continued, however, the effluent turbidities of all of the pilot scale filters did improve after ripening and stabilized below 0.2 NTU for the duration of the filter cycle.

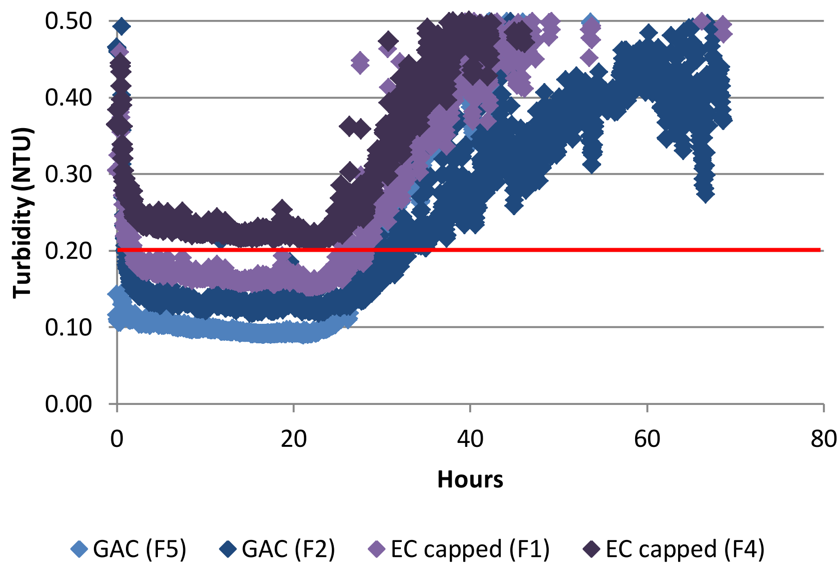

Figure 4.5: Pilot plant effluent turbidity data at warm water conditions (mean temperature = 16.9°C) from 12-15 May 2014. The red line illustrates the effluent turbidity operational cut-off of 0.2 NTU. This figure demonstrates an example of when a pilot filter had a filter run time of zero hours due to its inability to reach a stable turbidity below 0.2 NTU.

Notably, filter effluent turbidity performance improved in each of the filters on the same day (17 June 2014), approximately 38 days after the start of warm water operations. The temperature increased steadily during this period, rising from 15.8°C on 12 May 2014 to ~21°C on 2 June 2014 when it stabilized. Biomass attached to the filtration media were likely acclimating to the increase in temperature during this period; the data suggest the biomass in each of the filters generally acclimated at the same rate. The concurrent rapid turbidity breakthrough observed at the end of the filter cycles may have been biomass associated; however, it also could have been the result of a shift in the coagulation efficiency and associated particle destabilization or change in source water NOM associated with increasing temperature (Maulding and Harris, 1968).

4.2.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1

Filter effluent turbidity trends remained consistent during the course of the 100:10:1 nutrient dosing experiments at warm water conditions—all filters were able to achieve excellent (≤0.1 NTU) effluent turbidities. Increased variability in the effluent turbidity was observed near the end of the filter cycles of Filters 4 and 5 (EC capped with nutrient amendment and GAC control, respectively); however, the turbidity alarm level of 0.2 NTU was not exceeded (Figure 4.6). Accordingly, nutrient addition at a

C:N:P ratio of 100:10:1 (Filters 2 and 4) did not enhance filter effluent turbidity performance at warm water conditions. Rather, filter effluent turbidities in these filters were slightly higher than in filters without nutrient addition; this performance is consistent with previous studies that have suggested slightly higher turbidity and passage of heterotrophic bacteria from biological filters (Emelko et al., 2006; Huck et al., 1998).

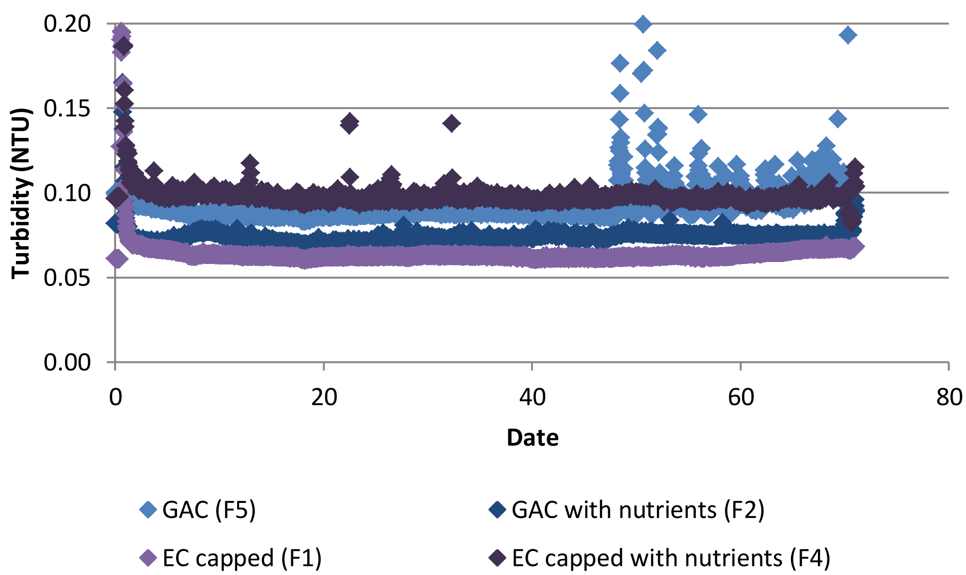

Figure 4.6: Pilot plant effluent turbidity at warm water conditions (mean temperature = 23.1°C) from 26-29 July 2014 with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1

4.2.7 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:20:2

Filter effluent turbidities between and within individual filters also remained consistent throughout the course of the 100:20:2 nutrient dosing experiments, during which excellent (≤0.1 NTU) turbidity removal performance was achieved and maintained by each filter during stable filter operation. Notably, the effluent turbidity from each filter increased rapidly 50-60 hours after filter ripening during the period of 28 August 2014 until 9 September 2014, similar to the trends presented in Figure 4.2. Thus, nutrient addition at a C:N:P ratio of 100:20:2 (Filters 2 and 4) did not enhance filter effluent turbidity removal at warm water conditions nor did it help to mitigate the rapid increase in effluent turbidity observed at the start of this experimental period.

4.3 Head Loss Accumulation

Head loss, or differential pressure, is a measure of the resistance of an element within a pipe run against fluid flow. Head loss is also indicative of the amount of energy the fluid loses as it is pumped between locations. It is used as a control parameter for the operation of filters to determine when a backwash needs to be performed. As filters operate, material accumulates on and between the filter media grains, reducing or preventing fluid flow. Detailed head loss data obtained during the course of this project are provided in Appendix A.

4.3.1 Cold Temperature Range (T < 5°C)

The head loss trends between and within individual filters remained consistent over the duration of the cold water operational experiments during which nutrients were not added to filter influent water. A representative filter cycle from January 2014 is presented in Figure 4.7.

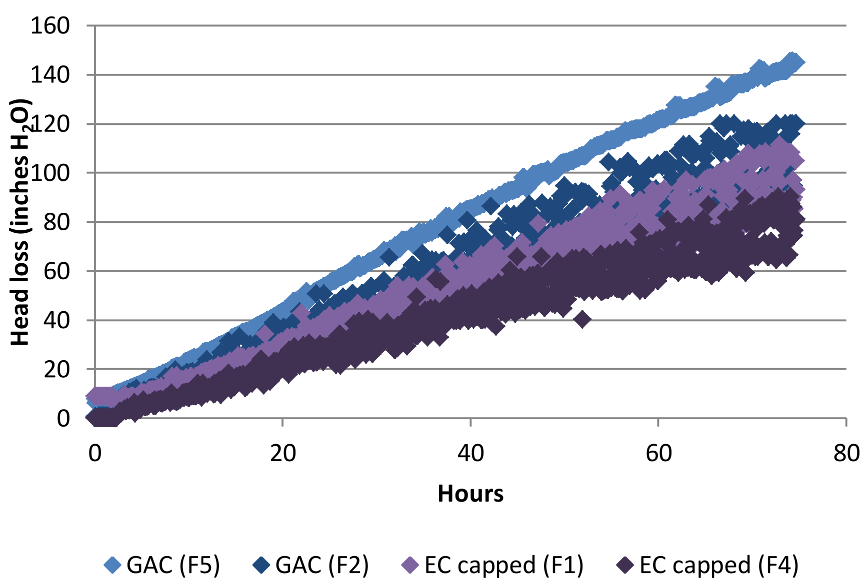

Figure 4.7: Pilot plant head loss at cold water conditions (mean temperature = 1.1°C) from 9-12 January 2014. This figure demonstrates that the rate of head loss accumulation of the EC capped filters was slower than the uncapped GAC filters.

The GAC control filters (Filters 2 and 5) yielded the most rapid increases in head loss among the pilot-scale filters; differences between these two replicate filters were not significant (p = 0.1344) (Appendix D). Compared to these control filters, the EC capping material in Filters 1 and 4 helped to decrease the rate of head loss accumulation (as discussed below; Figure 4.8). Mean head loss accumulation in the duplicate EC capped filters statistically significant (p = 0.0017) (Appendix D).

It should be noted that the difference in the mean rate of head loss accumulation between Filters 1 and 4 (i.e., “replicate” EC capped filters) was 5.41 inH_2O/day, and was 15.9% more than the mean rate of the head loss accumulation in Filter 4. While this difference was statistically significant (p = 0.0017), from an operational and practical perspective this degree of variability between filters that are considered replicates is not uncommon. Some factors that could not be controlled in these experiments include: the length of the pipe run from the full-scale piping to each filter column, filter influent water quality, water temperature, and the arrangement of filtration media grains after a backwash. Accordingly, it was concluded that observed differences in the rate of head loss accumulation between the duplicate EC capped filters *effectively* were not different at cold water conditions.

EC capping material effects on the rate of head loss accumulation were evaluated by pooling the data from replicate capped and control filters. A summary of these data is presented in Figure 4.8.

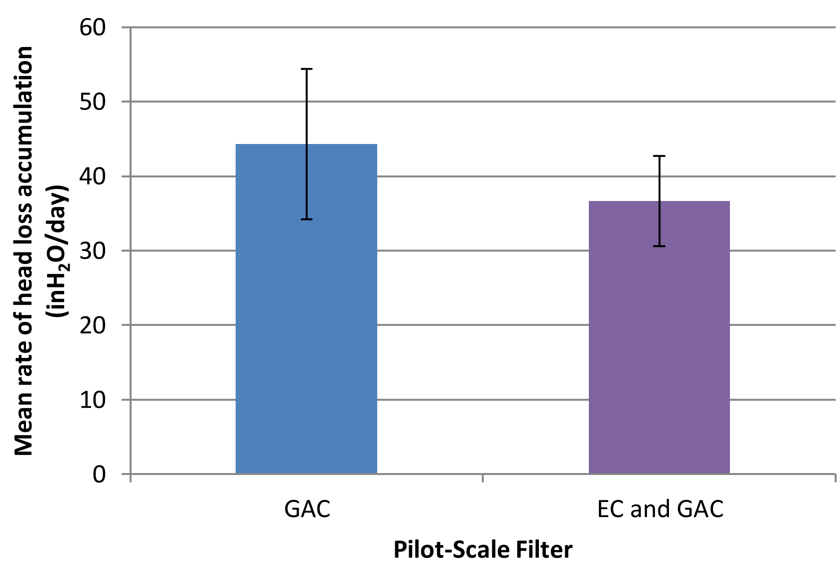

Figure 4.8: Mean rate of head loss accumulation± one standard deviation based on filter configuration at cold water conditions without nutrient amendments. This figure demonstrates that the EC capping layer reduced the rate of head loss accumulation as compared to the GAC pilot filter.

The difference in mean rate of head loss accumulation between the GAC control filters (mean ± standard deviation = 44.3 ± 10.1 inH_2O/d) and the EC capped filters (mean ± standard deviation = 36.6 ± 6.1 inH_2O/d) was statistically significant ($p < 0.001$) (Appendix D). On average, the EC capped filters took 13.6 hours longer to achieve terminal head loss than the GAC filters. Thus, these analyses demonstrate EC capping of GAC filters can significantly improve head loss accumulation during filtration, thus leading to energy, water, and associated cost savings.

4.3.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1

A summary of the mean rate of head loss accumulation at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1 is provided in Figure 4.9.

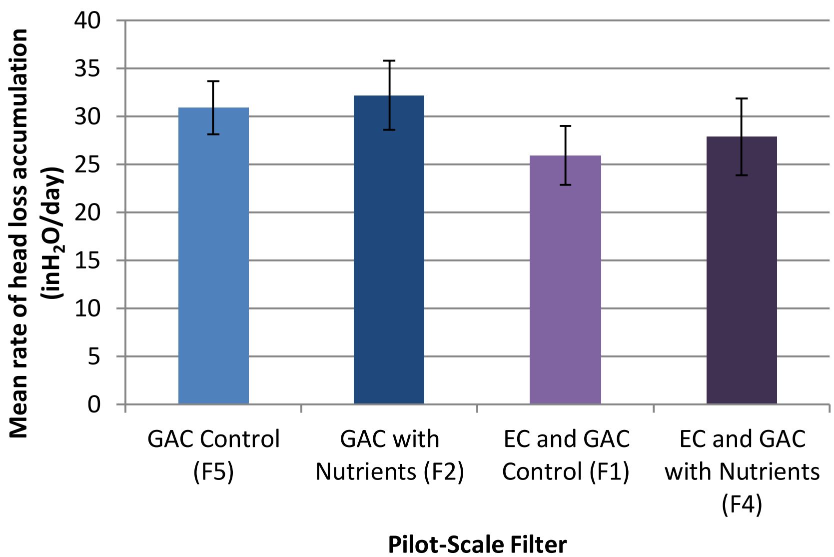

Figure 4.9: Mean rate of head loss accumulation± one standard deviation at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1. This figure demonstrates that amending the influent C:N:P ratio to 100:10:1 of the duplicate GAC and EC capped filters did not improve head loss performance.

In contrast to the capping materials, amending filter influent nutrient concentrations to a C:N:P of 100:10:1 did not enhance the head loss performance of either EC capped or control filters. The differences in head loss accumulation between the nutrient-amended and control GAC (p = 0.1634) and nutrient-amended and non-amended EC capped (p = 0.0992) filters were not statistically significant (Appendix D). Accordingly, amending the influent stoichiometric C:N:P ratio to 100:10:1

did not improve the rate of head loss accumulation in either the GAC or the EC capped filters, at cold water conditions.

4.3.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2

A summary of the mean rate of head loss accumulation at cold water conditions while amending the C:N:P ratio of Filters 2 and 4 to 100:20:12 is provided in Figure 4.10.

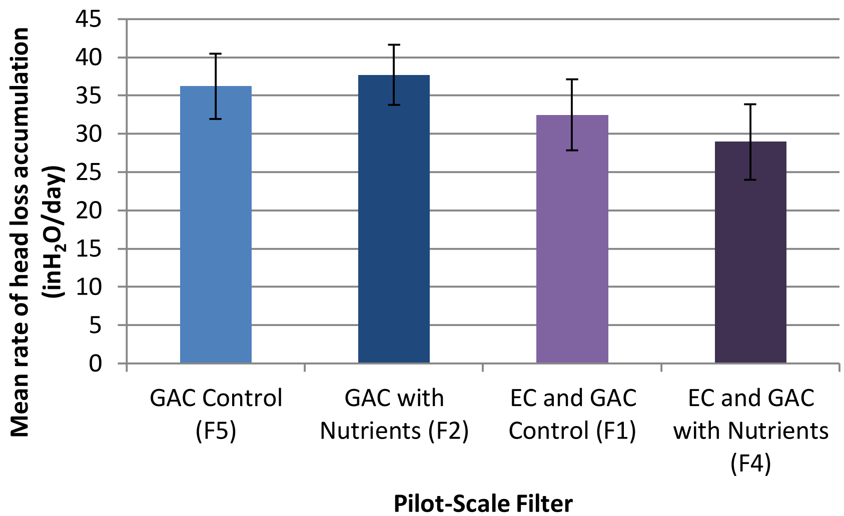

Figure 4.10: Mean rate of head loss accumulation ± one standard deviation at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates that amending the influent C:N:P ratio to 100:20:2 of the duplicate GAC and EC capped filters did not improve head loss performance.

Further amendment of influent nutrient concentrations to 100:20:2 also did not enhance the head loss performance of the pilot-scale filters. The differences in head loss accumulation between the nutrient-amended and non-amended GAC (p = 0.2142) and nutrient-amended and non-amended EC capped (p = 0.0689) filters were not statistically significant (Appendix D) and it was concluded that amending the influent stoichiometric C:N:P ratio to 100:20:2 did not improve the rate of head loss accumulation in either the GAC or the EC capped filters at cold water conditions. It could be argued that nutrient amendment enhanced head loss accumulation in the EC capped filters if a less stringent significance level (e.g., $\alpha/2$ = 0.10) was applied; however, in that case the effect of nutrient amendment would be significantly associated with media configuration. Unfortunately, further exploration of that possibility was beyond the scope of this investigation. Nonetheless, this investigation did demonstrate that nutrient amendment does not significantly enhance head loss accumulation ubiquitously or consistently.

4.3.4 Transitional Temperature Range (5°C ≤ T < 15°C)

Trends in head loss accumulation in the pilot-scale filters during the transitional water temperature period were generally consistent with those observed at cold water conditions: the GAC filters yielded the more rapid increases in head loss (mean ± standard deviation = 40.1 ± 15.0 inH_2O) than the EC filters (mean ± standard deviation = 32.3 ± 9.2 inH_2O). The difference in the mean rate of head loss accumulation between the two filter configurations was statistically significant ($p = 0.0096$) at transitional water temperatures (Figure 4.11; Appendix D; based on pooled data from replicate filters). In this case, the EC capped filters took an average of 17.4 hours longer to achieve terminal head loss than the GAC filters.

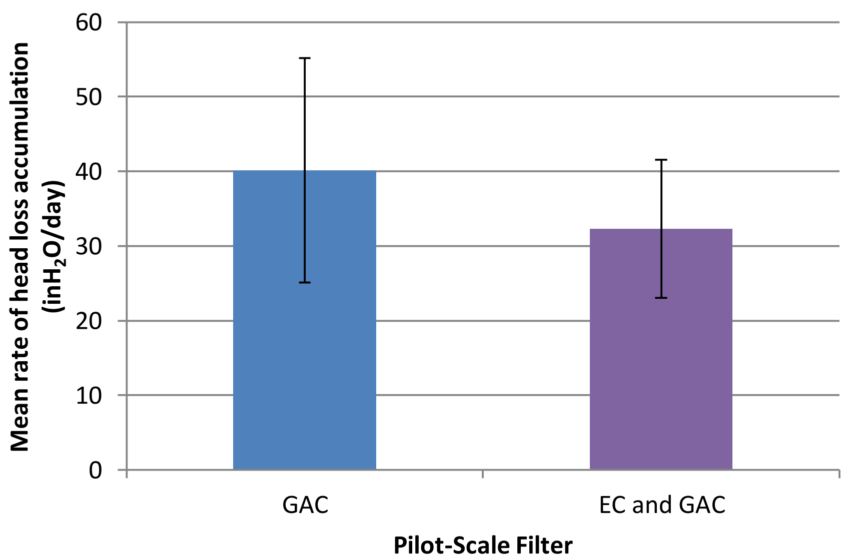

Figure 4.11: Mean rate of head loss accumulation ± one standard deviation categorized by filter configuration at transitional water temperatures without nutrient amendments. This figure demonstrates statistical significance between the two filter configurations.

4.3.5 Warm Temperature Range (T ≥ 15°C)

Trends in head loss accumulation in the pilot-scale filters remained consistent for the duration of the two periods of warm water operations without the addition of nutrients. Similar to the trends observed at cold and transitional water temperatures, Filters 2 and 5 (both containing GAC and sand) yielded the most rapid increase in head loss among the pilot-scale filters and the EC capping material in Filters 1 and 4 decreased the rate of head loss accumulation, compared to the GAC filters. As with previous analyses, the expected approach for data analysis was to pool the data from replicate filters because it would be expected two filters that contain the same type and amount of media, and are operated in the same fashion, would not yield statistically significant differences in the mean rate of head loss accumulation. Similar to the results obtained with Filters 1 and 4 at cold water conditions, differences in the mean rates of head loss accumulation between Filters 2 and 5 were statistically significant (p = 0.0163) at warm water conditions (Appendix D). Operational data for Filter 5 from 5 August 2013 to 17 October 2013 are not available because it was not connected to the SCADA system until 3 January 2014. While the mean temperatures for 5 August 2013 to17 October 2013, and 9 May 2014 to 5 July 2014 were approximately the same (20.0°C and 20.6°C, respectively), it cannot be assumed that the water quality entering the filters during these two periods of time was the same. The statistical analysis was repeated for the GAC filters using the rate of head loss accumulation data collected from both filters during 9 May 2014 to 5 July 2014. A summary of the data is presented in Table 4.3

Table 4.3: Summary the mean Filter 2 and 5 rate of head loss accumulation at warm water conditions without nutrient amendments from 9 May 2014 to 5 July 2014

	Filter 2	**Filter 5**
Media Configuration	GAC	GAC
Number of runs, n	15	15
Mean rate of head loss accumulation (inH_2O/day)	70.46	75.62
Standard Deviation (inH_2O/day)	11.24	14.92

Using the data summarized in Table 4.3, it was found that the differences in mean rate of head loss accumulation between Filters 2 and 5 were not statistically significant (p = 0.1466) (Appendix D); this was also the case for Filters 1 and 4 (p = 0.0664) when all of the warm water operational data were used (Appendix D). Accordingly, the head loss accumulation data were pooled for replicate filters and summarized (Figure 4.12). Comparison of these data demonstrated that differences in the mean rates of head loss accumulation in the GAC (mean ± standard deviation = 73.0 ± 13.2 inH_2O) and EC capped (mean ± standard deviation = 53.8 ± 9.8 inH_2O) were statistically significant (p < 0.0001), and it was concluded that the rate of head loss accumulation in the EC capped filters was slower than in the GAC filters at warm water conditions (Appendix D). In this case of warm water conditions, the EC capped filters took an average 14.1 hours longer to achieve terminal head loss than the GAC filters.

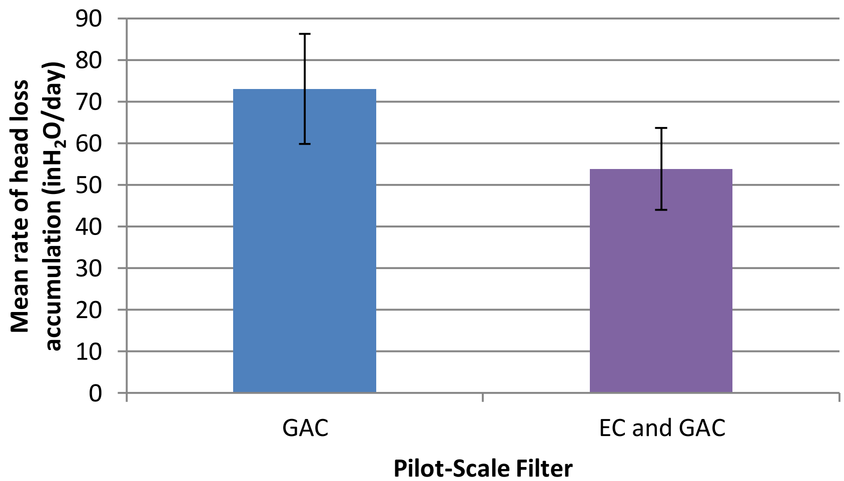

Figure 4.12: Mean rate of head loss accumulation± one standard deviation categorized by filter configuration at warm water conditions without nutrient amendments. This figure demonstrates statistical significance between the two filter configurations.

4.3.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1

A summary of the mean rate of head loss accumulation at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1 is presented in Figure 4.13.

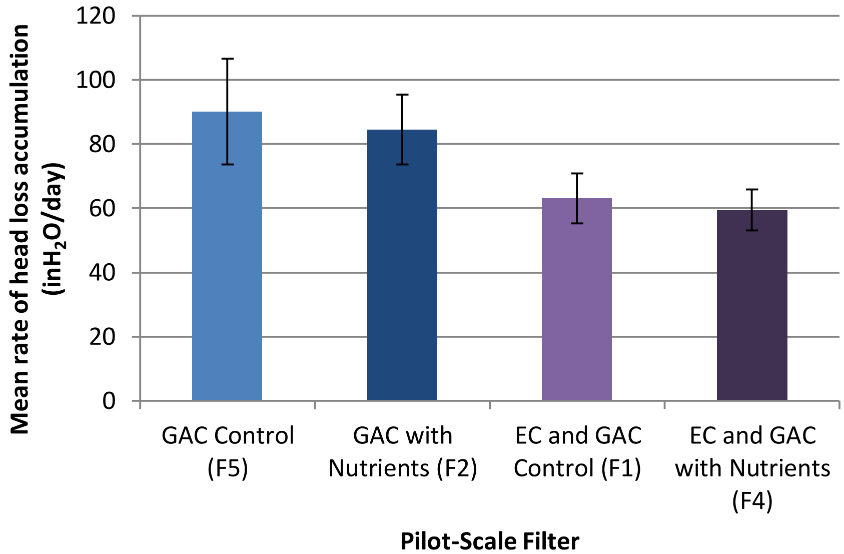

Figure 4.13: Mean rate of head loss accumulation ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrates no statistical significance with nutrient amendment.

Differences in the mean rates of head loss accumulation between the nutrient-amended and non-nutrient-amended GAC (p = 0.1498) and EC capped (p = 0.0947) filters were not statistically significant (Appendix D). Thus, it was concluded that amending the influent stoichiometric C:N:P ratio to 100:10:1 did not improve the rate of head loss accumulation in either the GAC, or the EC capped filters at warm water conditions.

4.3.7 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:20:2

Initially, the head loss trends of the pilot-scale filters were similar to those presented at the other operating conditions with or without nutrient addition. The GAC filters (Filter 2 and 5) with and without nutrient addition, achieved terminal head loss before the other filter configurations. The EC capped filters (Filter 1 and 4), with and without nutrient addition, reach terminal head loss at approximately the same time, but after the GAC filters. As the amendment of the influent C:N:P ratio to 100:20:2 continued, the EC capped filter with nutrient addition (Filter 4) achieved terminal head loss after its control filter (Filter 1). This was first observed on 12 September 2014. The filter cycle from 15-18 September 2014 is presented in Figure 4.14.

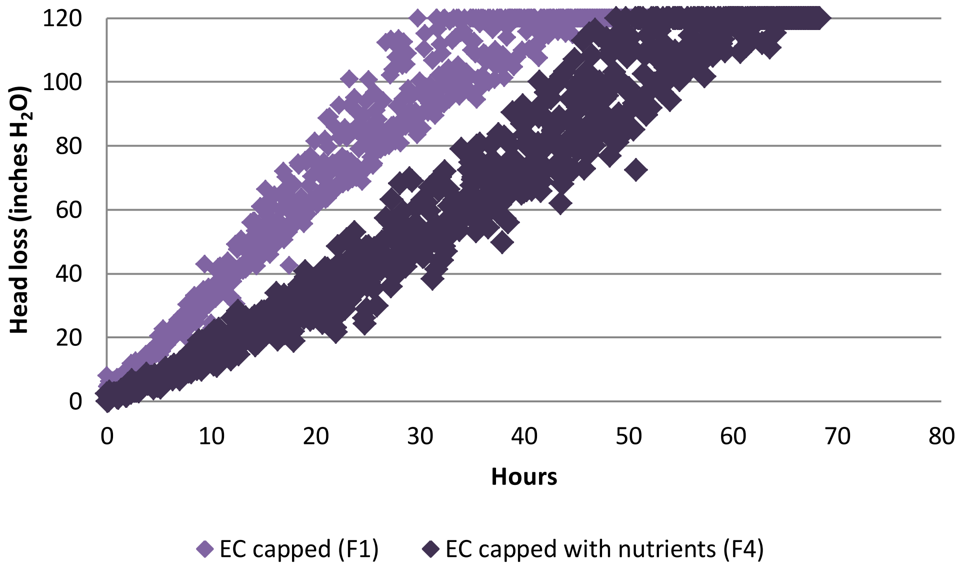

Figure 4.14: Pilot plant head loss data at warm water conditions (mean temperature = 19.5°C) of the EC capped filters with (Filter 4) and without nutrient addition (Filter 1) from 15-18 September 2014 . This figure demonstrates an improvement in head loss performance in the EC capped filter with nutrient amendment.

A summary of the mean rate of head loss accumulation at cold water conditions while amending the C:N:P ratio of Filters 2 and 4 to 100:20:2 is presented in Figure 4.15.

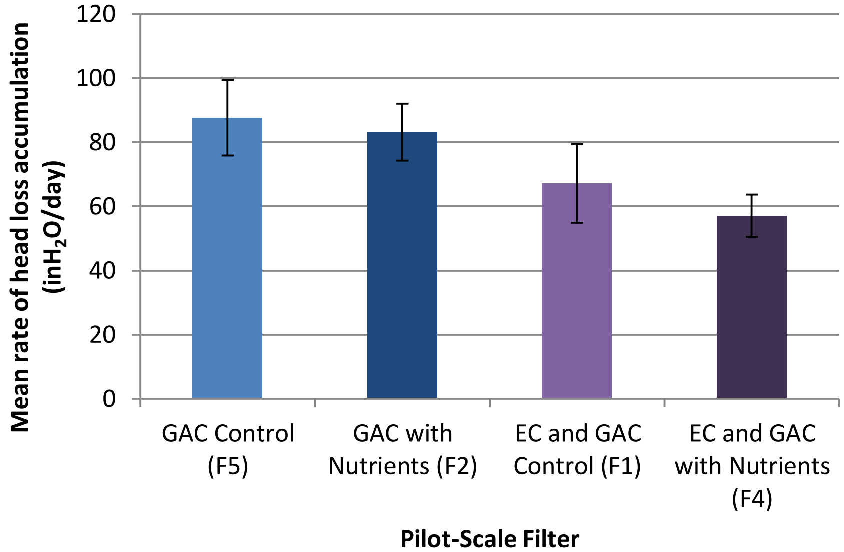

Figure 4.15: Mean rate of head loss accumulation ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates statistical significance between the two GAC filter configurations, but a statistical significance between the two EC capped filter configurations.

Amending the influent stoichiometric C:N:P ratio to 100:20:2 did not improve the rate of head loss accumulation in the GAC filter (p = 0.1533) (Appendix D). However, an improvement was observed in the EC capped filters (p = 0.0101) with the addition of nutrients (Appendix D). On average, the addition of nutrients allowed the EC capped filter to achieve terminal head loss 7.6 hours after its respective control filter, and this suggests that the EC capping material helped enhance the benefits of nutrient amendments in terms of the rate of head loss accumulation in a biological filter.

The influent of both the GAC and EC capped filters were amended to prescribed stoichiometric C:N:P ratio of 100:10:1 for 42 consecutive days, followed by amending the nutrient ratio of 100:20:2 for 26 consecutive days before a noticeable change in performance was observed. It is unknown if the first nutrient dosing experiment contributed towards shortening or lengthening the acclimation period of the second. However, based on a length of the acclimation period, implementing a nutrient amendment program for the purposes of achieving biological filtration performance may not be practical for utilities that operate in climates that experiences short, or no periods of warm water conditions.

4.4 Filter Run Time

As outlined in Section 3.4.1, the start of the filter cycle was denoted when the effluent turbidity improved after filter ripening and stabilized at a value < 0.2 NTU. The end of the filter cycle was denoted by an effluent flow rate < 4 L/min, a differential pressure across the filter ≥ 120 inH_2O, an effluent turbidity ≥ 0.2 NTU for a period of ten consecutive minutes, or when influent flow to the pilot-scale filters was closed to perform a backwash, as part of regular operation and maintenance. A summary of the filter run time data and temperature trends is presented in Figure 4.16. Detailed filter run time data obtained during the course of this project are provided in Appendix A.

4.4.1 Cold Temperature Range (T < 5°C)

The filter run time data collected from the GAC (Filters 2 and 5) and EC capped (Filters 1 and 4) filters during cold water conditions were compared. The observed differences in the filter run times of the two GAC (p = 0.2967) and two EC capped (p = 0.2598) replicate filters were not statistically significant at cold water conditions (Appendix D). Therefore, data from the two GAC and two EC capped filters were pooled to enable comparison of mean filter run times on a filter configuration basis. These data are presented in Figure 4.17. The filter run times of the GAC and EC capped filters were 46.9 ± 17.8 h and 49.0 ± 18.0 h, (mean ± standard deviation), respectively. Differences in mean filter run time between the filter configurations were not statistically significant (p = 0.1403; Appendix D) at cold water temperatures.

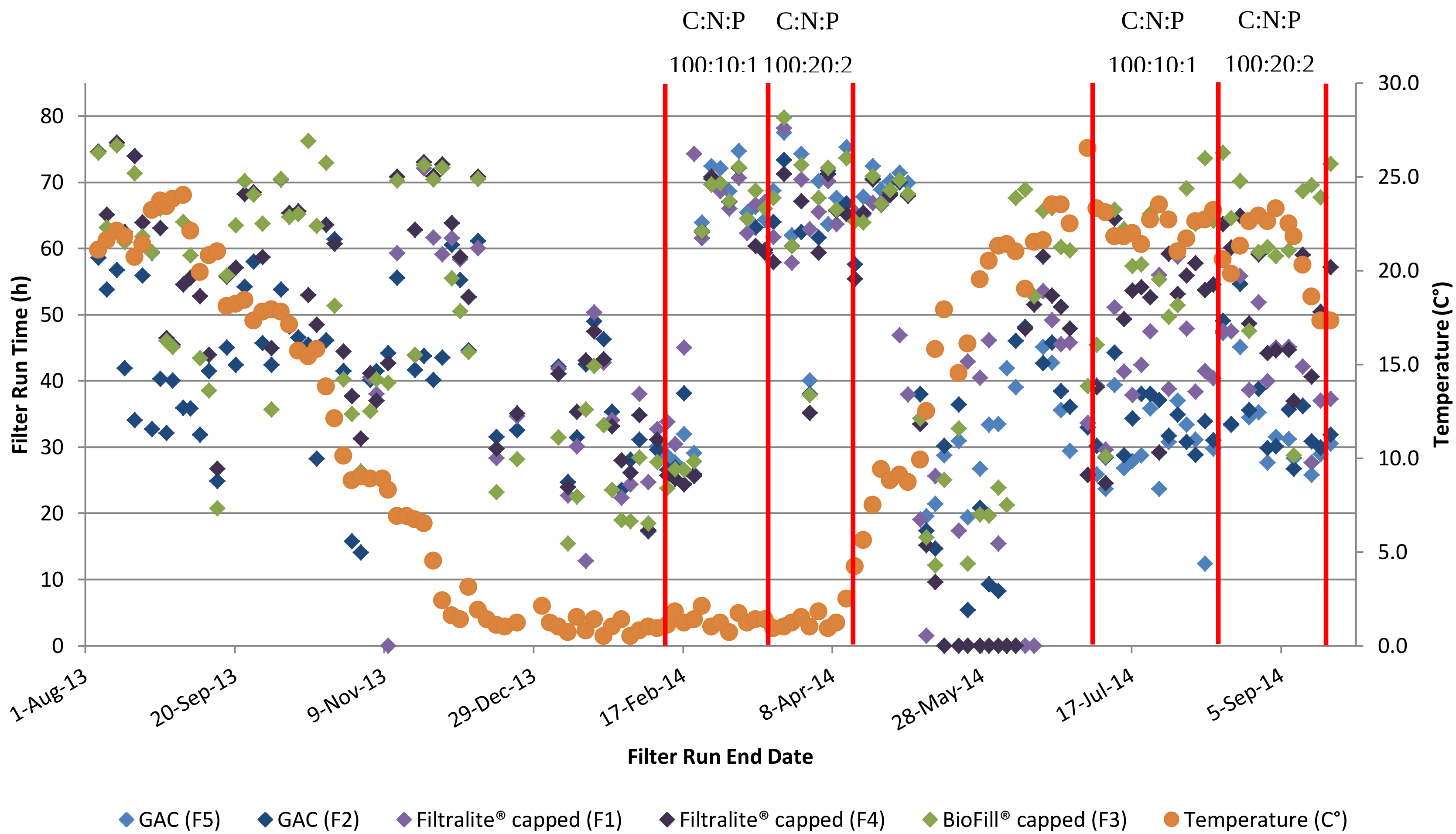

Figure 4.16: Summary of experimental pilot-scale filter run time and water temperature. The red vertical lines represent the periods when the influents of Filters 2 and 4 were nutrient-amended.

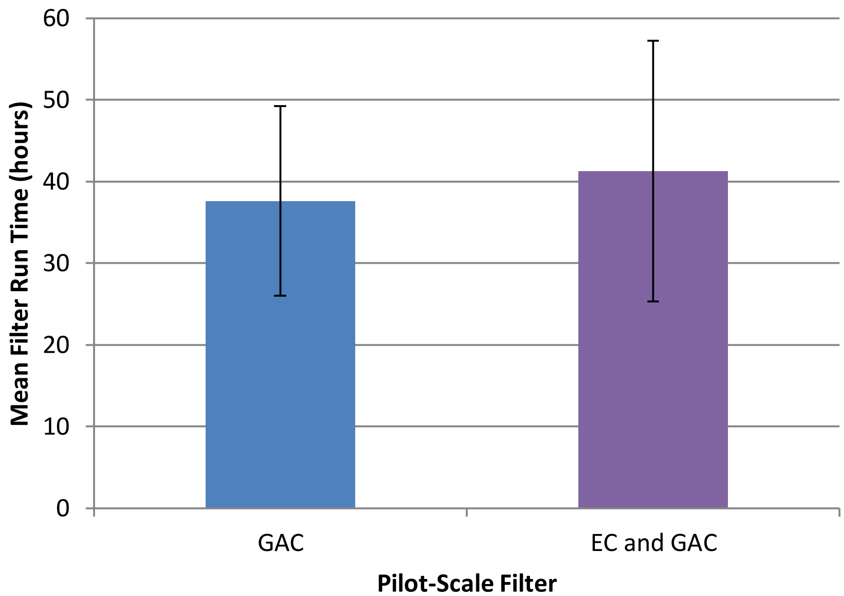

Figure 4.17: Mean filter run time ± one standard deviation categorized by filter configuration at cold water conditions, without nutrient amendments. This figure demonstrates no statistical significance between the GAC and EC capped pilot filters.

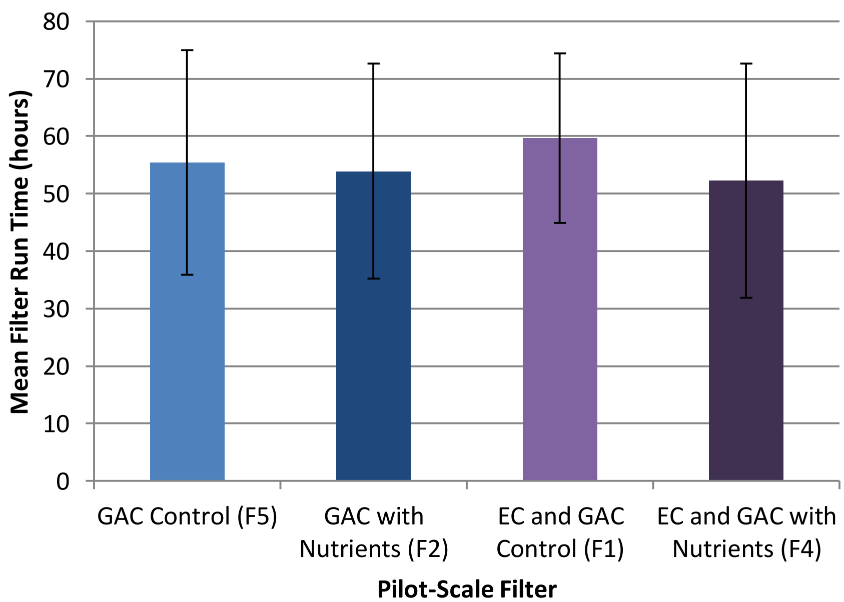

Figure 4.18: Mean filter run time ± one standard deviation at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrations no statistical signifiance between the different filter configurations.

4.4.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1

Mean filter run times during the investigations of nutrient amendment at C:N:P of 100:10:1 at cold water conditions are presented in Figure 4.18. Differences in the mean filter run time of nutrient-amended and non-nutrient amended GAC (p = 0.4243) and EC capped (p = 0.1601) filters were not statistically significant (Appendix D). Therefore, it was concluded that amending the influent stoichiometric C:N:P ratio to 100:10:1 did not improve mean filter run time of any of the filter configurations at cold water conditions.

4.4.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2

Mean filter run times during the investigations of nutrient amendment at C:N:P of 100:20:2 at cold water conditions are presented in Figure 4.19. Differences in mean filter run time of nutrient-amended (p = 0.1795) and EC capped (p = 0.0691) filters and their respective control filters were not statistically significant (Appendix D). Thus, it was concluded that amending the influent stoichiometric C:N:P ratio to 100:20:2 also did not improve the mean run times of any of the filter configurations investigated at cold water conditions.

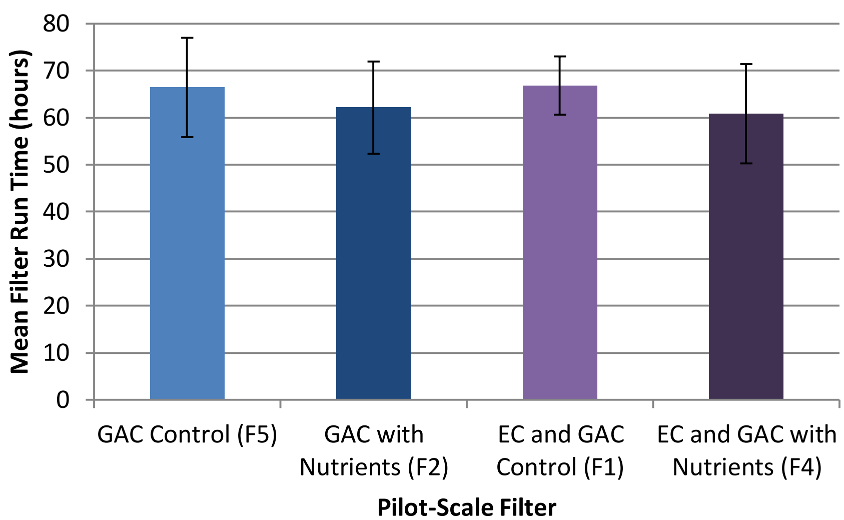

Figure 4.19: Mean filter run time ± one standard deviation at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates no statistical significance between the filter configurations.

4.4.4 Transitional Temperature Range (5°C ≤ T < 15°C)

Differences in mean filter run times of the two GAC (p = 0.0740) and two EC capped (p = 0.3964) replicate filters were not statistically significant during the transitional temperature range (Appendix D). Therefore, data from the replicate filter configurations were pooled. A summary of these data is presented in Figure 4.20.

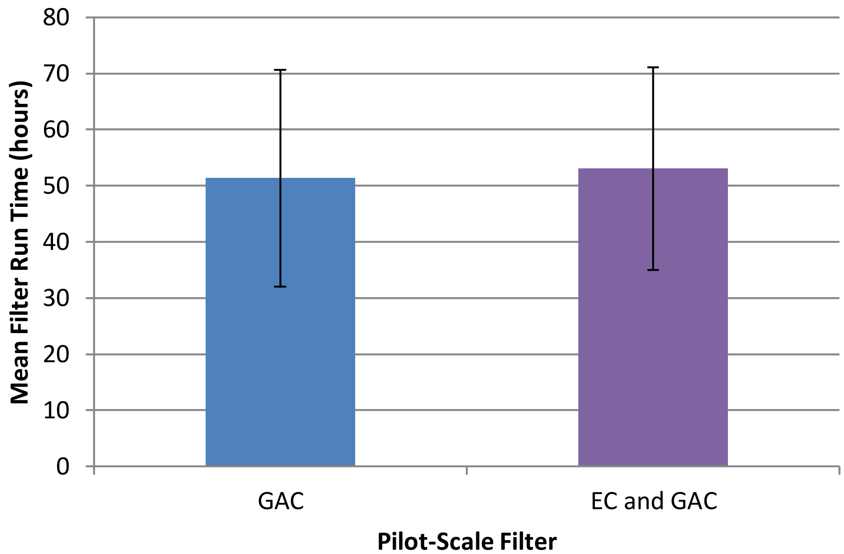

Figure 4.20: Mean pilot plant filter run time ± one standard deviation categorized by filter configuration at transitional water temperatures without nutrient amendments. This figure demonstrates no statistical significance between the GAC and EC capped pilot filters.

Differences in mean filter run time of the GAC (mean ± standard deviation = 51.4 ± 19.3 h) and EC capped (mean ± standard deviation = 53.0 ± 18.0 h) filters were not statistically significant (p = 0.3644; Appendix D) at transitional water temperatures.

4.4.5 Warm Temperature Range (T ≥ 15°C)

Differences in the mean filter run times of the two GAC (p = 0.0905) and EC capped (p = 0.0924) filters at warm water conditions were not statistically significant (Appendix D), so these data were also pooled (Figure 4.21). Using the pooled data, the difference in mean filter run time between the EC capped filters and the GAC filters was statistically significant (p = 0.0088; Appendix D), thereby supporting the conclusion that EC capping of GAC filters enabled longer filter run times at warm water conditions. On average, the EC capped filters extended the filter run time by 8.4 hours compared to the GAC filters.

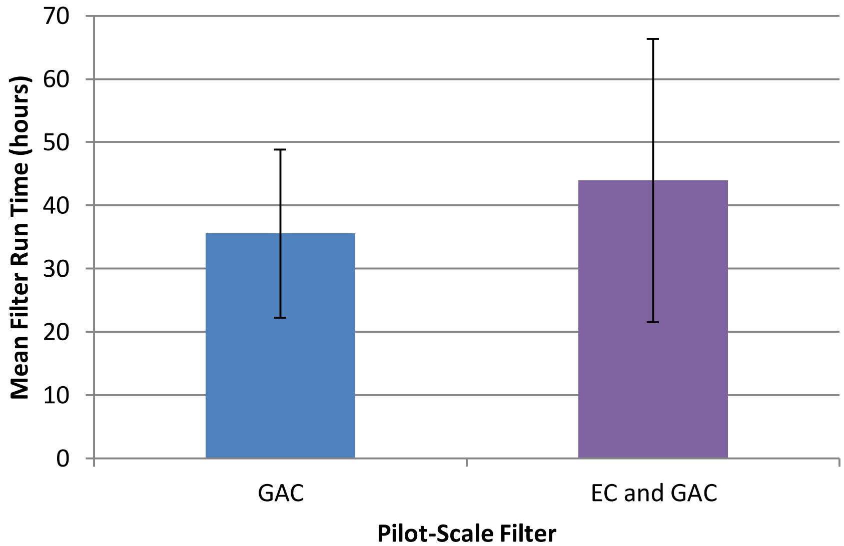

Figure 4.21: Mean pilot plant filter run time data ± one standard deviation categorized by filter configuration at warm water conditions without nutrient amendments. This figure demonstrates a statistical significance between the GAC and EC capped pilot filters.

EC capping of GAC filters significantly extended filter run times at warm water operating conditions; however, significant improvements in filter run time were not observed at other operational temperatures. It is hypothesized that the longer filter run times at warmer water conditions were attributable to the larger media size of the capping materials enabling better solids retention without relatively rapid accumulation in head loss; in essence, better utilization of filter bed depth given the character of solids (including biomass) in the top layer of the filter bed. Associated factors may include an improvement in floc strength and/or an increase in the biological activity leading to an increase the total biomass in the filters. The increase in biomass also may have provided the filter with more potential collectors, increasing its capacity for turbidity removal. Further detailed investigation to elucidate this exact mechanism(s) was beyond the scope of the current investigation.

4.4.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1

Mean filter run times during the investigation of influent nutrient amendment at a C:N:P ratio of 100:10:1 at warm water conditions are presented in Figure 4.22.

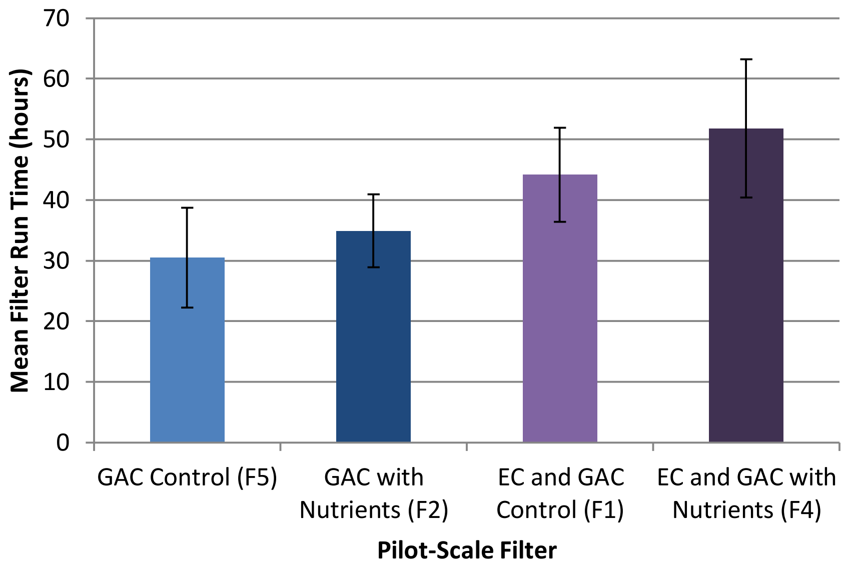

Figure 4.22: Mean pilot plant filter run time ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1. This figure demonstrated no statistical significance in the GAC filters, but a statistical significance in the EC capped filters.

Differences in the mean filter run times of the nutrient-amended and non-nutrient-amended GAC filters were not statistically significant (p = 0.0595; Appendix D); however, they would be considered statistically significant at a slightly higher significance level (e.g., $\alpha/2$ = 0.10). Similarly, the difference in mean filter run times of the nutrient-amended and non-nutrient-amended EC capped filters were statistically significant (p = 0.0245; Appendix D) and it was concluded that the larger EC media coupled with nutrient amendment enhanced filter run time. In this case, the mean filter run time of the EC capped filter was extended by approximately 7.6 hours by amending the influent stoichiometric C:N:P ratio to 100:10:1. As discussed above, increased biomass and/or better utilization of be4d depth may have enabled the longer filter run times.

4.4.7 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:20:2

The mean filter run time data at warm water conditions while amending the influent nutrient concentrations of Filters 2 and 4 to a C:N:P ratio of 100:20:2 are presented in Figure 4.23.

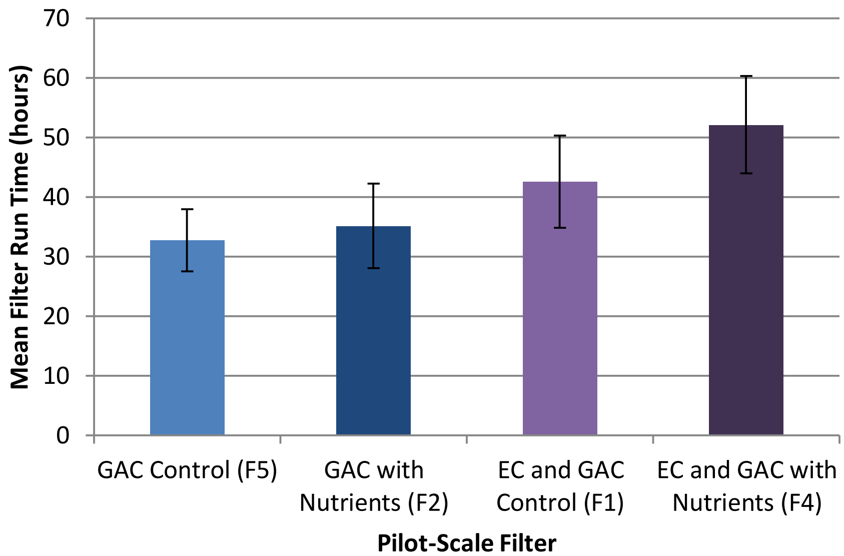

Figure 4.23: Mean pilot plant filter run time ± one standard deviation at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates no statistical significance between the GAC filters, but a statistical significance between the EC capped filters.

It is important to note that the differences between the mean filter run times of the nutrient-amended and non-nutrient amended GAC filters were not statistically significant (p = 0.1858; Appendix D); thus, it was concluded that amending the influent nutrient ratio to 100:20:2 did not extend GAC filter run time. This result also supports the same conclusion for the influent C:N:P ratio of 100:10:1 discussed above because while nutrients are understood to be sometimes limiting, it is unlikely that filter performance is so sensitive that it requires a narrow, optimal nutrient ratio and is significantly impacted when ratios are either below *or* above that optimum. In contrast, the difference between the mean filter run times of the nutrient-amended and non-nutrient amended EC capped filters (p = 0.0053) was also statistically significant (Appendix D) and influent nutrient amendment to the EC capped filter extended run time by approximately 8.1 hours. Similar to the observations in the head loss accumulation data, the EC capping layer enhanced the effect of the nutrient addition; however, contrasts between the various operational conditions investigated underscore that improved performance was not consistently observed with nutrient amendment or a specific nutrient ratio.

4.5 Head Loss Accumulation Temperature Dependence

The impact of temperature on head loss accumulation of each pilot-scale filter was evaluated for the GAC and EC capped filters. Operational data for the two filter configurations that were collected during the nutrient amendment experiments was not included in this analysis. The mean rate of head loss accumulation at both cold and warm water conditions is presented in Figure 4.24.

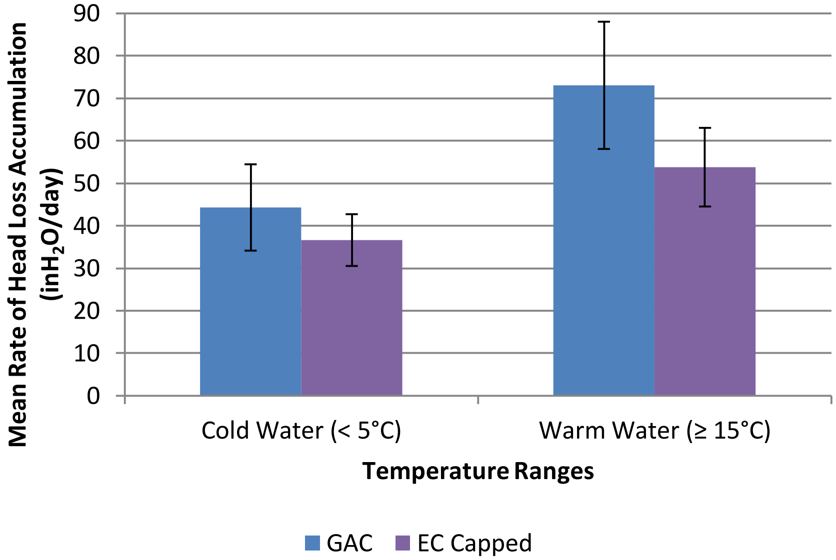

Figure 4.24: Pilot-scale filter mean rate of head loss accumulation ± one standard deviation vs cold and warm temperature ranges without nutrient amendments.

The data suggests that there is a direct relationship between the mean rate of head loss accumulation and water temperature. The observed increase in the rate of head loss accumulation is consistent with typical biological filtration performance. Higher temperatures often yield higher levels of microbiological activity and/or biomass production within the filter (Andersson et al., 2001; Lazarova and Manem, 1995; Persson et al., 2007), contributing to increases in filter head loss (Crittenden et al., 2012a).

As demonstrated in the previous sections of this chapter, the EC capped layer yielded slower rates of head loss accumulation compared to the GAC filters at all temperature ranges. Differences in the rate of head loss accumulation at cold (p = 0.0002) and warm (p < 0.0001) water conditions between the GAC and EC capped filters were statistically significant (Appendix E). If lines were drawn to connect the data points, the slopes of the lines would be indicative of the filter configuration's susceptibility to increases in head loss with increases in temperatures. The larger the slope is, or steeper the line, the more susceptible the filter configuration is to increases in the rate of head loss accumulation with increases in temperature. The EC capped filter data yielded the smaller slope, suggesting that using a capping material can lead to more robust filter operation by enabling lower rates of head loss accumulation at all temperatures, likely due to better utilization of bed depth due to the substantially larger effective size of the capping media.

4.6 Summary

- Turbidity trends of the GAC and EC capped filters were similar at all temperature conditions.
- No turbidity performance enhancement was observed while amending the influent molar C:N:P to 100:10:1 or 100:20:2 at cold and warm water conditions.
- The rate of head loss accumulation of the GAC filters was significantly improved with the EC capping layer at all temperature ranges tested.
- The rate of head loss accumulation of the EC capped filter was significantly improved when the influent molar C:N:P was amended to 100:20:2 at warm water conditions.
- No improvements in head loss performance was observed with the other filter configurations or operating conditions.
- There was no significant difference in the filter run times of any filter configuration at cold water conditions with and without nutrient amendment.
- Longer filter run times were achieved with the EC capping layer compared to the GAC filter at warm water conditions.
- Nutrient amendment helped extend filter run time of the EC capped filter at warm water conditions.
- Head loss has strong temperature dependence.

Chapter 5
Biodegradable Organic Matter Removal

5.1 Overview

The MWTP pilot-scale filters were configured to evaluate the efficacy of replacing the top layer of granular media in a filter with a capping material with a larger effective size, as well as amending the influent stoichiometric nutrient ratio on both traditional and biological filtration performance for the production of drinking water. This chapter examines the impact the capping materials and nutrient amendments had on biological performance parameters, including: total organic carbon (TOC), dissolved organic carbon (DOC), ammonia (NH_3-N), total phosphorus (TP), and soluble reactive phosphorus (SRP) removal. C:N:P ratios have been calculated using TOC, DOC, AOC, NH_3-N, NO_3-N, TP, and SRP. The influent and effluent DOC, NH_3-N, and SRP molar concentrations were used to calculate the influent and consumed molar C:N:P ratios. Authors have presented influent C:N:P ratios, but consumed C:N:P ratios have not been previously reported in water or wastewater treatment literature. Monitoring the amount of nutrients that are consumed by a biological process can provide insight on its behaviour and how it can be optimized.

At cold water conditions, the influent water of pilot-scale Filters 2 and 4 were nutrient-amended to a stoichiometric C:N:P ratio of 100:10:1 and 100:20:2 from 8 February 2014 to 16 March 2014 and 16 March to 18 April 2014, respectively. At warm water conditions, the influent water of pilot-scale Filters 2 and 4 were nutrient-amended to a stoichiometric C:N:P ratio of 100:10:1 and 100:20:2 from 5 July 2014 to 16 August 2014 and 16 August 2014 to 21 September 2014, respectively. During the nutrient amendment experiments, the relative stoichiometric nitrogen and phosphorus concentrations were adjusted according to the influent DOC concentration. Using the influent DOC concentration, as opposed to the steady state amount of DOC removed by a control filter, prevents the confounding of results with factors that cannot be controlled in a pilot system, such as: changes in water quality, operational changes to the full-scale plant, and temperature. Constant flow rate operation of pilot-scale Filter 5 did not begin until 3 January 2014 because Filter 5 was not connected to the SCADA system prior to this date. To ensure that the grab samples collected from Filter 5 were collected at similar conditions as the other pilot-scale filters between 8 August 2013 and 3 January 2014, the flow rate of Filter 5 was adjusted manually as needed, to the meet the targeted flow rate. The filter was operated for 15 minutes before a sample was collected.

The influent DOC, NH_3-N, and SRP concentrations, a summary of the influent stoichiometric C:N:P ratios during the nutrient amendment experiments is presented in Figure 5.1. The influent water did not meet the recommended 100:10:1 molar ratio at cold or warm water conditions.

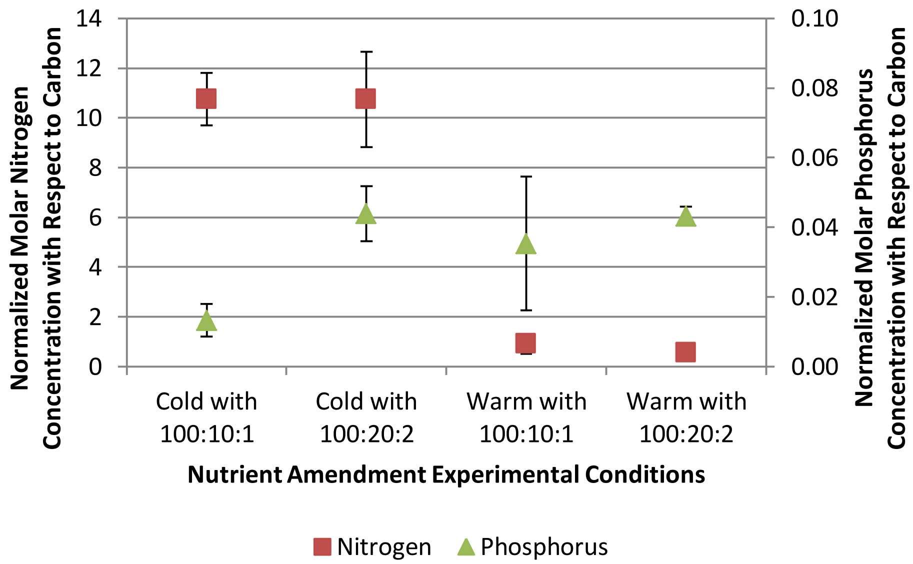

Figure 5.1: Influent stoichiometric C:N:P ratios just prior to nutrient amendment (error bars indicate ± one standard deviation)

Based on the influent stoichiometric ratio of 100:10:1 that has been recommended by LeChevallier et al. (1991) and Lauderdale et al. (2012), there was an excess of nitrogen, and a deficiency of phosphorus. The influent molar phosphorus concentration should be increased be a factor of approximately 35 at cold water conditions to meet the 100:10:1 target ratio. To increase the influent molar C:N:P to 100:20:2 at cold water conditions, the molar nitrogen and phosphorus concentrations were increased by factors of 1.8 and 50, respectively. To meet the recommended 100:10:1 ratio at warm water conditions, the influent stoichiometric nitrogen and phosphorus concentrations were increased by factors of 11.1 and 25, respectively. When the target influent stoichiometric ratio was increased to 100:20:2 at warm water conditions, the stoichiometric nitrogen and phosphorus concentrations were increased by a factor of 33.3 and 50, respectively. Based on the recommended C:N:P ratio, the influent nutrient concentrations should be increased by very large factors to achieve better or optimal biological filtration performance. Functioning biological or biochemical processes typically require incremental increases in the substrate concentrations to observe improvements in performance. In addition, most biological and biochemical degradation processes require enzymes, which follow saturation kinetic models like the one developed by Michaelis-Menten. As the substrate concentration increases the enzymes become saturated and the maximum degradation rate is achieved. The large increases in the nutrient concentrations that are required to achieve the recommended 100:10:1 molar nutrient ratio may be beyond the saturation limit.

5.2 Total and Dissolved Organic Carbon

Grab samples were collected from the combined influent line and the effluent of each pilot-scale filter column and analyzed for both TOC and DOC. Influent TOC and DOC concentrations are key design parameters for water treatment plants (Hallé, 2009). TOC can be used as a surrogate to estimate the amount of NOM in the water and DOC can be used as a surrogate for BOM (Urfer et al., 1997). Detailed TOC and DOC data obtained during the course of this project are provided in Appendix B.

5.2.1 Cold Temperature Range (T < 5°C)

The mean filter influent TOC and DOC concentrations at cold water conditions without nutrient amendments were 3.7 ± 0.6 mg/L and 3.5 ± 0.4 mg/L, respectively. Both TOC and DOC were removed by the pilot filters. The TOC and DOC data collected from the effluent of the GAC filters (TOC: p = 0.3326, DOC: p = 0.6077), and the EC capped filters (Filters 1 and 4) (TOC: p = 0.5278, DOC: p = 0.5008) without nutrient amendments were analyzed; differences between the mean values were not statistically significant for any of the parameters (Appendix D). The TOC and DOC data from the duplicate GAC and EC capped filters were pooled for each filter type and are presented in Figure 5.2.

The effluent TOC and DOC removal data were compared on a filter configuration basis. Differences in mean TOC and DOC removal between the GAC and EC capped filters (TOC: p = 0.4110, DOC: p = 0.7953) were not statistically significant (Appendix D). Thus, capping the GAC filters with EC did not cause significant changes in filter effluent TOC or DOC at cold water conditions.

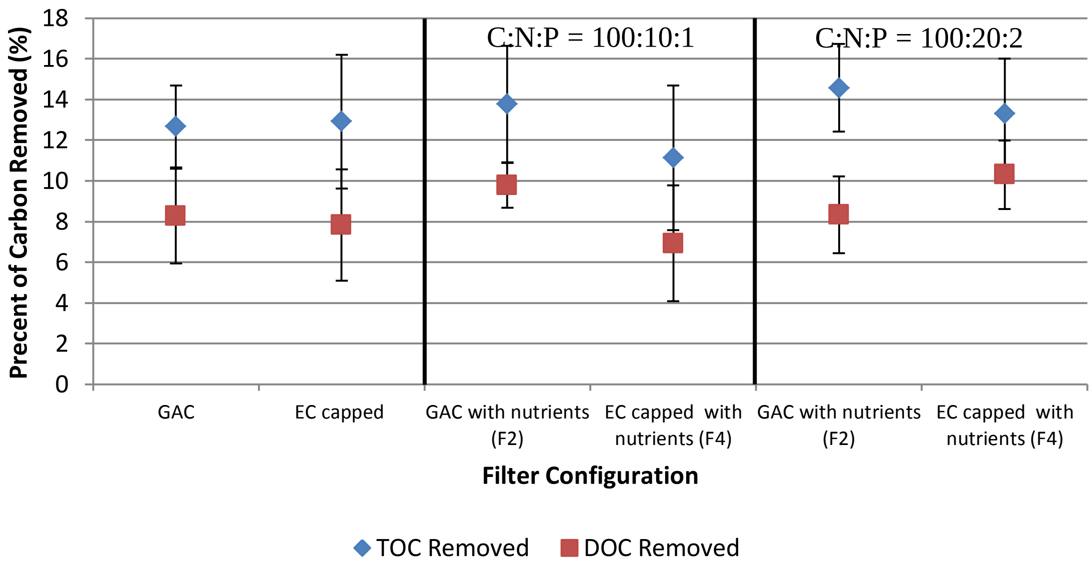

Figure 5.2: Mean percent of TOC and DOC removed ± one standard deviation at the effluent at cold water conditions with and without nutrient amendments. This figure demonstrates no statistical significance between the nutrient-amended and non-nutrient amended filters.

To evaluate the impact of the EC capping material on BOM removal within the filter, samples were collected 30 cm below the surface of the filter bed (sample port S2), and were analyzed for TOC and DOC. For the GAC filters (Filters 2 and 5), the samples were taken below the top 30 cm layer of GAC. For the EC capped filters (Filters 1 and 4), the samples were taken below the top 20 cm layer of EC and a 10 cm layer of GAC. The mean fraction of TOC and DOC that was removed at sample port S2 compared to the effluent was evaluated, and is presented in Table 5.1.

Table 5.1: Summary of the mean fraction of the total TOC and DOC removed at sample port S2 at cold water conditions without nutrient amendments

	Filter 2 + 5	**Filter 1 + 4**
Media Configuration	GAC	EC and GAC
Fraction of TOC removed at sample port S2 (%)	22.1	46.1
Fraction of DOC removed at sample port S2 (%)	56.8	78.1

The fraction of the total TOC and DOC removed 30 cm below the top of the GAC filter was improved by using EC as a capping material, at cold water conditions. However, the differences in the TOC or DOC removal at sample port S2 (TOC: $p = 0.1317$, DOC: $p = 0.3931$) between the two filter configurations were not statistically significant. Notably, over half of the total DOC that was removed by the filters was removed within the first 30 cm of each filter. This finding is consistent with other reports of TOC/DOC removal by biological filtration (Emelko et al., 2006; Moll et al., 1998; Servais et al., 1991; Wang et al., 1995).

5.2.2 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:10:1

The mean percent of TOC and DOC removed by the pilot plant during the 100:10:1 nutrient amendment experiment is presented in Figure 5.2. During this period, the mean influent TOC and DOC concentrations of each filter were 3.7 ± 0.3 mg/L and 3.5 ± 0.3 mg/L, respectively. Differences in mean TOC removal by the nutrient-amended (Filter 2) and non-nutrient amended (Filter 5) GAC filters, during the 100:10:1 nutrient amendment experiment, were not statistically significant ($p = 0.0798$); however, the differences in the mean DOC removal were statistically significant ($p = 0.0110$) (Appendix D). It should be noted that the difference in the mean DOC removed by Filters 2 and 5 was 0.100 mg/L, which is equal to the acceptable error of the organic carbon analyzer. From a practical point of view, it can be concluded that amending the C:N:P ratio to 100:10:1 had no impact the TOC or DOC removal at the effluent of the GAC filter at this temperature.

Differences in the mean effluent TOC ($p = 0.8575$) and DOC ($p = 0.6711$), between the nutrient-amended (Filter 4) and non-nutrient-amended (Filter 1) EC capped filters were not statistically significant (Appendix D). Accordingly, amending the influent C:N:P ratio to 100:10:1 did not improve either TOC or DOC removal at cold water conditions. In addition, there was no statistical difference in the mean effluent TOC ($p = 0.0952$) or DOC ($p = 0.0378$) removal between the two nutrient-amended GAC and EC capped filters (Appendix D). The GAC and EC capped filters removed organic carbon similarly when their influents were nutrient-amended to a C:N:P ratio of 100:10:1. Thus, it was concluded that amending the influent stoichiometric C:N:P ratio of 100:10:1 did not improve carbon removal by the pilot-scale filters. Further, EC capping material did not negatively impact TOC or DOC removal of during the 100:10:1 nutrient amendment experiments conducted at cold water conditions.

5.2.3 Cold Temperature Range (T < 5°C) with Nutrient Amendments at 100:20:2

The mean percent of TOC and DOC removal by the GAC and EC capped filters during the 100:20:2 nutrient amendment experiment is presented in Figure 5.2. During this period, the mean influent TOC and DOC concentrations for all the filters were 3.5 ± 0.3 mg/L and 3.3 ± 0.2 mg/L, respectively. The differences in the mean effluent TOC (p = 0.6391) and DOC (p = 0.1576) concentrations between nutrient amended (Filters 2) and non-nutrient-amended (Filter 5) GAC filters, while amending the influent C:N:P ratio to 100:20:2, were not statistically significant (Appendix D). In addition, the differences in the mean effluent TOC (p = 0.3301) and DOC (p = 0.1316) concentrations between the nutrient-amended (Filter 4) and non-nutrient-amended (Filter 1) EC filters, while amending the influent C:N:P ratio to 100:20:2, were not statistically significant (Appendix D). The differences in the mean TOC (p = 0.1742) and DOC (p = 0.0360) removal of the GAC and EC capped nutrient-were also found to be not statistically significant (Appendix D). It is concluded that amending the influent C:N:P ratio to 100:20:2 at cold water conditions had no impact on the removal of TOC or DOC. In addition, the EC capping material did not impact either the TOC or DOC removal when amending the influent nutrient ratio.

5.2.4 Transitional Temperature Range (5°C ≤ T < 15°C)

The mean filter influent TOC and DOC concentrations at the transitional temperature range for all the pilot-scale filters were 3.9 ± 1.3 mg/L and 3.6 ± 1.1 mg/L, respectively. The differences in the effluent TOC and DOC of the two GAC filters (TOC: p = 0.6442, DOC: p = 0.8657), and two EC capped filters (TOC: p = 0.8327, DOC: p = 0.6009) were found to not be statistically significant, respectively (Appendix D). The TOC and DOC removal data of the two GAC and EC capped filters were combined, respectively, and presented in Figure 5.3.

Differences in the TOC and DOC removal of the GAC and EC capped filters (TOC: p = 0.5967, DOC: p = 0.1651) were not statistically significant (Appendix D). It is concluded that in terms of TOC and DOC removal, there was no change if effluent water quality by capping the GAC filters with EC, at the transitional temperature range.

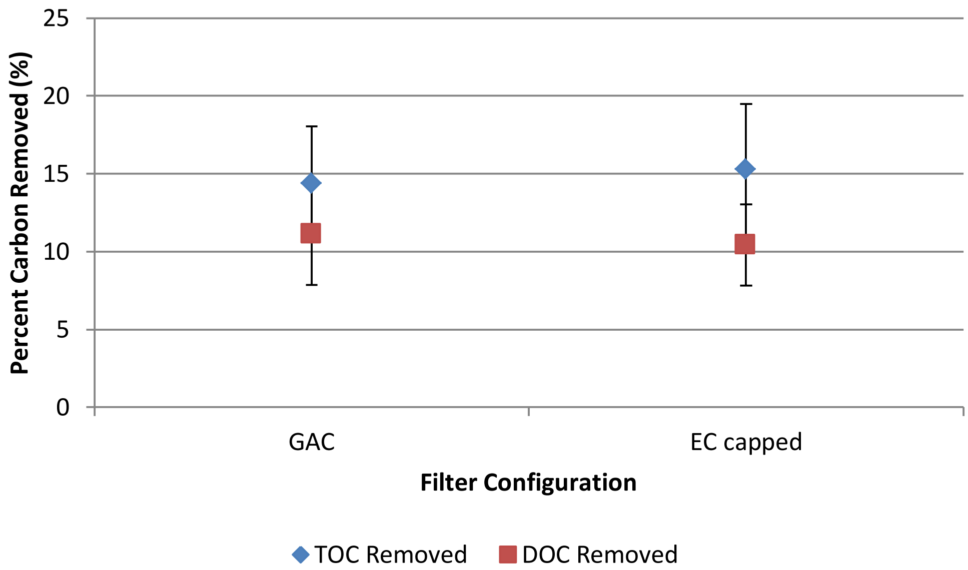

Figure 5.3: Mean percent of TOC and DOC removed ± one standard deviation at the effluent at transitional water temperatures without nutrient amendments. This figure demonstrates no significant difference between the GAC and EC capped filters.

To evaluate the impact of the EC capping material on BOM removal within the filter, samples collected 30 cm below the surface of the filter bed (sample port S2), and were analyzed for TOC and DOC. The mean fraction of TOC and DOC that was removed at sample port S2 compared to the effluent was evaluated, and is presented in Table 5.2.

Table 5.2: Mean fraction of the total TOC and DOC removed at sample port S2 at transitional water temperatures

	Filter 2 + 5	**Filter 1 + 4**
Media Configuration	GAC	EC and GAC
Fraction of TOC removed at sample port S2 (%)	54.9	33.6
Fraction of DOC removed at sample port S2 (%)	60.4	56.6

The fraction of the total TOC and DOC removed 30 cm below the top of the filter media by the GAC filter was better than using EC as a capping material, at the transitional temperature range. However, the differences in the TOC or DOC removal at sample port S2 (TOC: p = 0.8577, DOC: p =

0.7803) between the two filter configurations were not statistically significant. It is concluded that there were no negative impacts on water quality within the filter immediately after the capping material layer. Notably, over half of the total DOC that was removed at the effluent was removed within the first 30 cm of the each filter. This finding is consistent with existing biological filtration literature (Emelko et al., 2006; Moll et al., 1998; Servais et al., 1991; Wang et al., 1995).

5.2.5 Warm Temperature Range (T ≥ 15°C)

The mean influent TOC and DOC concentrations at warm water conditions for all the pilot-scale filters without nutrient amendments were 3.8 ± 0.2 mg/L and 3.5 ± 0.2 mg/L, respectively. The differences in the TOC and DOC between the two GAC filters (TOC: p = 0.3994, DOC: p = 0.5854), and the two EC capped filters (TOC: p = 0.7273, DOC: p = 0.7400) without nutrient amendments were found to not be statistically significant, respectively (Appendix D). The TOC and DOC data of the two GAC and two EC capped filters were pooled together, respectively, and presented in Figure 5.4. Differences in the mean TOC and DOC removal data were compared on a filter configuration basis (TOC: p = 0.4055, DOC: p = 0.4751, Appendix D) and it was found that they were not statistically significant. Thus, capping the GAC filters did not cause significant changes in filter effluent TOC or DOC at warm water conditions.

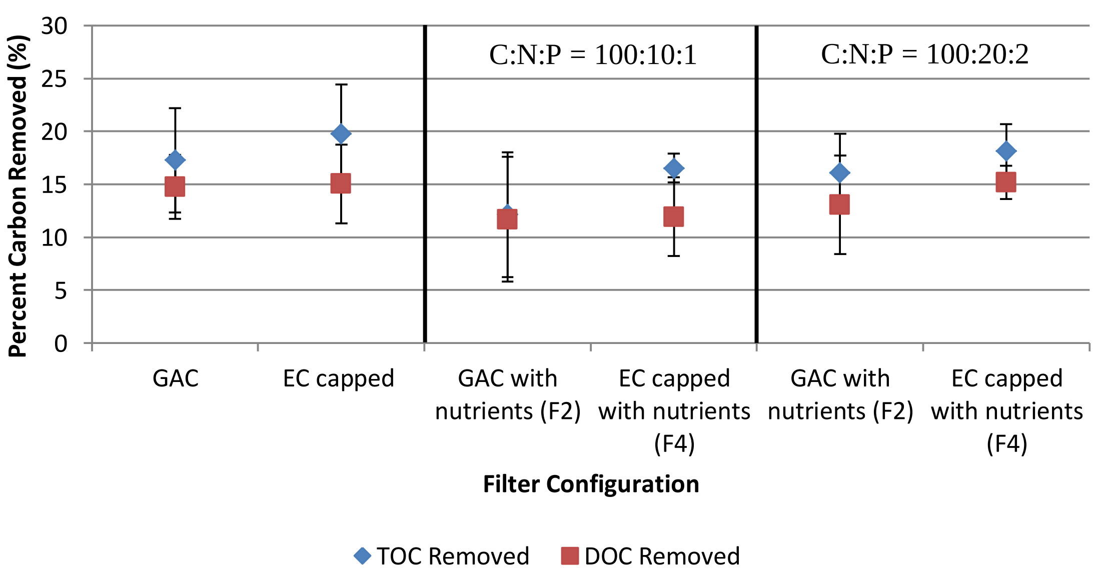

Figure 5.4: Mean concentration of TOC and DOC removed ± one standard deviation at the effluent at warm water conditions with and without nutrient amendments. This figure demonstrates no significant differences between the nutrient and non-nutrient-amended filters.

To evaluate the impact of the EC capping layer on BOM removal within the filter, samples collected at 30 cm below the surface the filter bed (sample port S2), and were analyzed for TOC and DOC. The mean fraction of TOC and DOC that was removed at sample port S2 compared to the effluent was evaluated, and is presented in Table 5.3.

Table 5.3: Mean fraction of the total TOC and DOC removed at sample port S2 at warm water conditions without nutrient amendments

	Filter 2 + 5	**Filter 1 + 4**
Media Configuration	GAC	EC and GAC
Fraction of TOC removed at sample port S2 (%)	63.9	54.1
Fraction of DOC removed at sample port S2 (%)	70.8	63.2

The fraction of the total TOC and DOC removed 30 cm below the top of the filter media by the GAC filter was better than using EC as a capping material, at the warm water conditions. However, differences in the TOC or DOC removal at sample port S2 (TOC: p = 0.2102, DOC: p = 0.1694) between the two filter configurations were not statistically significant. It is concluded that there were no impacts on water quality within the filter immediately after the capping material layer. Notably, over half of the total DOC that was removed at the effluent was removed within the first 30 cm of the each filter. This finding is consistent with existing biological filtration literature (Emelko et al., 2006; Moll et al., 1998; Servais et al., 1991; Wang et al., 1995).

5.2.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1

The mean percent of TOC and DOC removed by the GAC and EC capped filters during the 100:10:1 nutrient amendment experiment, with and without nutrient addition is presented in Figure 5.4. During this period, the mean influent TOC and DOC concentrations for each pilot-scale filter were 3.9 ± 0.2 mg/L and 3.7 ± 0.3 mg/L, respectively. The differences in the mean effluent TOC (p = 0.6679) and DOC (p = 0.5758) between the nutrient-amended (Filter 2) and non-nutrient-amended (Filter 5) GAC filters were not statistically significant (Appendix D). In addition, the differences in the mean effluent TOC (p = 0.7607) and DOC (p = 0.7456) between the nutrient-amended (Filter 4) and non-nutrient-amended (Filter 1) were not statistically significant (Appendix D). The differences in the mean TOC (p = 0.9252) and DOC (p = 0.5020) removal of the GAC and EC capped nutrient-amended filters were not statistically significant (Appendix D). Thus, amending the influent C:N:P ratio to 100:10:1 at warm water conditions had no impact on the removal of TOC or DOC. In addition, the EC capping material did not negatively impact either the TOC or DOC removal when amending the influent nutrient ratio.

5.2.7 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:20:2

The mean percent of TOC and DOC removed by the GAC and EC capped filters during the 100:20:2 nutrient amendment experiment is presented in Figure 5.4. During this period, the mean influent TOC and DOC concentrations for each pilot-scale filter were 4.6 ± 0.3 mg/L and 4.5 ± 0.3 mg/L, respectively. The differences in the mean effluent TOC (p = 0.6338) and DOC (p = 0.8283) between nutrient-amended (Filter 2) and non-nutrient-amended (Filter 5) GAC filters were not statistically significant (Appendix D). The differences in the mean effluent TOC (p = 0.0169) between the nutrient-amended (Filter 4) and non-nutrient-amended (Filter 1) EC capped filters was statistically significant, and higher removals were. However, differences in the DOC removal (p = 0.4877) were not statistically significant.

Amending the C:N:P ratio to 100:20:2 did not yield any improvements in either the TOC or DOC removal of the GAC filter. An improvement in the TOC removal was observed in the nutrient-amended EC capped filter compared to its control; however, no improvement in its DOC removal was observed. The lack of improvement in the DOC removal with nutrient addition at the filter configurations examined suggest that the consumption of DOC is not nutrient limited in terms of nitrogen or phosphorus and may be carbon limited. In addition, the EC capping material did not negatively impact either the TOC or DOC removal when amending the influent nutrient ratio.

5.3 Ammonia-Nitrogen

Samples were collected from the combined influent line and the effluent of each pilot-scale filter column and analyzed for NH_3-N. It is a key nutrient for heterotrophic bacteria and has been linked to regrowth in the distribution system. Detailed NH_3-N data obtained during the course of this project are provided in Appendix B.

5.3.1 Cold Temperature Range (< 5°C)

At cold water conditions without nutrient amendments, the mean influent NH_3-N concentration was 0.44 ± 0.07 mg/L. The differences in the NH_3-N removal by the two GAC filters (p = 0.5031) (Filters

2 and 5) and the two EC capped filters (p = 0.4624) (Filters 1 and 4) were not statistically significant, respectively (Appendix D). The GAC and EC capped filter data sets were pooled to evaluate the NH_3-N removal on a media configuration basis, and is presented in Figure 5.5.

Differences in the NH_3-N removal between the two filter configurations (p = 0.5609, Appendix D) were not statistically significant. Thus, there was no loss of performance in terms of the effluent NH_3-N removal by capping the GAC filter with EC at cold water conditions. A small increase in the NH_3-N concentration was observed at the effluent of each pilot scale filter compared to the influent NH_3-N concentration. Notably, the mean increase in the NH_3-N concentrations in the GAC filters were within range of the error of the ammonia ion-selective electrode that was used (± 0.01 mg/L).

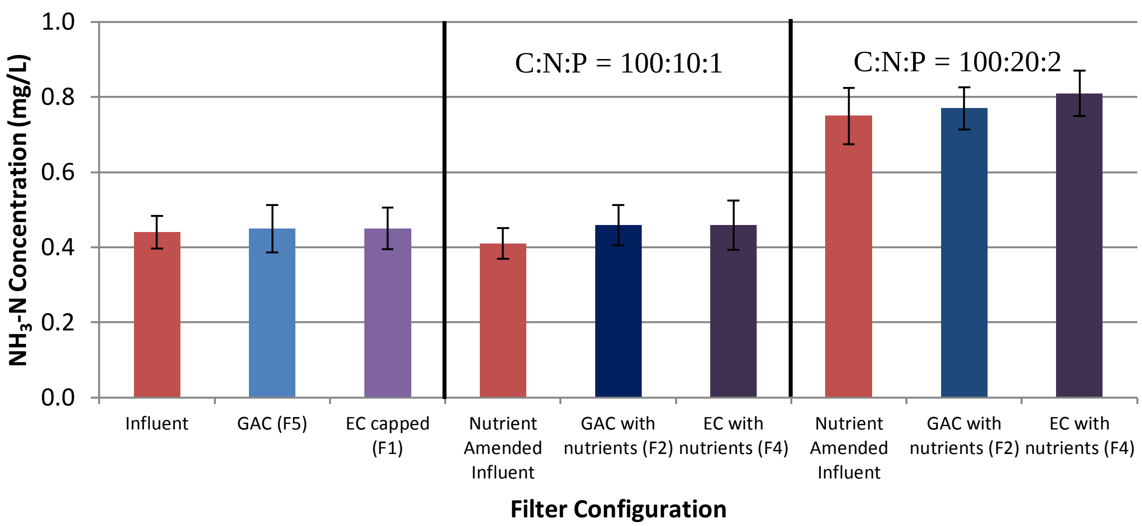

Figure 5.5: Mean NH_3-N concentration ± one standard deviation at the effluent at cold water conditions with and without nutrient amendments.

5.3.2 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:10:1

At cold water conditions the influent of the GAC (Filter 2) and EC capped (Filter 4) filters were amended to a stoichiometric C:N:P ratio of 100:10:1, and the NH_3-N data are presented in Figure 5.5. During the 100:10:1 nutrient amendment experiment, the mean influent NH_3-N concentration was 0.44 ± 0.04 mg/L. Based on the prescribed stoichiometric C:N:P ratio of 100:10:1, the mean influent NH_3-N concentration is in excess; the target NH_3-N concentration was 0.41 mg/L. During the course of the experiment, a small amount of NH_3-N was added to some filter cycles while others received none, depending on the relative DOC and NH_3-N concentrations measured at the last sampling event.

Differences in the NH_3-N removal between the nutrient-amended GAC (p = 0.4098) and EC capped (p = 0.4638) filters and their respective control filters were not statistically significant (Appendix D). It is concluded that there were no improvements in NH_3-N removal while amending the influent C:N:P stoichiometric ratio to 100:10:1 with either the GAC or EC capped filter at cold water conditions; the 100 fold increase in the molar concentration of phosphorus did not improve the NH_3-N removal. Additionally, the changes in the NH_3-N concentrations that were observed at each sampling location were small. Most of the mean differences fell within the acceptable error of the ion-selective electrode that was used (± 0.01 mg/L).

5.3.3 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:20:2

At cold water conditions the influent of the GAC (Filter 2) and EC capped (Filter 4) filters were amended to a stoichiometric C:N:P ratio of 100:20:2, and the NH_3-N data are presented in Figure 5.5. During this period, the mean influent NH_3-N concentration was 0.41 ± 0.07mg/L for each pilot-scale filter. Based on the stoichiometric C:N:P ratio of 100:20:2, the mean influent NH_3-N concentration was low and needed to be increased to 0.75 mg/L.

Differences in the NH_3-N removal between GAC (p = 0.3033) and EC capped (p = 0.9584) filters, and their respective control filters were not statistically significant (Appendix D). Thus, there were no improvements in NH_3-N removal while amending the influent molar C:N:P to 100:20:2 with either the GAC or EC capped filter, at cold water conditions; the 50 fold increase in the molar concentration of phosphorus yielded no positive impacts on the removal of NH_3-N. Increasing the ammonia concentration increased its mass transfer driving force, yet there was no increase in its removal. This suggests that NH_3-N was not a limiting nutrient at cold water conditions, and is not required by the microorganisms contained within the filter. This also suggests that adsorption was not a primary mechanism for the removal of NH_3-N in this system.

5.3.4 Transitional Temperature Range (5°C ≤ T < 15°C)

At transitional water temperatures without nutrient amendments for NH_3-N analyses. During these periods, the mean influent NH_3-N concentration was 0.10 mg/L for each pilot-scale filter. This is 74% lower than at cold water conditions. The differences in NH_3-N removal by the two GAC (p = 0.7626) or two EC capped (p = 0.4399) filters were not statistically significant, respectively (Appendix D). To compare the NH_3-N removed at the effluent of the filters on a media configuration basis, data from the two GAC and two EC capped filters were combined, respectively, and is presented in Figure 5.6.

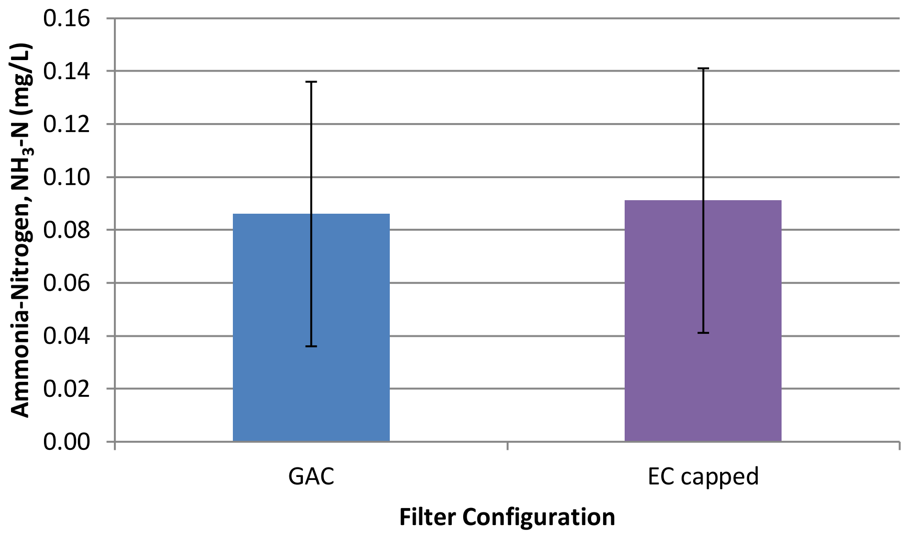

Figure 5.6: Mean NH_3-N concentration ± one standard deviation at the effluent categorized by filter configuration at transitional water temperatures without nutrient amendments. This figure demonstrates no statistical significance between the two configurations.

Differences in the NH_3-N removal between the two filter configurations (p = 0.5608) were not statistically significant (Appendix D). Thus, there was no loss of performance in terms of the effluent NH_3-N removal by capping the GAC filter with the EC media at transitional water temperatures. On average, a small decrease in the NH_3-N concentration was observed at the effluent compared to the influent concentration. Notably, the mean decreases in the NH_3-N concentrations that were observed were within the range of the acceptable error of the ammonia ion-selective electrode that was used (± 0.01 mg/L).

5.3.5 Warm Temperature Range (≥ 15°C)

At warm water conditions without nutrient amendments, the mean influent NH_3-N concentration was 0.03 mg/L for each pilot-scale filter. This was 93% lower than at cold water conditions. Differences in the NH_3-N removed by the GAC (Filters 2 and 5), and EC capped filters (Filters 1 and 4) were analyzed, and there were no statistical significance between the two GAC (p = 0.4292) and two EC capped (p = 0.6575) filter data sets, respectively (Appendix D). The GAC and EC capped filter data sets were pooled to evaluate the NH_3-N removal on a media configuration basis and is presented in Figure 5.7.

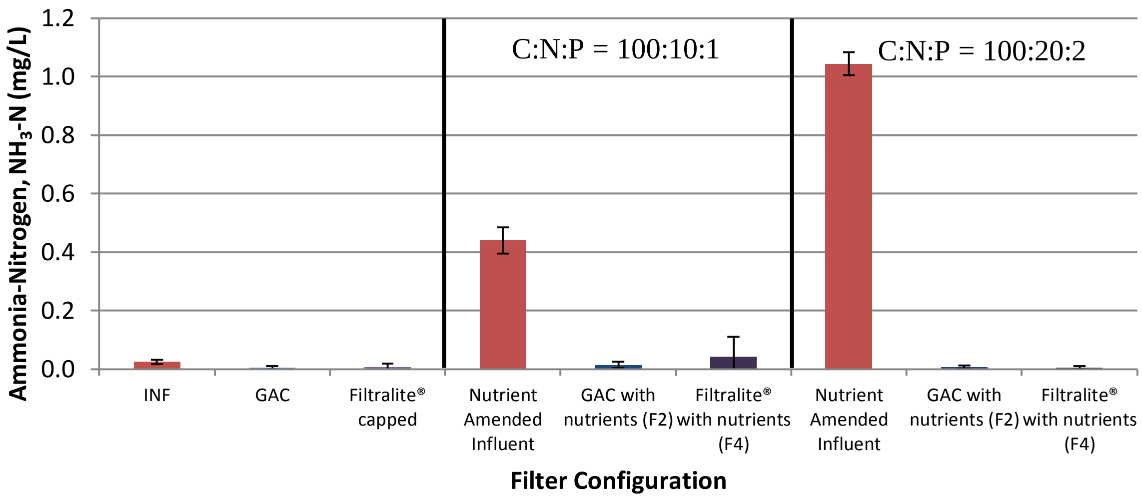

Figure 5.7: Mean NH_3-N concentration ± one standard deviation at the influent and effluent at warm water conditions with and without nutrient amendments

Differences in the mean effluent NH_3-N removal between the two filter configurations (p = 0.6522) were not statistically significant (Appendix D). Thus, there was no loss of performance in terms of effluent NH_3-N removal by capping the GAC filter with EC at warm water conditions.

5.3.6 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:10:1

At warm water conditions the influent of the GAC (Filter 2) and EC capped filters (Filter 4) were amended to a stoichiometric C:N:P ratio of 100:10:1 and analyzed for NH_3-N, is presented in Figure 5.7. During this period, the mean influent NH_3-N concentration was 0.04 ± 0.02 mg/L for each pilot-scale filter. Based on the prescribed stoichiometric C:N:P ratio of 100:10:1, the mean influent NH_3-N concentration needed to be increased to 0.44 mg/L. During the course of the experiments, NH_3-N was adjusted as necessary depending on the relative DOC and NH_3-N measured from the last sampling event.

Differences in the mean NH_3-N removal between the nutrient-amended GAC and EC capped filters (Filters 2 and 4) (p = 0.8339) were not statistically significant (Appendix D). An increase in the influent NH_3-N concentration of the GAC and EC capped filters, at warm water conditions, led to an increase in the amount that of NH_3-N that was removed. In contrast, at cold water conditions no increase in NH_3-N removal was observed when more was added. This suggests that there is increased biological activity within the filter. Additionally, the differences between effluent NH_3-N concentrations of the non-nutrient and nutrient-amended GAC (p = 0.5083) and EC capped (p =

0.4913) filters were not statistically significant, respectively (Appendix D). This indicates that adding NH_3-N to the influent did not negatively impact the effluent water quality of the effluent NH_3-N concentration. This also suggests that the system was deficient in NH_3-N, since at least 90% of the NH_3-N that was added to the influent GAC and EC capped filters was removed at the effluent. Residual NH_3-N that is not removed before disinfection will consume chlorine and may lead to regrowth in the distribution system.

5.3.7 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:20:2

At warm water conditions the influent of the GAC (Filter 2) and EC capped (Filter 4) filters were amended to a stoichiometric C:N:P ratio of 100:20:2 and analyzed for NH_3-N, is presented in Figure 5.7. During this period, the mean influent NH_3-N concentration was 0.03 ± 0.01 mg/L for each pilot-scale filter. Based on the molar C:N:P ratio of 100:20:2, the mean influent NH_3-N concentration needed to be increased to a concentration of 1.04 mg/L. During the course of the experiments, NH_3-N was adjusted as necessary depending on the relative DOC and NH_3-N measured from the last sampling event.

Differences in the mean NH_3-N removal between the GAC and EC capped nutriment-amended filters (p = 0.3284) were not statistically significant (Appendix D). Similar to the 100:10:1 nutrient amendment experiment at warm water conditions, a larger increase in the influent NH_3-N concentration of the GAC and EC capped filters led to an additional increase in the amount that was removed. Thus, there is increased biological activity within the filter. Additionally, the differences in the effluent NH_3-N concentrations of the non-nutrient and nutrient-amended GAC (p = 0.5173) and EC capped (p = 0.4969) filters were not statistically significant, respectively (Appendix D). Thus, adding NH_3-N to the influent did not negatively impact the effluent water quality in terms of the effluent NH_3-N concentration. This also suggests that the system was deficient in NH_3-N, because at least 99% of the NH_3-N that was added to the GAC and EC capped filters was removed.

5.4 Phosphorus

Grab samples were collected from the combined influent line and the effluent of each pilot-scale filter column and analyzed for total phosphorus (TP) and soluble reactive phosphorus (SRP). Phosphorus is a key nutrient for bacteria and has been linked to regrowth in the distribution system, as well as algal and cyanobacterial blooms around the world. SRP was the focus of the phosphorus investigation since it is the most assimilable form of phosphorus by microorganisms. It was found that the TP and SRP concentrations were equal to each other in most cases. This was expected since all samples were collected following chemical pre-treatment (coagulation, flocculation, and settling). Chemical coagulation and flocculation is very efficient at aggregating particles and enhancing their removal by gravity settling (Metcalf & Eddy, 2003). The agreement between the TP and SRP concentrations is of no surprise as most, or all of the particulate phosphorus would be removed from the water by settling before proceeding to the filters (Ebeling et al., 2003; Metcalf & Eddy, 2003). The analysis of the TP data is presented in Appendix D. Detailed TP and SRP data obtained during the course of this project are provided in Appendix B.

5.4.1 Cold Temperature Range (< 5°C)

During cold water conditions, the mean influent SRP concentration was 4.3 ± 1.8 µg/L for each pilot-scale filter. On average, each filter demonstrated reductions in the SRP concentration at the effluent. The SRP concentrations in the filter effluents were frequently measured near, or below the MDL. The differences in the SRP removal of the GAC (p = 0.3523) and EC capped (p = 0.4691) filters were not statistically significant (Appendix D). The impacts of capping material on SRP removal was compared between the GAC and EC capped filters (Figure 5.8).

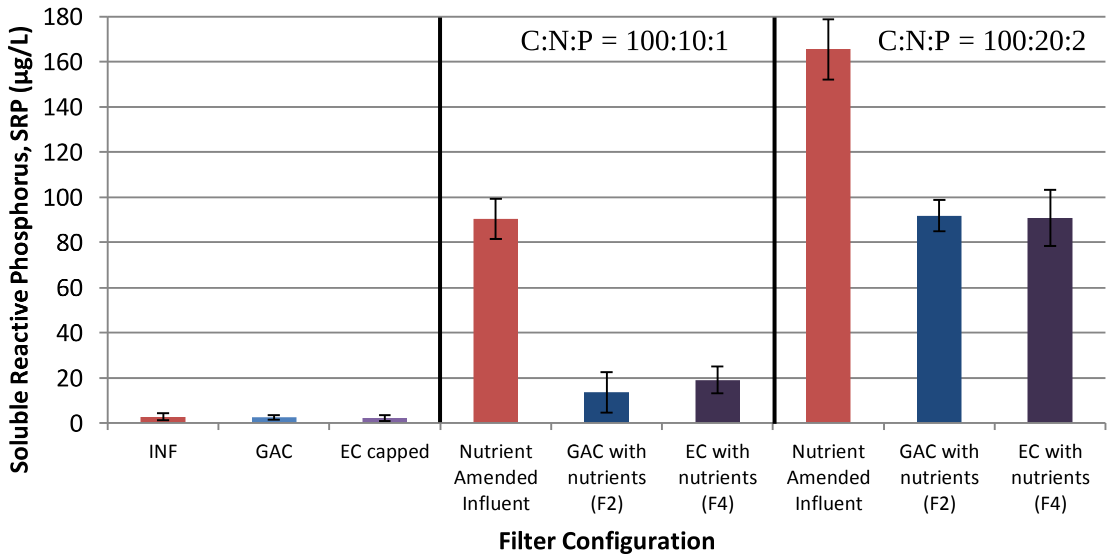

Figure 5.8: Mean concentration of SRP ± one standard deviation at the influent and effluent at cold water conditions with and without nutrient amendments

Differences in the mean SRP removals between the GAC and EC capped filters (p = 0.5451) were not statistically significant (Appendix D). Thus, there was no loss of performance in terms of effluent SRP removal by capping the GAC filter with EC media, at cold water conditions. The observed decreases in the mean SRP concentration at the effluent were small, and it should be noted that the mean decreases in the SRP concentrations were close to being within range of the acceptable error of the AutoAnalyzer II (± 1 µg/L).

5.4.2 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:10:1

At cold water conditions the influent of the GAC (Filter 2) and EC capped filter (Filter 4) were amended to a stoichiometric C:N:P ratio of 100:10:1, and analyzed for SRP. A summary of the mean SRP concentrations at the influent and the effluent is presented in Figure 5.8. During this period, the mean influent SRP concentration was 1.2 ± 0.4 µg/L for each pilot-scale filter. Based on the prescribed stoichiometric C:N:P ratio of 100:10:1, the mean influent SRP concentration was below the target of 90.5 µg/L. During the course of the experiments, the influent SRP concentrations were monitored regularly, and the addition of H_3PO_4 to Filters 2 and 4 were adjusted as required depending on the relative DOC and SRP concentrations measured from the last sampling event. The SRP concentrations at the effluent of the non-nutrient-amended filters were essentially unchanged from the influent. However, a significant amount of SRP was removed from the nutrient-amended filters relative to their amended influent.

Difference in the mean SRP removals between nutrient-amended GAC and EC capped filters (p = 0.8810) were not statistically significant (Appendix D). This suggests that the EC capping material did not impact the amount of SRP removed at the effluent when the influent C:N:P ratio was amended to 100:10:1, at cold water conditions. It is concluded that the mass of SRP removed by both the GAC and EC capped filters were not different.

The mean reduction of the SRP concentration by the GAC and EC capped filters were 76.9 µg/L and 71.4 µg/L, respectively. Thus, phosphorus was a limiting nutrient in the system. This was expected considering that the filters are located downstream of chemical pre-treatment at the MWTP. Soluble phosphorus readily reacts with iron, aluminum, or calcium ions to form insoluble complexes; iron, aluminum, and calcium salts are typically used in water treatment as a coagulant. Since the coagulant used at the MWTP is PACl, the low influent phosphorus concentrations to the pilot plant suggest that the coagulation, flocculation, and clarifications steps were operating properly (Ebeling et al., 2003; Metcalf & Eddy, 2003).

Even though a large amount of SRP was removed by the nutrient-amended filter, the improvements in performance that were observed by Lauderdale et al. (2012) were not observed in this system. No improvements in the rate of head loss accumulation, DOC removal, or NH_3-N removal were observed. While the additional phosphorus was being metabolized by the biofilm, it did not enhance biological filtration performance. There are a variety of ways in which heterotrophic bacteria can use substrates, nutrients, and growth factors. A summary of the potential metabolic pathways are illustrated in Figure 5.9.

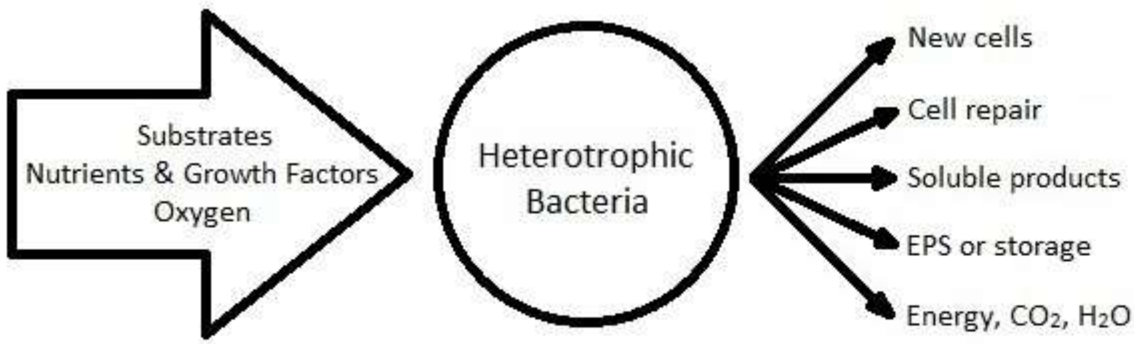

Figure 5.9: Summary of potential metabolic pathways of heterotrophic bacteria adapted from Blanch & Clark (1997)

Substrates, nutrients, and growth factors that are taken up by heterotrophic bacteria can be used: to produce new cells, to repair existing cells, to produce a soluble product released into the environment, to produce extracellular polymeric substances (EPS), for reserve resources stored within the cell, or to produce energy through respiration (Figure 5.9). Since no change in the rate of head loss accumulation was observed with the nutrient amendments, it is deduced that there was no significant change in microorganism population or production of EPS. If there was an increase in the microorganism concentration or production of EPS, an increase in the rate of head loss accumulation would be expected. It is also deduced that the addition of the nutrients did not yield a change in the activity of the microorganisms within the filter since the removal of DOC at the effluent of the filters were not different. A change in the soluble products produced by the microorganisms could not be determined since a distribution of the molecular weight of the DOC in the influent and effluent streams was not evaluated. It is hypothesized that the phosphorus taken up by the microorganisms is being used for cell repair, or storage while being exposed to long periods of phosphorus limited conditions.

The mean effluent SRP concentrations of the GAC and EC capped nutrient-amended filters were 13.6 µg/L and 19.1 µg/L, respectively. These levels of SRP may lead to microbial regrowth in the drinking water distribution system. It has been demonstrated in a number of studies that concentrations of phosphorus from 1 µg/L to 400 µg/L can lead to increases in microbial growth in the water and biofilms within distribution systems (Chu et al., 2005; Fang et al., 2009; Hozalski et al., 2005; Lehtola et al., 2002).

5.4.3 Cold Temperature Range (< 5°C) with Nutrient Amendments at 100:20:2

At cold water conditions the influent of the GAC (Filter 2) and EC capped filter (Filter 4) were amended to a stoichiometric C:N:P ratio of 100:20:2, and analyzed for SRP. A summary of the mean SRP at the influent and the effluent is presented in Figure 5.8. During this period, the mean influent SRP concentration was 3.7 ± 0.7µg/L for each pilot-scale filter. Based on the stoichiometric C:N:P ratio of 100:20:2, the mean influent SRP concentration was below the target of 165.5 µg/L. During the course of the experiments, the influent SRP concentrations were monitored regularly, and the addition of H_3PO_4 was adjusted as required depending on the relative DOC and SRP concentrations measured from the last sampling event. The SRP concentration at the effluent of the non-nutrient-amended filters appeared to be unchanged from the influent. However, a significant amount of SRP was removed from nutrient-amended filters relative to their amended influent.

Differences in the mean SRP removal between the GAC and EC capped nutrient-amended filters ($p = 0.4268$) were not significantly different (Appendix D). Thus, the EC capping material did not impact the amount of SRP removed at the effluent when their influent stream C:N:P ratio is amended to 100:20:2, at cold water conditions. It is also concluded that the mass of SRP removed by each filter was not different.

The mean reduction of SRP by the nutrient-amended GAC and EC capped filters were 73.6 µg/L and 74.7 µg/L, and this suggests that phosphorus is a limiting nutrient in this system. This was expected since the pilot-scale filters are located downstream of the coagulation, flocculation, and clarification processes at the WMTP. The differences in the SRP removals by the nutrient-amended filters during both the 100:10:1 and 100:20:2 nutrient dosing experiments for the GAC filter ($p = 0.2461$) or the EC capped filter ($p = 0.7142$) were not statistically significant, respectively (Appendix D). While the system was phosphorus limited, the data suggest that there is a limit to the amount of phosphorus that could be taken up by the microorganisms within the filters. It can also be concluded that the mechanism for phosphorus uptake is not primarily adsorption to the filtration media. If the primary mechanism was adsorption, the removal of SRP would have increased with the increase in the influent concentration, or mass transfer driving force.

Even though a large amount of SRP was removed by the nutrient-amended filter, the associated performance that were observed by Lauderdale et al. (2012) were not observed in this system. No improvements in the rate of head loss accumulation, or DOC removal were observed. While the additional phosphorus was being metabolized by the biofilm, it did not respond in a way that either enhanced or diminished biological filtration performance. As illustrated in Figure 5.9, there are a number ways in which substrates, nutrients, and growth factors can be utilized by heterotrophic bacteria. The phosphorus that was metabolized by the microorganisms in the filter may have utilized it for cell repair or storage, and not for enhancing BOM removal or reducing EPS production. Lastly, the mean effluent SRP concentrations of the nutrient-amended GAC and EC capped filters were 91.9 µg/L and 90.8 µg/L, respectively. SRP levels of these magnitudes may lead to microbial regrowth in the drinking water distribution system. This also suggests that there is a limit to the amount of phosphorus that the microorganisms can metabolize at experimental conditions.

5.4.4 Transitional Temperature Range (5°C ≤ T < 15°C)

At transitional water temperatures without nutrient amendments were analyzed for SRP. During this period, the mean influent SRP concentration was 4.8 ± 1.4 µg/L for each pilot-scale filter. The differences in the SRP removed by the GAC filters ($p = 0.9181$) and the EC capped ($p = 0.1110$) filters were not statistically significant, respectively (Appendix D). To compare the effluent SRP removal on a capping material basis, data from the GAC and EC capped filters were combined, respectively. A summary of this data is presented in Figure 5.10.

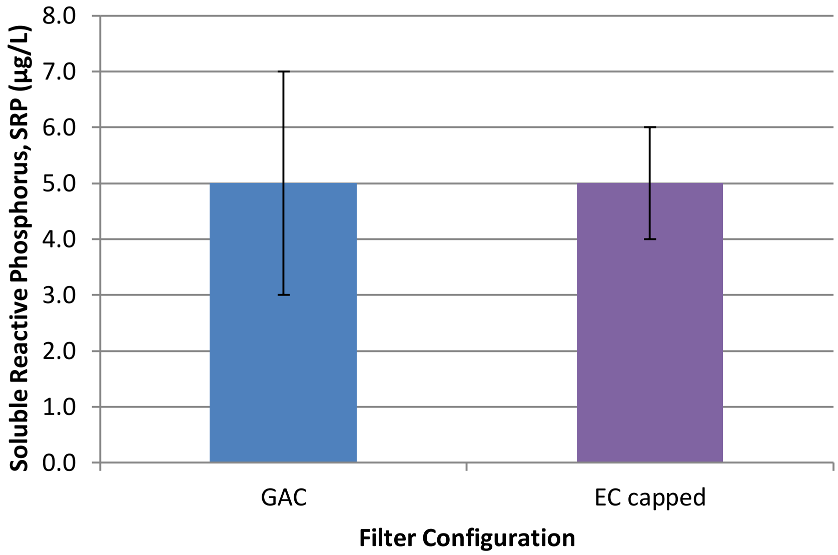

Figure 5.10: Mean concentration of SRP± one standard deviation at the effluent at transitional water temperatures without nutrient amendments. This figure demonstrates no statistical significance between the two configurations.

The differences in the SRP removal from the GAC and EC capped filters were compared and found not to be statistically significant (Appendix D). Thus, there was no loss of performance in terms of effluent SRP removal by capping the GAC filter with EC media, at transitional water temperatures. The observed decreases and increases in the mean SRP concentration at the effluent were small. It should be noted that the mean decreases in the SRP concentrations were within range of the acceptable error of the AutoAnalyzer II that was used (± 1 µg/L). Consequently, the SRP concentration may actually be unchanged from the influent, and the observed mean decreases may be associated with instrument error.

5.4.5 Warm Temperature Range (T ≥ 15°C)

At warm water conditions the mean influent SRP concentration was 1.3 ± 0.7 µg/L for each pilot-scale filter. Differences in the SRP removed by the GAC (p = 0.4101) and EC capped filters (p = 0.3692) were not statistically significant (Appendix D). To compare the effluent SRP removed on a capping material basis, data from GAC and EC capped filters were combined, respectively. A summary of this data is presented in Figure 5.11.

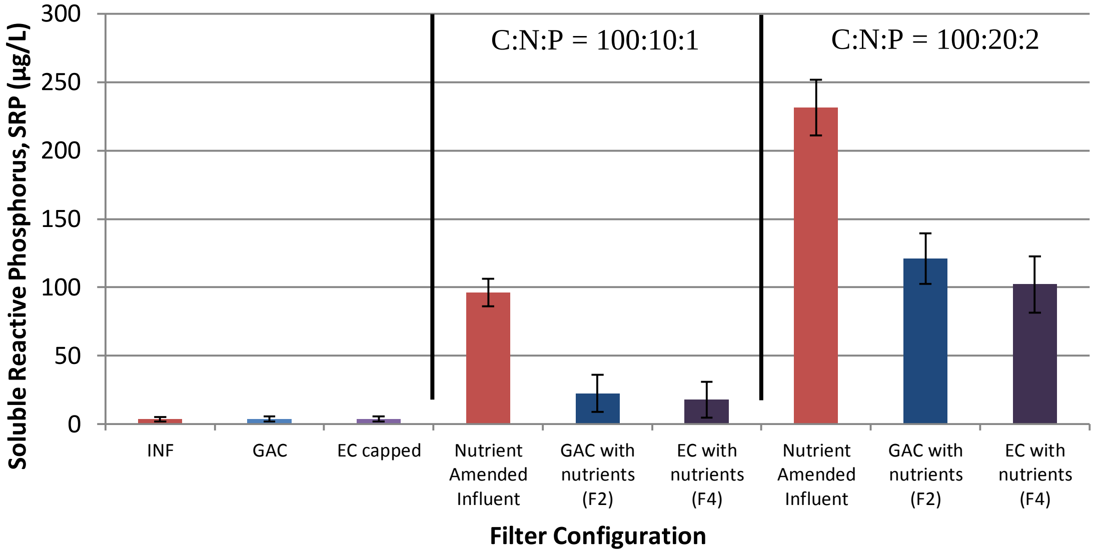

Figure 5.11: Mean SRP concentration ± one standard deviation at the influent and effluent at warm water conditions with and without nutrient amendments

Differences in the SRP removal between the two filter configurations (p = 0.3798) were not statistically significant (Appendix D). Thus, there was no loss of performance in terms of effluent SRP removal by capping the GAC filter with EC media, at warm water conditions. The observed decreases in the mean SRP concentration at the effluent were small. It should be noted that these differences in mean concentrations fall within the acceptable range of the error of the instrument (± 1 µg/L).

5.4.6 Warm Temperature Range (T ≥ 15°C) with Nutrient Amendments at 100:10:1

At warm water conditions while the influent of the GAC (Filter 2) and EC capped filter (Filter 4) were amended to a stoichiometric C:N:P ratio of 100:10:1. A summary of the mean SRP concentrations at the influent and the effluent are presented in Figure 5.11. During this period, the mean influent SRP concentration was 3.4 ± 1.9 µg/L for each pilot-scale filter.

Based on the prescribed stoichiometric C:N:P ratio of 100:10:1, the mean influent SRP concentration was below the target of 96.4 µg/L. During the course of the experiments, the influent SRP concentrations were monitored regularly, and the addition of H_3PO_4 was adjusted as required depending on the relative DOC and SRP concentrations measured from the last sampling event. The SRP concentration at the effluent of the non-nutrient-amended GAC and EC capped filters appeared to be unchanged from the influent. In contrast, a large amount of SRP was removed from nutrient-amended filters relative to their amended influent.

Differences in the SRP removed by the GAC and EC capped nutrient-amended filters (p = 0.2893) were not statistically significant (Appendix D). Thus, the EC capping material did not impact the amount of SRP removed at the effluent while amending the influent C:N:P ratio to 100:10:1, at warm water conditions. It is concluded that the mass of SRP removed by the nutrient-amended filters were not significant.

The mean reduction of SRP by the nutrient-amended GAC and EC capped filters were 74.0 µg/L and 78.4 µg/L, respectively; this suggests that phosphorus is a limiting nutrient in this system. This was expected since the pilot-scale filters are located downstream of the coagulation, flocculation, and clarification processes at the WMTP. However, the mean effluent SRP concentrations of the GAC and EC capped filters were 22.4 µg/L and 18.0 µg/L, respectively. These levels of SRP may lead to microbial regrowth in the drinking water distribution system.

Even though a relatively large amount of both NH_3-N and SRP were removed by the nutrient-amended filters, compared to the non-nutrient-amended filter, the improvements in performance that were observed by Lauderdale et al. (2012) were not observed in this system at warm water conditions, while amending the stoichiometric C:N:P ratio to 100:10:1. No improvements in the rate of head loss accumulation or DOC removal were observed. However, there was an improvement in the filter run time with the nutrient-amended EC capped filter only; no change in the filter run time was observed with nutrient-amended GAC filter. This supported the earlier conclusions that using a capping material with a larger effective grain size can help enhance the impact of nutrient addition.

Since no change in the rate of head loss accumulation was observed when the influent C:N:P ratio was amended to 100:10:1, it can be concluded that there was no significant change in microorganism population or EPS production. It is also deduced that the addition of the nutrients did not yield a change in the activity of the microorganisms within the filter since the removal of DOC at the effluent of the filters were not different. Accordingly, it is hypothesized that the nitrogen and phosphorus metabolized by the microorganisms is being used for cell repair, or storage while being exposed to long periods of nitrogen and phosphorus limited conditions.

5.4.7 Warm Temperature Range (≥ 15°C) with Nutrient Amendments at 100:20:2

Samples were collected at warm water conditions while the influent of the GAC (Filter 2) and EC capped filters (Filter 4) were amended to a stoichiometric C:N:P ratio of 100:20:2, and analyzed for SRP. A summary of the mean SRP concentrations at the influent and the effluent are presented in Figure 5.11. During this period, the mean influent SRP concentration was 5.0 ± 0.3 µg/L for each pilot-scale filter.

Based on the stoichiometric C:N:P ratio of 100:20:2, the mean influent SRP concentration was below the target of 231.3 µg/L. During the course of the experiments, the influent SRP concentrations were monitored regularly, and the addition of H_3PO_4 to Filters 2 and 4 was adjusted as required depending on the relative DOC and SRP concentrations measured from the previous sampling event. The SRP concentration at the effluent of the non-nutrient-amended GAC and EC capped filters appeared to be unchanged from the influent. However, a significant amount of SRP was removed from nutrient-amended filters relative to their amended influent.

The SRP removed at the effluent of the nutrient-amended filters were analyzed, and no statistical significance was observed (Appendix D). Thus, the EC capping material did not impact the amount of SRP removed at the effluent when their influent stream C:N:P ratio is amended to 100:20:2, at warm water conditions. It is concluded that the mass of SRP removed by each filter was not different.

The mean reduction in the SRP concentration by the nutrient-amended GAC and EC capped filters at the 100:20:2 C:N:P ratio were 110.3 µg/L and 129.1 µg/L, and this suggests that phosphorus is a limiting nutrient in this system. As more phosphorus was added to the nutrient-amended filters, there was a significant increase in the amount of phosphorus that was removed by both the GAC (p = 0.0023) and the EC capped (p = 0.0004) filters (Appendix D). With the increase in both the nitrogen and phosphorus concentrations, there was an increase in the amount of SRP removed. While the system was phosphorus limited, the data suggests that there is a limit to the amount of phosphorus that could be taken up by the microorganisms within the filters. It can also be concluded that the mechanism for phosphorus removal by the biological filters is not primarily adsorption to the media. If the primary mechanism was adsorption, the removal of SRP would have doubled with the doubling of the influent concentration, or mass transfer driving force.

With the amendment of the nutrients to the 100:20:2 stoichiometric C:N:P ratio, an improvement in the rate of head loss accumulation and filter run time was observed in the EC capped filter. The nutrients that were taken up allowed the biofilm to respond in such a way that reduced the rate of head loss development (Lauderdale et al., 2012) helping to extend filter run time. This could have allowed the microorganisms to consume their stored resources and led to more efficient respiration and energy production. The nutrients that were taken up may have also contributed towards cell repair or storage. Similar improvements in head loss accumulation and filter run time were not observed in the GAC filter even though the same amount of nitrogen and phosphorus was removed. This suggests that the layer of EC helped enhance the benefits of nutrient amendments due to the difference in grain size. However, no improvements in DOC removal were observed in either filter configuration while amending the stoichiometric C:N:P ratio to 100:20:2. Lastly, the mean effluent SRP concentrations of Filters 2 and 4 were 121.0 µg/L and 102.2 µg/L, respectively. SRP levels of these magnitudes may lead to microbial regrowth in the drinking water distribution system. In contrast, the average effluent SRP concentrations of the non-nutrient-amended pilot-scale filters was 4.9 ± 0.6 µg/L.

5.5 DOC Removal Temperature Dependence

The impact of temperature on the percent effluent DOC removed, without nutrient amendments, of each pilot-scale filter was evaluated on a filter configuration basis. The mean percent of DOC removed was plotted against the cold and water temperature ranges are presented in Figure 5.12.

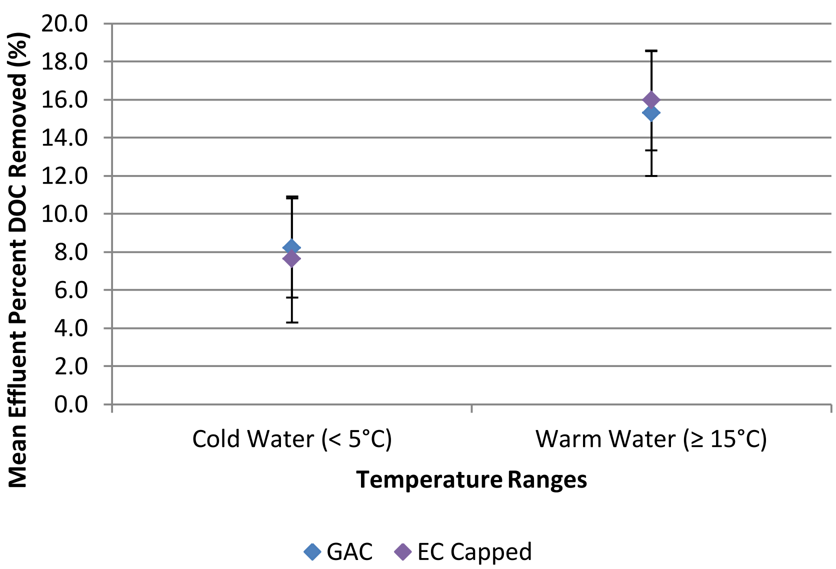

Figure 5.12: Pilot-scale filter mean percent DOC removal ± one standard deviation vs cold and warm temperature ranges without nutrient amendments

The data suggests that there is a direct relationship between the mean percent of DOC removed at the effluent and the water temperature. The observed increase in the percent of DOC removed is consistent with typical biological filtration performance. Higher temperatures often yield higher levels of microbiological activity leading to higher removals of DOC. It was found that difference in the percent of effluent DOC removed at cold and warm water conditions for each filter configuration were statistically significant (Appendix E).

Since it was concluded that there was no statistical significance in the removal of DOC of each filter at all temperatures, it can be assumed that the slopes of lines drawn between the data points would be similar. This provides evidence that the DOC removed at the effluent of each filter were not different at the observed temperature ranges. It can be concluded that the capping materials that were tested did not have any negative impacts on effluent water quality, in terms of effluent DOC removal, at all temperature ranges.

5.6 Consumed Nutrient Ratios

As illustrated previously, the concept of nutrient amendments has sparked a lot of interest in the drinking water industry through the work LeChevallier et al. (1991), and in large part by the results published by Lauderdale et al. (2012). Based on these two publications, the importance of amending the influent stoichiometric concentrations of carbon, nitrogen, and phosphorus to a C:N:P ratio of 100:10:1 has been presented. Amending the influent stoichiometric C:N:P ratio to 100:10:1 was reported to have decreased terminal head loss, as well as led to higher removals of DOC, manganese (Mn), and 2-methylisoborneol (MIB) (Lauderdale et al., 2011).

To assess the validity of the C:N:P ratio of 100:10:1, it was evaluated using the molar concentrations of carbon, nitrogen, and phosphorus that were removed by the pilot-scale filter and nutrient dosing configuration. Nutrients dosed into the influent streams were based on the measured influent DOC concentrations. The nutrients were dosed this way to maximize the potential amount of DOC that could be removed, based on 100:10:1 ratio recommended by LeChevallier et al. (1991) and Lauderdale et al. (2012). Further, the dosage rates were calculated in this way to prevent factors that could not be controlled during the pilot experiments from confounding the results and conclusions. To evaluate the relative nutrient ratios, the concentrations of the nutrients that were consumed were normalized with respect to the amount of carbon, or DOC, that was removed by each filter. The carbon concentrations were normalized to a value of 100.

The relative C:N:P stoichiometric ratios of the consumed nutrients at cold water conditions with and without nutrient amendments are presented graphically in Figure 5.13(a) and Figure 5.13(b), respectively. The relative C:N:P stoichiometric ratios of the consumed nutrients at warm water conditions with and without nutrient amendments are presented graphically in Figure 5.13(c) and Figure 5.13(d), respectively.

Without the addition of nutrients at cold water conditions, the C:N:P ratio of the consumed nutrients was 100:0:02 for the GAC, EC capped filters. This indicates that the removal of nutrients at cold water conditions was not impacted by the capping materials that were tested. Since the mass of nutrients consumed was the same, this may also suggest that the microbial communities within each filter were not different. When the nutrient dosage rate was adjusted to amend the influent C:N:P ratio to 100:10:1 with respect to the total influent DOC concentration, it was found that the consumed nutrient ratio was approximately 100:0:11.1. With the increase in removal of phosphorus, no change in the DOC removal or head loss was observed compared to the control filters. This observation is not in agreement with the results that were obtained by Lauderdale et al. (2012). The additional phosphorus that was removed from the water could have been used for other purposes other than to metabolize carbon. Further, the removals of nutrients were not impacted by the capping materials that were tested. When the nutrient dosage rate was adjusted to amend the influent C:N:P ratio to 100:20:2 with respect to the total influent DOC concentration, it was found that the consumed nutrient ratios were approximately 100:0:9.6.

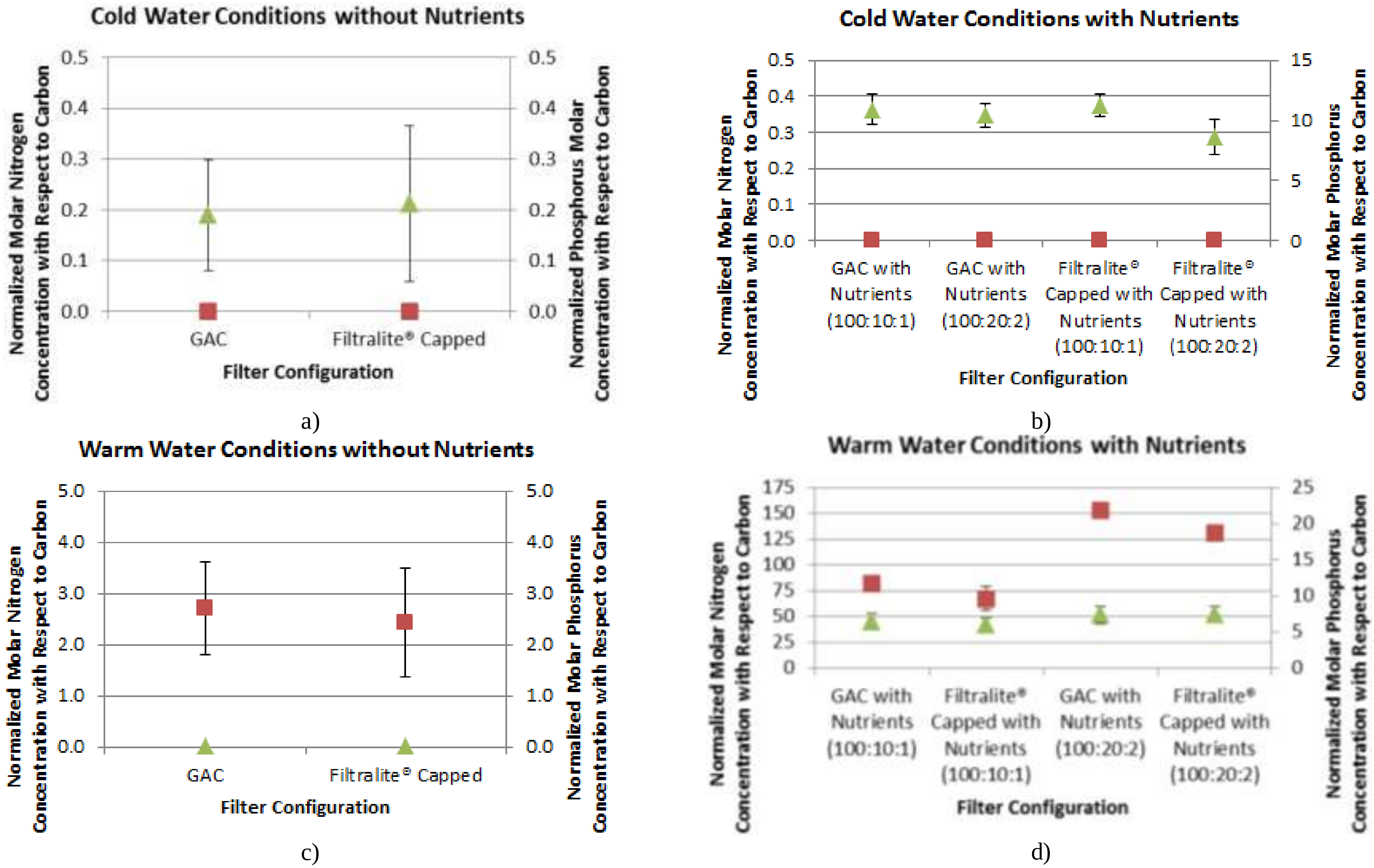

Figure 5.13: Normalized molar N (■) and P (▲) concentrations removed with respect to C at a) cold water conditions without nutrients, b) cold water conditions with nutrients, c) warm water conditions without nutrients, and d) warm water conditions with nutrients

At the different nutrient dosing rates at cold water conditions, the consumed nutrient ratios were essentially unchanged. Because there was no increase in the removal of nitrogen or phosphorus with the increase in their respective dosage rates, it can be concluded that the primary mechanism for nutrient removal was not adsorption. If adsorption was the primary mechanism for nutrient removal, the increase in amount of nutrients removed would match the amount that was added, due to an increase in the mass transfer driving force. This also suggests that the maximum amount, and theoretical ideal amount, of nitrogen and phosphorus for the microbiology in the filters was achieved during the cold water experiments. The ideal nutrient ratio for the biological filters at the MWTP at cold water conditions, with respect to the amount of DOC removed at the effluent is approximately 100:0:10. Based on the parameters that were monitored, there was no benefit to dosing nutrients at cold water conditions. However, there may be other benefits to amending the influent nutrient ratio for other operational parameters that were not monitored during these experiments. Nutrient amendments may shorten the acclimation time for a biological filter when starting with virgin media at cold water conditions.

Without the addition of nutrients at warm water conditions, the C:N:P ratio of the consumed nutrients was approximately 100:2.5:0 for both the GAC and EC capped filters. This indicates that the removal of nutrients at warm water conditions was not impacted by the capping materials that were tested. Additionally, this may suggest that the microbial communities within each filter likely were not significantly different. When the nutrient dosage rate was adjusted to amend the influent C:N:P ratio to 100:10:1 with respect to the total influent DOC concentration, it was found that the consumed nutrient ratio in the GAC and EC capped filters were 100:81.5:6.4 and 100:67.3:6.0, respectively. Although the ratios of the nitrogen removed appear to be different, the mass of DOC and NH_3-N removed by both nutrient-amended filters were found to not be statistically different (Appendix D). The consumed nutrient ratio of 100:67.3:6.0 in the EC capped filter did lead to an improvement in the filter run time, but no improvements in the rate of head loss accumulation or DOC removal. In contrast, no changes in the performance of the nutrient-amended GAC filter were observed. When the nutrient dosage rate was adjusted to amend the influent C:N:P ratio to 100:20:2 with respect to the total influent DOC concentration, it was found that the consumed nutrient ratios in the GAC and EC capped filters were 100:153.3:7.4 and 100:131.4:7.4, respectively. Although the ratios of the nitrogen removed appear to be different, the mass of DOC and nitrogen removed in both nutrient-amended filters were found to be not statistically different. The consumed nutrient ratio of 100:131.4:7.4 in the EC capped filter did lead to an improvement in the rate of head loss accumulation and filter run time, but not changes in DOC removal. In contrast, no changes in the performance of the nutrient-amended GAC filter were observed.

At the different nutrient dosing rates at warm water conditions, the consumed nutrient ratios changed based on the availability of nitrogen and phosphorus. This suggests that there is an increase in the biological activity, and possibly a shift in the microbiological community. The effects of nutrient amendments on microbial activity and communities have been investigated extensively in studies of soil ecology. Chaudhry et al. (2012) found that the form of the nutrients (chemical or natural) that were added affected both the microbial activity and diversity of the microbial community. Shifts in microbial activity also can lead to the dominance of certain species over others, leading to a shift in the microbial community (Øvreås et al., 1998). In another study, nitrogen amendments to soil samples altered enzyme production of the existing microbial community and concurrently shifted microbial community composition (Ramirez et al., 2012). To better understand the impact of nutrient amendments on biological filters, microbiological techniques to assess biological activity and community structures should be applied. Based on the data collected, the optimal consumed nutrient ratio was not achieved during the course of the warm water experiments because the nitrogen that was added to the pilot-scale filters was removed to concentrations that were not different from the respective control filters. Unlike at cold water conditions, there was an increase in the phosphorus removal with the increase in the nutrient influent dosage rate from 100:10:1 to 100:20:2. It may be possible for more phosphorus to be removed with the addition of more nitrogen. It may also be possible that higher removals of DOC could be achieved with the addition of higher concentrations of nitrogen.

Lauderdale et al. (2011) performed two nutrient dosing experiments, initial and validation, at an amended influent C:N:P ratio at 100:10:1 at warm water conditions. The amended influent nutrient ratio was based on the amount of DOC that was removed by the control filter, and not the total influent DOC. Lauderdale et al. (2011) noted that breakthrough of NH_3-N and PO_4-P were observed in the effluent during their experiments. Using the data that was presented, the consumed nutrient ratios were evaluated and are presented in Figure 5.14. The mean consumed C:N:P ratios during the initial and validation experiments were 100:4.6:0.3 and 100:2.9:0.5, respectively. Accordingly, the data presented by Lauderdale et al. (2011) provides additional evidence that a C:N:P ratio of 100:10:1 is not optimal for biological filtration performance enhancement.

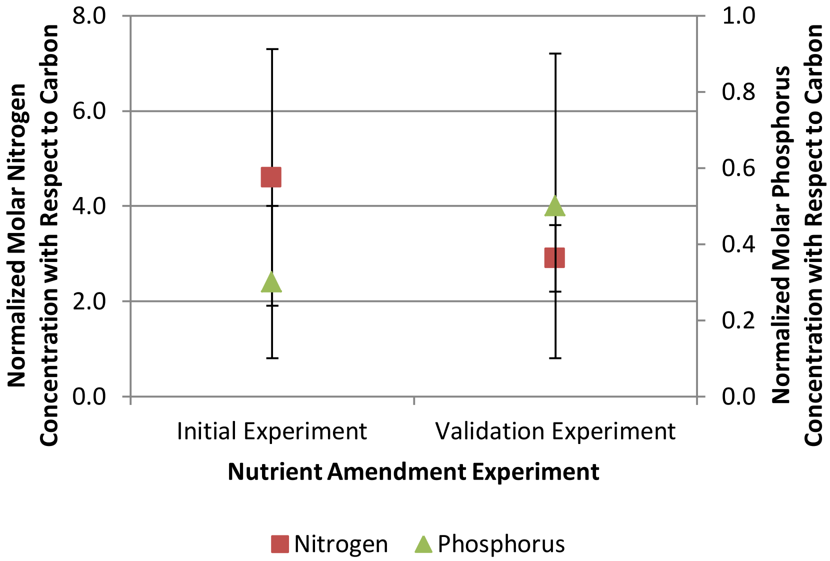

Figure 5.14: Consumed nutrient ratios during experiments by Lauderdale et al. (2011)

It can be concluded that the microorganisms within the pilot-scale filters did not consume nutrients at the prescribed 100:10:1 stoichiometric ratio. Additional nutrient amendment studies at different dosage rates should be tested. A different consumed nutrient ratio may yield similar improvements in the rate of head loss accumulation in the GAC filter that were observed in the EC capped filter. Further, nutrient dosing experiments should be conducted with the BioFill® capped filter to determine if the improvements seen in the EC capped filter with nutrient addition at warm water conditions could be observed with a larger, non-adsorptive media. Additionally, nutrient amendments may shorten the acclimation time for a biological filter when starting with virgin media at warm water conditions.

5.7 Summary

- The EC capping layer did not negatively impact TOC or DOC removal at the temperature conditions that were examined.
- Amending the influent molar C:N:P ratio to 100:10:1 or 100:20:2, generally, did not improve the TOC or DOC removal of any of the filter configurations or temperature conditions examined.

- When NH_3-N was added at cold water conditions, no additional NH_3-N was removed by the biological filters. This suggests that the system was deficient in nitrogen, but not nitrogen limited with respect to DOC removal.
- When NH_3-N was added at warm water conditions, 90-99% of the NH_3-N that was added was removed by the biological filters. This suggests that the system was nitrogen deficient, but not nitrogen limited with respect to DOC removal.
- When H_3PO_4 was added at both cold and warm water conditions it was removed by the filters. However, there was a limit to the amount that could be removed. This suggests that the system was phosphorus deficient, but not phosphorus limited with respect to DOC removal.
- DOC removal demonstrated a strong temperature dependence, which is consistent with literature.
- The consumed nutrient ratios that were calculated were not consistent with the recommended molar C:N:P ratio of 100:10:1.

Chapter 6

Efficacy of Plastic Capping Material for Biological Filtration

6.1 Overview

The MWTP pilot-scale filters were configured to evaluate the applicability of replacing the top layer of GAC in a biological filter with a capping material with a larger effective size, as well as amending the influent stoichiometric nutrient ratio, on both traditional and biological filtration performance for the production of drinking water. A plastic BioFill® media with a diameter of 2.5 cm was selected for the purposes testing a capping material that was significantly larger than the bulk granular material in the filter. Since the pilot plant consists of five filter columns, the EC capped filter was duplicated for the purposes of conducting the nutrient amendment experiments since this filter configuration is more likely to be found in a drinking water treatment plant. This in turn would yield results that may be more applicable to municipal drinking water providers. This chapter examines the impact the using the BioFill® media as a capping layer for a biologically active GAC filter on its operational performance and nutrient removal.

6.2 Traditional Filtration Performance

6.2.1 Effluent Turbidity

The effluent turbidity trends of the plastic capped filter were similar to the other filter configurations at all temperature conditions. Rapid increases in effluent turbidity that were observed in the GAC or EC capped filters were similarly observed in the plastic capped filter. These trends are presented in Figure 6.1 and Figure 6.2 at cold and warm water conditions, respectively. The plastic capped filter was able to achieve excellent effluent turbidities ≤ 0.1 NTU; the plastic capping layer did not negatively impact the effluent filter turbidity. The turbidity trends of the plastic capped filter were also similar to the effluent turbidity trends of the nutrient-amended GAC and EC capped filters at cold and warm water conditions. Detailed turbidity data obtained during the course of this project are provided in Appendix A.

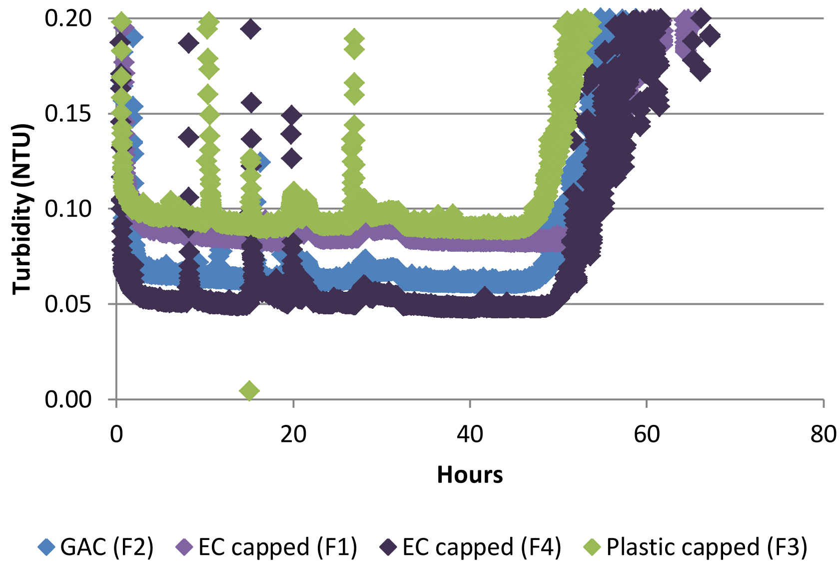

Figure 6.1: Pilot plant effluent turbidity data at cold water conditions (mean temperature =1.5°C) from 1-4 December 2013. This figure demonstrates that similar turbidity trends were observed by all filter configurations at cold water conditions.

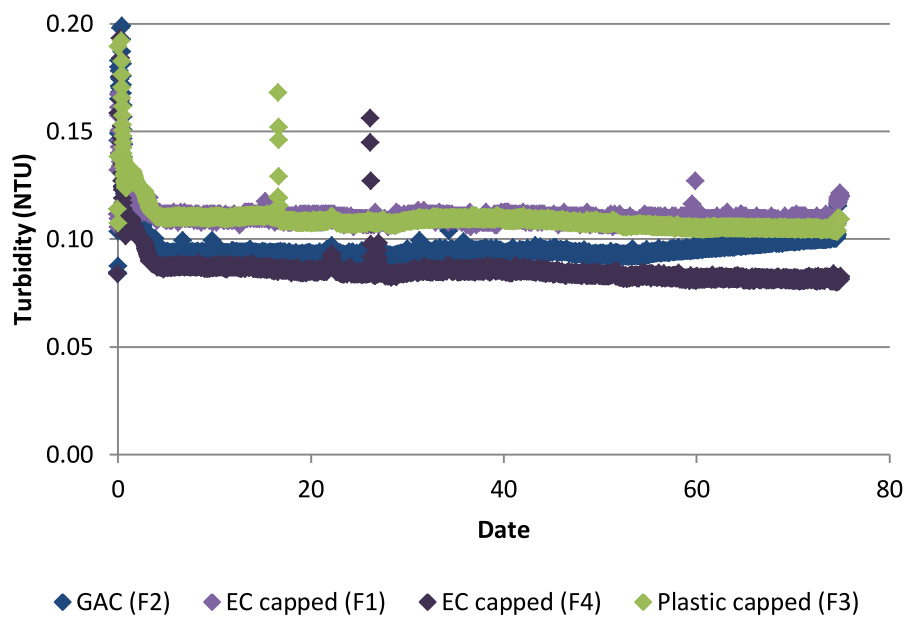

Figure 6.2: Pilot plant effluent turbidity data at warm water conditions (mean temperature = 21.3°C) from 14-17 August 2013. This figure demonstrates that similar turbidity trends were observed by all filter configurations at warm water conditions.

6.2.2 Head Loss

At cold water conditions, the rate of head loss accumulation was slowest in the plastic capped filter. Differences in the mean rate of head loss accumulation between the plastic capped and GAC ($p < 0.0001$) and EC capped ($p < 0.0001$) filters were statistically significant (Appendix D). On average, at cold water conditions the plastic capped filter took 33.1 hours and 19.5 hours longer to reach terminal head loss compared to the GAC and EC capped filters, respectively. The relative performance (i.e., slower accumulation of head loss) of the plastic capped filter was similar at warm water conditions. Differences in the mean rate of head loss accumulation between the plastic capped filter and the GAC ($p < 0.0001$) and EC capped ($p < 0.0001$) filters were statistically significant (Appendix D). At warm water conditions, the plastic capped filter took 39.4 hours and 25.3 hours longer to reach terminal head loss compared to the GAC and EC capped filters, respectively.

The data suggests that the EC capping layer yielded intermediate improvements in head loss accumulation as compared to the plastic capping layer. The capping materials that were tested yielded improvements in the mean rate of head loss accumulation compared to the control GAC filters, the plastic media yielded the greatest improvements, at cold water conditions. This represents a significant reduction in energy consumption with respect to filter operation, and may lead to longer filter run times.

During the nutrient amendment experiments, an improvement in the rate of head loss accumulation was only observed at warm water conditions while amending the EC capped filter influent stoichiometric C:N:P ratio to 100:20:2. However, during this experiment the mean rate of head loss accumulation in the plastic capped filter without nutrient enhancement was slower than in the nutrient-amended EC capped filter; the difference in mean performance was statistically significant ($p < 0.0001$; Appendix D). On average, the plastic capped filter took 19.5 hours longer to achieve terminal head loss, and is presented in Figure 6.4. The data consistently demonstrates that the filter with the plastic capping material consistently had the slowest rate of head loss accumulation relative to the other filter configurations investigated, regardless of operational temperature and nutrient amendments. Detailed head loss data obtained during the course of this project are provided in Appendix A.

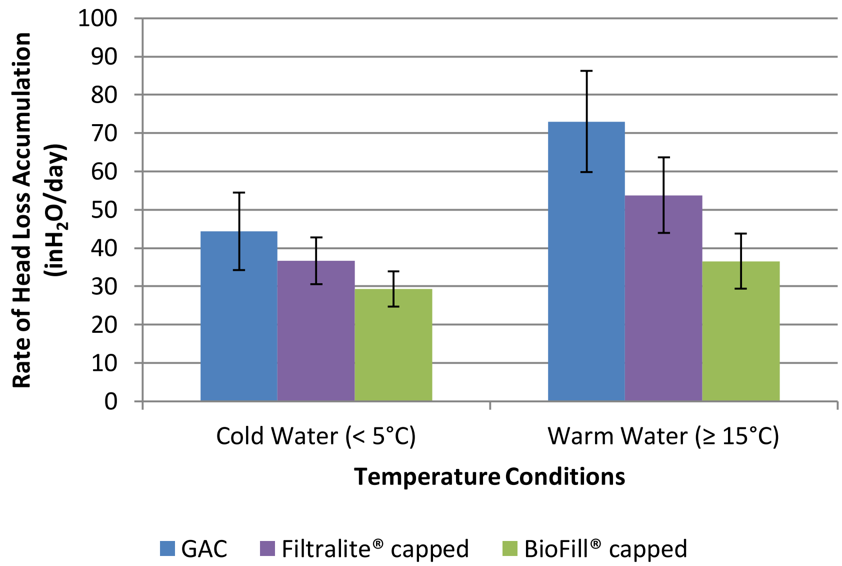

Figure 6.3: Mean rate of head loss accumulation based on filter configuration at cold and warm water conditions without nutrient amendments ± one standard deviation. This figure demonstrates that both capping materials improved the rate of head loss accumulation at cold and warm water conditions.

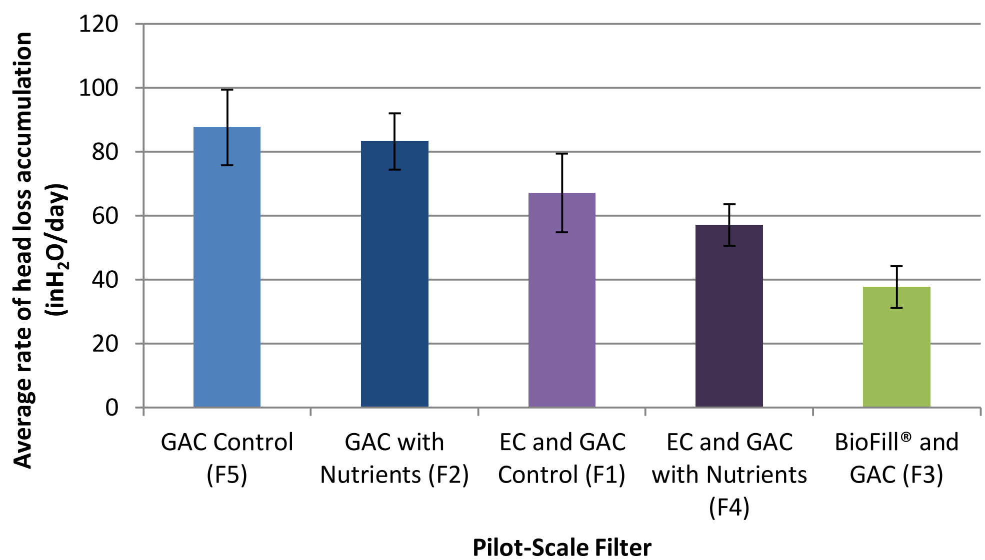

Figure 6.4: Mean rate of head loss accumulation ± one standard deviation at warm water conditions while Filters 2 and 4 were nutrient-amended to a C:N:P ratio of 100:20:2. This figure demonstrates that the plastic capped filter performed the best at warm water conditions.

6.2.3 Filter Run Time

The mean filter run times at cold and warm water conditions is presented in Figure 6.5. At cold water conditions, differences in mean filter run time between the plastic capped filter and the GAC (p = 0.6569, Appendix D) and EC capped (p = 0.4533, Appendix D) filters were not statistically significant. At warm water conditions, differences in mean filter run times between the GAC and plastic capped filters were statistically significant (p < 0.0001, Appendix D); the plastic capping layer helped extend the filter run time by 16.2 hours, on average. However, there was no statistical difference between the plastic and EC capped filters (p = 0.0394, Appendix D). The mean filter run time of the EC capped filter while amending the influent nutrient ratio to 100:10:1 was not significantly different than that of the plastic capped filter (p = 0.0377, Appendix D). However, the mean filter run time of the 100:20:2 nutrient-amended EC capped filter was significantly different and shorter than the plastic capped filter (p = 0.0012, Appendix D) (Figure 6.6). Accordingly, these analyses underscored that using the plastic material as a capping layer in a GAC filter could match or lead to longer filter run times than a GAC or EC capped filters with or without nutrient amendments at all water temperatures. Detailed filter run time data obtained during the course of this project are provided in Appendix A.

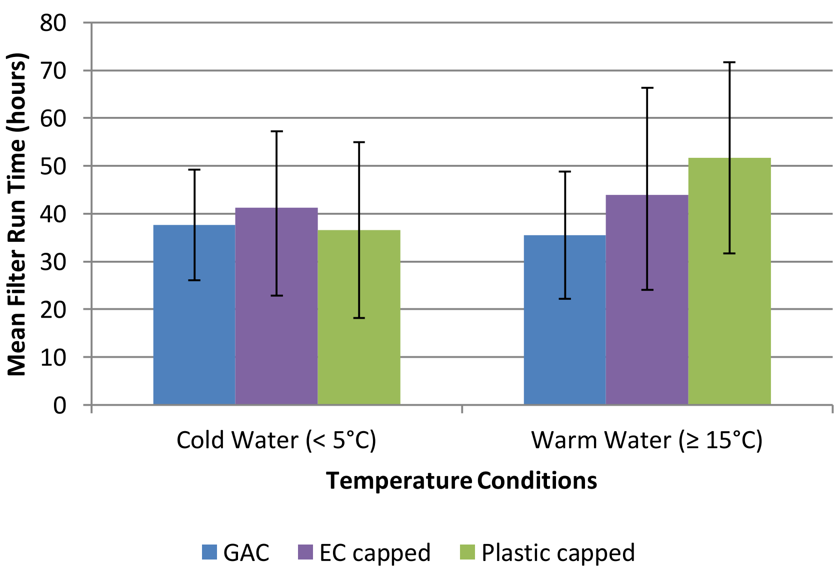

Figure 6.5: Mean filter run time± one standard deviation at cold and warm water conditions without nutrient amendments. This figure demonstrates that at cold water conditions they were not different, but longer run times were achieved with capping layers at warm water conditions.

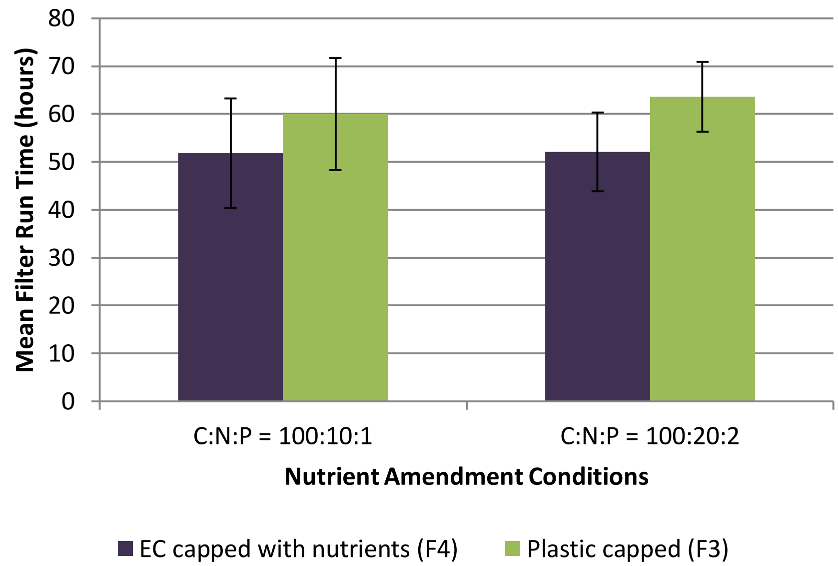

Figure 6.6: Mean filter run time± one standard deviation of the EC capped filter with nutrient amendments and the plastic capped filter without nutrient amendments at warm water conditions. This figure demonstrates that longer filter run times can be achieved with the plastic capping material than all the other filter configurations tested, with or without nutrient enhancement.

6.3 Biodegradable Organic Matter Removal

6.3.1 DOC Removal

Mean DOC removal by each filter configuration without nutrient amendments at both cold and warm water conditions is presented in Figure 6.7. Differences in DOC removal between the GAC, EC capped, and plastic capped filters at either cold or warm water conditions were not statistically significant (Appendix D); thus, capping a GAC filter with a layer of EC or plastic medium did not negatively impact DOC removal, at the temperature ranges evaluated. As would be expected, increases in DOC removed occurred at warmer temperatures (Figure 6.7) and were consistent with typically reported biological filtration performance; specifically, increases in biological activity associated with higher temperature (Andersson et al., 2001; Lazarova and Manem, 1995; Persson et al., 2007). Detailed DOC data obtained during the course of this project are provided in Appendix B.

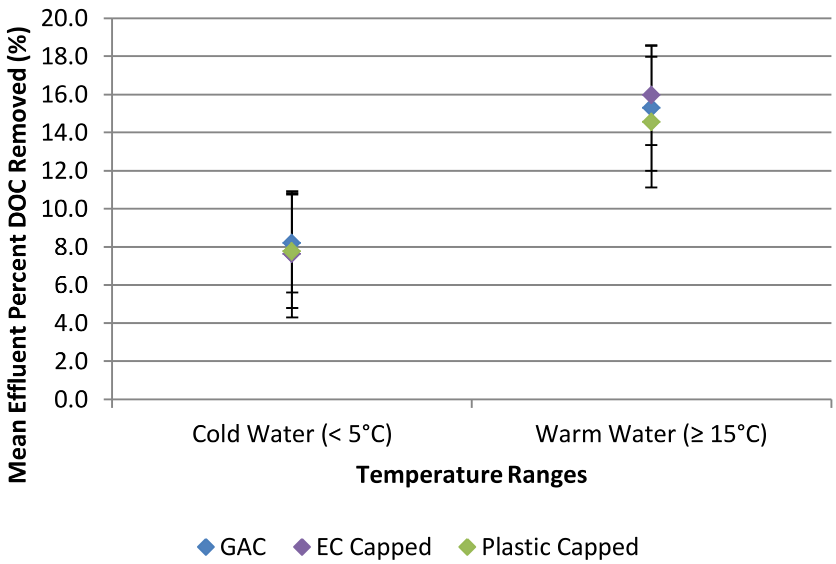

Figure 6.7: Pilot-scale filter mean effluent percent DOC removal vs cold and warm temperature ranges without nutrient amendments

6.3.2 Consumed Nutrient Ratios

The relative stoichiometric C:N:P ratios of consumed nutrients were evaluated at cold and warm water conditions without amending the influent nutrient concentrations; these are presented in Figure 6.8(a) and (b), respectively. Without the addition of nutrients at cold water conditions, the C:N:P ratio of the consumed nutrients was 100:0:0.2 for the GAC, EC and plastic capped filters. This indicates that only carbon and phosphorus were being consumed at cold water conditions. However, at warm water conditions there was a shift in the consumed nutrient ratio to 100:2.5:0, indicating that carbon and nitrogen were being consumed. Consideration of consumed nutrients in these cases is particularly informative because the relative stoichiometric C:N:P ratios in the influent to each filter configuration were the same at all times. This suggests that using either the EC or plastic as a capping material in a GAC filter does not affect the nutrient removal at the temperature ranges examined; it may also suggest that the microbial communities within each filter were not different.

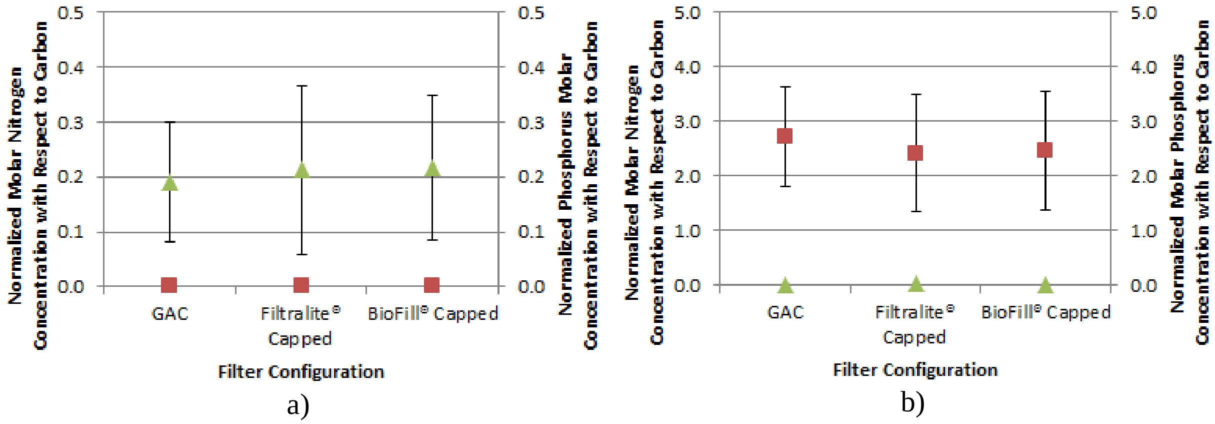

Figure 6.8: Normalized molar N (■) and P (▲) concentrations removed with respect to C at a) cold water conditions without nutrients, b) warm water conditions without nutrients

6.4 Material Accumulation

Throughout the course of this research, at all temperature conditions, accumulation of material was observed periodically at the top of each pilot-scale filter. Photographs taken during warm water operations, on 2 September 2013, of a GAC (Filter 2) and the plastic capped (Filter 3) filters are presented in Figure 6.9 and Figure 6.10, respectively.

In Figure 6.9, a thin layer of material accumulation, approximately 0.5 cm thick, was observed. In contrast, in Figure 6.10, material accumulation around each plastic element for the full 20 cm depth of the capping layer was observed. Figure 6.11 illustrates the material accumulation around a single plastic element; the layer of material surrounding each plastic element was approximately 1 cm thick.

Figure 6.9: Material accumulation at the top of Filter 2 containing GAC media only

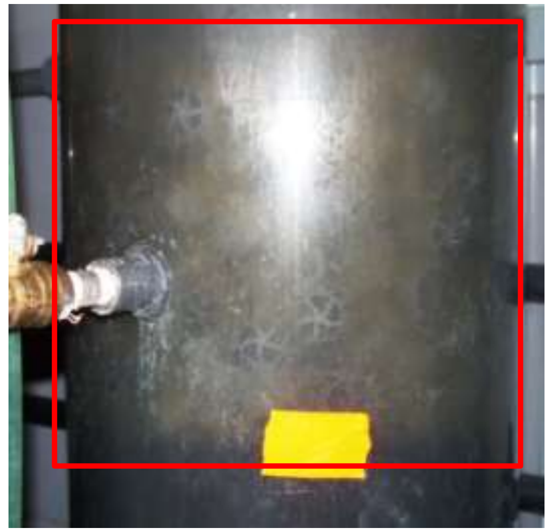

Figure 6.10: Material accumulation at the top of Filter 3 capped with BioFill® media

Figure 6.11: Material accumulation around an individual BioFill® plastic element

It is suspected that the observed material that accumulated in the plastic capping layer media accumulated within the GAC filter media bed and/or became compressed into the thin layer of material that was observed at the top of the GAC filter. The suspected material compression and/or accumulation, in addition to the larger media size resulting in an increase in void space within the filter, could thus contribute to the observed improvement in the rate of head loss accumulation at all temperature conditions, which has positive energy and water saving implications. Additionally, both the plastic and EC media extended filter run time at warm water conditions, which has positive water production, energy savings, and wastewater reduction implications. Longer filter run times can also reduce the risk of the passage of smaller particles (Di Bernardo and Escobar Rivera, 1996), and possibly pathogens. The suspected cake style filtration achieved in the GAC filter is effective at removing material and reducing turbidity, but at a higher rate of head loss accumulation and energy. The plastic media demonstrates good material removal and retention, while still allowing water to flow through the capping layer freely.

A sample of the accumulated material collected from the plastic capping layer was collected. It was suspected that the accumulated material was floc carryover from the full-scale clarification step at the MWTP. The sample collected was analyzed for total suspended solids (TSS) and aluminum, for the purposes of identifying the source of the accumulated material. The sample collected was not representative of the influent water quality, nor the true concentration of material accumulated in the plastic capping layer. A summary of the analyses are presented in Table 6.1.

Table 6.1: Summary of TSS and aluminum analyses of material collected from the Filter 3 BioFill® capping layer

Analysis	**Concentration**
Total Suspended Solids, TSS (mg/L)	533
Aluminum (mg/L)	110

The measured aluminum concentration is approximately 21% of the measured TSS concentration. This relatively high fraction of aluminum suggests that the material collected from the plastic capping layer is floc carryover from the full-scale clarification step, since PACl is the coagulant used all year round at the MWTP. Aluminum has been demonstrated to have negative impacts on microbial growth and biofilm formation (Hoellein et al., 2014; Piña and Cervantes, 1996). The accumulation of aluminum within a biological filter may negatively impact its capacity for BOM removal. Since occasional floc carryover at water (and wastewater) treatment plants is common, media caps on top of granular filters can help make filtration performance more robust and energy efficient, and potentially minimize the amount of aluminum accumulating at deeper layers in biological filters.

6.5 Summary

- The plastic capping layer yielded similar effluent turbidity trends as the other filter configurations, with and without nutrient amendment, at the temperature conditions examined.
- The plastic capping layer outperformed or matched the other filter configurations in terms of the rate of head loss accumulation and filter run time, with or without nutrient amendment, at the temperature conditions examined.
- The plastic capping layer did not negatively impact BOM removal as compared to the other filter configurations at the temperature conditions that were examined.

Chapter 7
Conclusions

The overall goal of this research was to investigate the impact of both media selection and nutrient amendment strategies on biological filtration performance. To assess these impacts, experiments were conducted over a 14 month period using parallel pilot-scale filters at the Mannheim Water Treatment Plant. The key conclusions of this work are listed below.

Capping material selection

1. The use of EC and plastic capping layers did not significantly affect turbidity or nutrient removal by biological filtration at any of the temperature ranges ($T < 5°C$; $5°C \geq T < 15°C$; $T \geq 15°C$; overall range 0.5-26.5°C) investigated.

2. The EC and plastic capping layers above the GAC medium improved the rate of head loss accumulation at all temperature ranges. In addition, the plastic capping layer offered the lowest rate of head loss accumulation at all temperature ranges.

3. The EC and plastic capping layers extended filter run time at warm water conditions compared to the GAC filter. In addition, the plastic capping layer offered the longest filter run time at warm water conditions.

4. A viable biofilm can be grown on the capping materials that were tested. This was demonstrated by DOC removals collected just below the capping layers in the filters.

Nutrient amendments at cold water conditions

5. Amending the influent stoichiometric C:N:P ratio of either GAC or EC capped filters to 100:10:1 or 100:20:2 (based on the influent DOC concentration) at cold water conditions did not yield improvements in turbidity trends, rates of head loss accumulation, filter run time, or DOC removal; the performance of the pilot-scale filters was not nutrient limited.

6. The mean NH_3-N and SRP removed by the nutrient-amended filters at cold water conditions was zero and 74.1 µg/L respectively, with an amended influent C:N:P ratio of either 100:10:1 or 100:20:2, thereby indicating that the control filters were operating at phosphorus deficient, but not nitrogen deficient conditions. Notably, the system was not nutrient limited with respect to BOM removal or operational performance.

7. The residual amount of SRP that was measured at the effluent of the nutrient-amended filters at both nutrient dosing rates indicated that there was a maximum threshold of phosphorus that could be removed by the biological filters at cold water conditions.

8. The optimal C:N:P ratio at cold water conditions for this system, based on the molar concentrations of nutrients that were removed by the nutrient-amended filters, was 100:0:10. Notably, the commonly recommended stoichiometric C:N:P ratio of 100:10:1 was not optimal for biological filtration performance enhancement at cold water conditions.

9. The plastic capped filter outperformed or matched the head loss accumulation and filter run time performance of the nutrient-amended filters without any loss in turbidity and DOC removal performance at cold water conditions.

Nutrient amendments at warm water conditions

10. Amending the influent stoichiometric C:N:P ratio of the GAC filter to 100:10:1 or 100:20:2, based on the influent DOC concentration, at warm water conditions did not yield improvements in turbidity trends, rates of head loss accumulation, filter run time, or DOC removal; the performance of the GAC pilot-scale filter was not nutrient limited.

11. Amending the influent stoichiometric C:N:P ratio of the EC capped filter to 100:10:1, based on the influent DOC concentration, at warm water conditions lead to an improvement in the filter run time only.

12. Amending the influent stoichiometric C:N:P ratio of the EC capped filter to100:20:2, based on the influent DOC concentration, at warm water conditions lead to an improvement in the rate of head loss accumulation, filter run time, and TOC removal.

13. The larger EC media enhanced the benefits of nutrient amendments within a biological filter.

14. The mean percent of NH_3-N and SRP removed while amending the influent stoichiometric C:N:P ratio to 100:10:1 were approximately 93.5% and 79.0%, respectively. While amending the influent stoichiometric C:N:P ratio to 100:20:2 the mean percent of NH_3-N and SRP removed were approximately 99.4% and 51.7%, respectively. This indicates that the control filters were operating under nitrogen and phosphorus deficient conditions at warm water conditions.

15. The optimal C:N:P ratio at warm water conditions for this system, based on the molar concentrations of nutrients that were removed by the nutrient-amended filters, could not be determined since a maximum removal threshold of NH_3-N or SRP was not reached.

16. The observed C:N:P ratio at warm water conditions for this system, based on the molar concentrations of nutrients that were removed by the nutrient-amended filters ranged from 100:67.3:6.0 to 100:153.3:7.4; the commonly recommended stoichiometric C:N:P ratio of 100:10:1 was not optimal for biological filtration performance enhancement.

17. Monitoring the influent and effluent nutrient concentrations and relative molar ratios provides information on whether nutrients are exiting the biological filter and may cause downstream issues for disinfection processes or in the distribution system.

18. Monitoring the consumed amount of nutrients, or the relative consumed molar nutrient ratios, provides information on the environment within the biological filter and how it is using the nutrients.

19. The plastic capped filter outperformed or matched the rate of head loss accumulation and filter run time performance of nutrient-amended filters without any loss in turbidity and DOC removal performance at warm water conditions.

Chapter 8
Implications and Recommendations

Several of the outcomes of this research have implications for optimizing of the design and operation of biological filters for drinking water treatment. These include:

1. The replacement of a layer of media from an existing filter with a capping material that has a larger grain size can enhance filter operations (i.e., rate of head loss accumulation and filter run time) without compromising effluent turbidity performance or nutrient removal.

2. The plastic BioFill® media, typically used in wastewater applications, can be used effectively as a capping layer in a conventional granular filter for drinking water treatment. However, the backwash protocol would have to be modified to ensure that the larger plastic media remains on top of the bulk granular media.

3. Adding a layer of capping material and modifying the backwash protocol, as necessary, would cost less than installing a nutrient dosing system to achieve a similar level of performance enhancement. Further, the addition of a capping layer is operationally less complicated and requires less attention from the plant operator than optimizing and maintaining a nutrient dosing system.

4. Monitoring the amount of consumed nutrients, and calculating the consumed molar nutrient ratios, is an effective way to assess the performance of the biological filter and provides information on how to optimize the addition of nutrients to the system to minimize their concentrations at the effluent. Monitoring the inlet and outlet nutrient concentrations only may lead to over- or under-dosing of nutrients.

5. Nutrient amendment programs may not be an effective operational strategy at water treatment facilities in northern climates where there are either short, or no periods of warm water conditions. However, amending the nutrients may be used effectively to optimize biological filtration in warmer climates.

6. Nutrients amendments for biological filters must be optimized to minimize the amount of nitrogen and phosphorus in filter effluents, as they may lead to the formation of disinfection by-products, operational issues for disinfection systems, or regrowth in the distribution system.

7. Nutrient amendments may be an effective strategy to promote biofilm growth on new filtration media.
8. The optimum ratio of consumed nutrients by a biological filter is different at cold and warm water conditions, and may also differ by source water. Pilot scale experiments should be conducted to determine the optimal nutrient ratios on a site specific basis.

Other research outcomes warrant further investigation. These include:

1. Investigate the impact of nutrient amendments on the plastic capped filter to see if similar improvements in the performance observed in the EC capped filter could be observed.
2. Further investigations into the optimal nutrient ratio at warm water conditions are needed.
3. Detailed characterization of the microbial communities within the filter at cold and warm water conditions, with and without nutrient amendments, may help in determining how they behave at the various conditions and how nutrients are used.
4. Investigate the impacts of dosing micronutrients into the influent of the biological filters.
5. Investigate the impact of nutrient amendments on the removal of dissolved organic nitrogen (DON), dissolved organic phosphorus (DOP), and the disinfection by-product formation potential.

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Appendix A

Operational Data

			F1								
				Flow Alarm		Head loss Alarm		Turbidity Alarm			
Start Date	End Date	Temperature (C°)	End of Ripening	Flow Rate (L/min)	Date	Head loss (in H2O)	Date	Turbidity (NTU)	Date	Alarm Condition	Filter Run Time (h)
2013-07-19 10:04	2013-07-23 7:46	26.3	2013-07-19 10:51	< 4	2013-07-21 8:34	120.00	41475.93				35.38333
2013-07-23 10:38	2013-07-25 9:04		2013-07-23 20:25								36.65
2013-07-25 11:13	2013-07-28 7:47	21.1	2013-07-25 11:43								68.06959
2013-07-28 9:57	2013-07-30 17:05		2013-07-28 10:30								54.56922
2013-07-30	2013-08-02										
2013-08-02 9:56	2013-08-05 13:18	21.1	2013-08-02 10:42								74.60322
2013-08-05 15:25	2013-08-08 8:59	21.6	2013-08-05 15:57			120	2013-08-07 16:46				48.8323
2013-08-08 11:01	2013-08-11 15:33	22.1	2013-08-08 11:33	< 4	2013-08-11 13:33	120	41497.21				65.48239
2013-08-11 18:06	2013-08-14 9:10	21.8	2013-08-11 18:45								62.41917
2013-08-14 11:26	2013-08-17 14:01	20.7	2013-08-14 12:07	< 4	2013-08-17 6:31	120	41502.99				59.70103
2013-08-17 16:05	2013-08-20 8:35	21.4	2013-08-17 16:40								63.91942
2013-08-20 10:52	2013-08-23 9:24	23.2	2013-08-20 11:33	< 4	2013-08-22 22:26	120	41508.79				55.44903
2013-08-23 11:36	2013-08-26 8:02	23.7	2013-08-23 12:16	< 4	2013-08-25 19:22	120	41511.65				51.25089
2013-08-	2013-08-	23.4	2013-08-								46.4002

26 10:17	28 9:16		26 10:51								
2013-08-28 11:26	2013-08-30 9:29	23.8	2013-08-28 12:03								45.448
2013-08-30 11:36	2013-09-02 19:34	24.0	2013-08-30 12:11	< 4	2013-09-01 17:24	120	41518.34				43.86723
2013-09-02 21:43	2013-09-05 9:54	22.1	2013-09-02 22:24	< 4	2013-09-05 2:34	120	41521.80				44.81608
2013-09-05 12:01	2013-09-08 13:39	19.9	2013-09-05 12:40	< 4	2013-09-07 15:39	120	41524.42				45.29942
2013-09-08 15:48	2013-09-11 10:37	20.8	2013-09-08 16:55	< 4	2013-09-10 18:29	120	41527.59				45.31611
2013-09-11 12:44	2013-09-14 7:31	21.0	2013-09-11 14:07	< 4	2013-09-13 15:01	120	41530.35				42.38258
2013-09-14 9:41	2013-09-17 10:23	18.1	2013-09-14 11:19	< 4	2013-09-16 18:17	120	41533.47				48.03391
2013-09-17 12:28	2013-09-20 9:31	18.2	2013-09-17 13:18	< 4	2013-09-19 22:57	120	41536.68				51.03443
2013-09-20 11:30	2013-09-23 10:23	18.4	2013-09-20 11:59			120	41540.13				63.03243
2013-09-23 12:33	2013-09-26 9:33	17.3	2013-09-23 13:05			120	41543.19				63.36537
2013-09-26 11:40	2013-09-29 9:40	17.8	2013-09-26 17:26	< 4	2013-09-29 7:34	120	41546.18				58.93506
2013-09-29 11:47	2013-10-02 9:38	17.9	2013-09-29 12:20	< 4	2013-10-02 7:04	120	41548.98				59.1675
2013-10-02 14:24	2013-10-05 14:52	17.8	2013-10-02 15:56	< 4	2013-10-05 6:40	120	41552.20				60.73383
2013-10-05 17:06	2013-10-08 10:54	17.1	2013-10-05 17:35	< 4	2013-10-08 10:16	120	41555.22				59.59877
2013-10-08 13:47	2013-10-11 8:17	15.7	2013-10-08 14:17	< 4	2013-10-11 4:13	120	41558.12				60.48465
2013-10-11 10:27	2013-10-14 17:51	15.4	2013-10-11 11:47	< 4	2013-10-13 4:11	120	41560.05				37.48292

2013-10-14 19:54	2013-10-17 12:06	15.8	2013-10-14 20:25	< 4	2013-10-16 4:24	120	41563.04				28.533
2013-10-17 14:21	2013-10-20 16:52	13.8	2013-10-17 15:42	< 4	2013-10-20 4:42	120	41567.02				56.76567
2013-10-20 19:01	2013-10-23 11:03	12.1	2013-10-20 20:21								62.69974
2013-10-23 13:02	2013-10-26 10:12	10.1	2013-10-23 14:23			120	41573.19				62.19892
2013-10-26 12:18	2013-10-29 8:56	8.8	2013-10-26 13:44	< 4	2013-10-29 7:58						66.23623
2013-10-29 12:09	2013-11-01 7:32	9.0	2013-10-29 13:44								65.81338
2013-11-01 10:15	2013-11-04 10:57	8.9	2013-11-01 11:56					0.2	2013-11-03 4:28	turbidity	40.52996
2013-11-04 15:16	2013-11-06 10:36		2013-11-04 20:37							end of run	37.96713
2013-11-06 10:36	2013-11-08 13:02	8.9									
2013-11-08 13:02	2013-11-10 10:44	8.3	2013-11-08 15:27	< 4	2013-11-08 14:00	120	41587.95			flow rate	0
2013-11-10 12:52	2013-11-13 12:00	6.9	2013-11-10 13:52	< 4	2013-11-13 4:32	120	41591.05			head loss	59.28206
2013-11-13 14:02	2013-11-16 14:28	6.9				120	41594.20				
2013-11-16 16:39	2013-11-19 7:51	6.7	2013-11-16 17:39					0.28	2013-11-18 13:29	turbidity	43.83333
2013-11-19 9:18	2013-11-22 10:39	6.5	2013-11-19 10:35							end of run	72.08003
2013-11-22 12:48	2013-11-25 12:10	4.5	2013-11-22 13:49			120	41603.14			head loss	61.59916
2013-11-	2013-11-	2.4	2013-11-	< 4	2013-11-					flow rate	59.05255

25 14:09	28 15:13		25 15:16		28 2:19						
2013-11-28 17:19	2013-12-01 17:01	1.6	2013-11-28 18:18	< 4	2013-12-01 15:13			0.22	2013-12-01 7:50	turbidity	61.52821
2013-12-01 19:08	2013-12-04 14:23	1.4	2013-12-01 20:16					0.2	2013-12-04 6:34	turbidity	58.3
2013-12-04 16:19	2013-12-07 9:05	3.1	2013-12-04 17:38					0.2	2013-12-06 22:16	turbidity	52.63333
2013-12-07 11:24	2013-12-10 10:41	1.9	2013-12-07 12:35			120	41618.02			head loss	60.0008
2013-12-10 12:39	2013-12-13 10:18	1.4									
2013-12-13 12:30	2013-12-16 16:32	1.1	2013-12-13 14:09			120	41623.91	0.21	2013-12-14 18:29	turbidity	28.33097
2013-12-16 18:42	2013-12-19 13:12	1.0				120	41627.10				
varied	2013-12-23 12:36	1.2	2013-12-19 17:27	< 4	2013-12-23 0:34	120	41630.60	0.2	2013-12-21 4:07	turbidity	34.66667
2013-12-23	2014-01-01 0:00	2.1									
2014-01-01 14:46	2014-01-03 13:22	1.2									
2014-01-03 15:33	2014-01-06 9:48	1.0	2014-01-03 18:05			120	41645.28	0.21	2014-01-05 11:55	turbidity	41.83508
2014-01-06 12:00	2014-01-09 12:14	0.7	2014-01-06 14:38	< 4	2014-01-09 10:32			0.2	2014-01-07 13:18	turbidity	22.66761
2014-01-	2014-01-	1.5	2014-01-					0.21	2014-	turbidity	30.03458

09 15:02	12 15:24		09 18:40						01-11 0:42		
2014-01-12 17:51	2014-01-15 12:32	0.8	2014-01-12 20:13					0.22	2014-01-13 8:59	turbidity	12.7672
2014-01-15 14:26	2014-01-18 10:29	1.4	2014-01-15 16:24					0.2	2014-01-17 18:42	turbidity	50.3021
2014-01-18 12:52	2014-01-21 12:09	0.5	2014-01-18 18:52	< 4	2014-01-21 12:03			0.23	2014-01-20 13:34	turbidity	42.70178
2014-01-21 14:13	2014-01-24 9:41	1.0	2014-01-21 19:02					0.2	2014-01-23 5:06	turbidity	34.06525
2014-01-24 11:47	2014-01-27 10:31	1.4	2014-01-24 16:27					0.2	2014-01-25 14:47	turbidity	22.33333
2014-01-27 13:02	2014-01-30 11:26	0.5	2014-01-27 17:14	< 4	2014-01-30 11:14			0.23	2014-01-28 17:32	turbidity	24.30101
2014-01-30 13:24	2014-02-02 13:16	0.8	2014-01-30 15:02					0.26	2014-02-01 5:04	turbidity	38.03492
2014-02-02 16:13	2014-02-05 12:23	1.0	2014-02-02 17:59	< 4	2014-02-05 12:08			0.2	2014-02-03 18:41	turbidity	24.70103
2014-02-05 14:21	2014-02-08 12:47	0.9	2014-02-05 15:58					0.22	2014-02-07 0:38	turbidity	32.66531
2014-02-08 14:54	2014-02-11 17:24	1.1	2014-02-08 16:27					0.22	2014-02-10 2:15	turbidity	33.79859
2014-02-	2014-02-	1.8	2014-02-					0.21	2014-	turbidity	30.43207

11 19:29	14 10:31		11 21:12						02-13 3:38		
2014-02-14 13:13	2014-02-17 11:05	1.2	2014-02-14 14:57	< 4	2014-02-17 10:57			0.21	2014-02-16 11:55	turbidity	44.96854
2014-02-17 13:02	2014-02-20 17:02	1.4	2014-02-17 14:46							end of run	74.26991
2014-02-20 19:06	2014-02-23 10:18	2.1	2014-02-20 20:44							end of run	61.5668
2014-02-23 12:45	2014-02-26 12:12	1.0	2014-02-23 14:19	< 4	2014-02-26 11:59					flow rate	69.66957
2014-02-26 14:56	2014-03-01 13:16	1.2	2014-02-26 16:39							end of run	68.60323
2014-03-01 15:27	2014-03-04 11:08	0.7	2014-03-01 17:07	< 4	2014-03-04 11:04					flow rate	65.96391
2014-03-04 14:47	2014-03-07 15:26	1.7	2014-03-04 16:46							end of run	70.66372
2014-03-07 17:44	2014-03-10 10:41	1.2	2014-03-07 20:24							end of run	62.29704
2014-03-10 12:48	2014-03-13 9:59	1.4	2014-03-10 15:24							end of run	66.59705
2014-03-13 12:21	2014-03-16 10:31	1.4	2014-03-13 15:30							end of run	67.00021
2014-03-16 12:57	2014-03-19 8:50	0.9	2014-03-16 19:11							end of run	61.66342
2014-03-19 11:00	2014-03-22 19:17	1.0	2014-03-19 13:10							end of run	78.12992
2014-03-22 21:23	2014-03-25 10:29	1.2	2014-03-23 0:22	< 4	2014-03-25 10:11					flow rate	57.8028
2014-03-25 13:24	2014-03-28 14:26	1.5	2014-03-25 16:01							end of run	70.40022
2014-03-28 16:46	2014-03-31 10:42	1.0	2014-03-28 19:18	< 4	2014-03-31 10:12					flow rate	62.90281

2014-03-31 13:55	2014-04-03 10:01	1.8	2014-03-31 16:33							end of run	65.4694
2014-04-03 12:14	2014-04-06 13:00	0.9	2014-04-03 14:54							end of run	70.10293
2014-04-06 15:24	2014-04-09 9:48	1.2	2014-04-06 18:08							end of run	63.66647
2014-04-09 12:31	2014-04-12 17:10	2.5	2014-04-09 14:28							end of run	73.69688
2014-04-12 19:21	2014-04-15 12:09	4.2	2014-04-12 19:39							end of run	64.49992
2014-04-15 14:08	2014-04-18 10:03	5.6	2014-04-15 17:00							end of run	65.06355
2014-04-18 12:18	2014-04-21 11:48	7.5	2014-04-18 16:56							end of run	66.86946
2014-04-21 14:29	2014-04-24 9:56	9.4	2014-04-21 14:43	< 4	2014-04-24 9:36					flow rate	66.8971
2014-04-24 12:18	2014-04-27 9:33	8.8	2014-04-24 13:26							end of run	68.13036
2014-04-27 11:38	2014-04-30 10:27	9.1	2014-04-28 11:35							end of run	46.86471
2014-04-30 12:39	2014-05-03 9:29	8.7	2014-04-30 15:49	-21.11323				0.2	2014-05-02 5:45	turbidity	37.93333
2014-05-03 11:32	2014-05-07 10:36	9.9	2014-05-03 13:02					0.22	2014-05-04 8:02	turbidity	19
2014-05-07 12:43	2014-05-09 12:46	12.5	2014-05-07 13:35					0.26	2014-05-07 15:05	turbidity	1.5
2014-05-09 14:45	2014-05-12 10:36	15.8	2014-05-11 0:21			120	41771.32	0.22	2014-05-12 1:57	turbidity	25.60107
2014-05-	2014-05-	17.9	2014-05-	< 4	2014-05-	120	41774			turbidity	0

12 13:38	15 9:34		12 15:49		15 5:46		.11				
2014-05-15 11:58	2014-05-20 8:20	14.5	2014-05-17 3:19	< 4	2014-05-18 2:26	120	41776.86			head loss	17.35268
2014-05-20 10:27	2014-05-23 9:07	16.1	2014-05-20 16:15	< 4	2014-05-23 0:07	120	41781.46			head loss	42.8675
2014-05-23 11:32	2014-05-27 10:13	19.5	2014-05-23 23:38	< 4	2014-05-25 23:17	120	41784.67			head loss	40.41756
2014-05-27 12:16	2014-05-30 9:04	20.5	2014-05-27 15:42	< 4	2014-05-29 21:40	120	41788.58			head loss	46.13398
2014-05-30 11:25	2014-06-02 11:49	21.3	2014-05-30 11:25	< 4	2014-06-01 23:55	120	41791.95	1.07	2014-05-31 2:48	turbidity	15.39923
2014-06-02 13:55	2014-06-05 9:29	21.4	2014-06-02 17:13	< 4	2014-06-05 4:59	120	41794.69			turbidity	0
2014-06-05 12:01	2014-06-08 9:29	21.0	2014-06-05 18:43	< 4	2014-06-07 18:33	120	41797.63			turbidity	0
2014-06-08 12:15	2014-06-11 11:30	19.0	2014-06-08 19:35	< 4	2014-06-10 19:26					turbidity	0
2014-06-12 8:12	2014-06-14 13:36	21.5	2014-06-12 14:19							turbidity	0
2014-06-14 15:44	2014-06-17 9:58	21.6	2014-06-14 16:24	< 4	2014-06-16 21:56	120	41806.95			flow rate	53.53557
2014-06-17 11:47	2014-06-20 9:41	23.5	2014-06-17 12:29	< 4	2014-06-19 16:53	120	41809.57			head loss	49.09923
2014-06-20 12:21	2014-06-23 9:54	23.5	2014-06-20 13:55	< 4	2014-06-22 11:26	120	41812.59			flow rate	45.53143
2014-06-23 13:04	2014-06-26 11:26	22.5	2014-06-23 13:44	< 4	2014-06-25 12:00	120	41815.48	0.21	2014-06-25 23:08	head loss	45.76658
2014-06-26 13:20	2014-07-02 9:18	26.5	2014-06-26 14:05	< 4	2014-06-28 13:24	120	41818.37	0.21	2014-06-27 23:44	turbidity	33.65114

2014-07-02 11:34	2014-07-05 11:38	23.3	2014-07-02 16:17	< 4	2014-07-04 10:44	120	41824.31	0.21	2014-07-04 16:45	head loss	39.25103
2014-07-05 13:57	2014-07-08 9:43	23.1	2014-07-05 16:55	< 4	2014-07-07 9:49	120	41827.18	0.24	2014-07-06 22:31	turbidity	29.60123
2014-07-08 12:32	2014-07-11 8:39	21.8	2014-07-08 13:50	< 4	2014-07-10 19:03	120	41830.70			head loss	51.06768
2014-07-11 10:56	2014-07-14 14:00	21.8	2014-07-11 12:00	< 4	2014-07-13 10:26	120	41833.22			head loss	41.33272
2014-07-14 16:09	2014-07-17 11:01	22.0	2014-07-14 16:51	< 4	2014-07-16 6:41	120	41836.47			flow rate	37.83511
2014-07-17 12:59	2014-07-20 10:02	21.4	2014-07-17 13:33	< 4	2014-07-19 16:16	120	41839.33			head loss	42.38342
2014-07-20 13:30	2014-07-23 10:55	22.7	2014-07-20 14:12	< 4	2014-07-22 22:57	120	41842.57			head loss	47.41756
2014-07-23 12:50	2014-07-26 10:28	23.5	2014-07-23 13:40	< 4	2014-07-25 21:38	120	41845.56			head loss	55.96676
2014-07-26 12:43	2014-07-29 11:05	22.7	2014-07-26 13:23	< 4	2014-07-28 4:07	120	41848.38			flow rate	38.73515
2014-07-29 13:48	2014-08-01 10:47	21.0	2014-07-29 14:26	< 4	2014-08-01 7:49	120	41852.05			head loss	58.78
2014-08-01 13:03	2014-08-04 10:31	21.7	2014-08-01 13:35	< 4	2014-08-03 13:25	120	41854.57			flow rate	47.83343
2014-08-04 12:37	2014-08-07 10:40	22.6	2014-08-04 13:09	< 4	2014-08-06 10:50	120	41857.15			head loss	38.35076
2014-08-07 12:42	2014-08-10 14:39	22.7	2014-08-07 13:16	< 4	2014-08-09 14:19	120	41860.28			head loss	41.41731
2014-08-10 16:57	2014-08-13 9:36	23.2	2014-08-10 17:29	< 4	2014-08-12 14:38	120	41863.41			head loss	40.36596
2014-08-13 12:03	2014-08-16 14:50	20.6	2014-08-13 12:41	< 4	2014-08-15 21:28	120	41866.51			head loss	47.51677
2014-08-	2014-08-	19.8	2014-08-	< 4	2014-08-	120	41869			head loss	47.43407

16 17:02	19 10:00		16 17:32		18 20:10		.71				
2014-08-19 11:54	2014-08-22 10:18	21.3	2014-08-19 12:28	< 4	2014-08-22 5:32	120	41872.85			head loss	55.8323
2014-08-22 12:29	2014-08-25 10:25	22.6	2014-08-22 12:59	< 4	2014-08-24 3:33	120	41875.34			flow rate	38.56828
2014-08-25 12:15	2014-08-28 14:38	22.9	2014-08-25 12:49	< 4	2014-08-27 18:46	120	41878.69			head loss	51.83325
2014-08-28 16:56	2014-08-31 11:49	22.6	2014-08-28 17:26	< 4	2014-08-30 10:45	120	41881.39	0.31	2014-08-30 14:50	head loss	39.98263
2014-08-31 13:59	2014-09-03 9:54	23.3	2014-08-31 14:33	< 4	2014-09-02 14:34	120	41884.48			head loss	45.03255
2014-09-03 11:49	2014-09-07 16:32	22.5	2014-09-03 12:19	< 4	2014-09-05 15:36	120	41887.39	0.2	2014-09-07 9:14	head loss	45.11752
2014-09-07 18:46	2014-09-09 10:01	21.8	2014-09-07 19:28					0.2	2014-09-09 8:21	turbidity	36.89846
2014-09-09 12:02	2014-09-12 9:16	20.3	2014-09-09 12:38	< 4	2014-09-11 14:22	120	41893.28			head loss	42.15074
2014-09-12 11:28	2014-09-15 9:44	18.6	2014-09-12 12:00	< 4	2014-09-13 22:16	120	41895.65			head loss	27.65059
2014-09-15 11:52	2014-09-18 8:15	17.3	2014-09-15 12:30	< 4	2014-09-17 6:57	120	41899.06			head loss	36.98259
2014-09-18 10:25	2014-09-21 14:53	17.3	2014-09-18 11:03	< 4	2014-09-20 6:15	120	41902.01			head loss	37.28258

			F2								
				Flow Alarm		Head loss Alarm		Turbidity Alarm			
Start Date	End Date	Temperature (C°)	End of Ripening	Flow Rate (L/min)	Date	Head loss (in H2O)	Date	Turbidity (NTU)	Date	Alarm Condition	Filter Run Time (h)
2013-07-19 10:04	2013-07-23 7:46	26.3	2013-07-19 10:58	< 4	2013-07-19 10:46	120	2013-07-19 10:24	0.12	2013-07-23 8:14	head loss	-0.19989
2013-07-23 10:38	2013-07-25 9:04		2013-07-23 17:42	< 4	2013-07-24 3:58	120	2013-07-23 19:39			head loss	1.9664931
2013-07-25 11:13	2013-07-28 7:47	21.1	2013-07-25 11:50			120	2013-07-27 14:00			head loss	50.16754
2013-07-28 9:57	2013-07-30 17:05		2013-07-28 10:41			120	41485.55			head loss	50.401081
2013-07-30	2013-08-02										
2013-08-02 9:56	2013-08-05 13:18	21.1	2013-08-02 10:51	< 4	2013-08-05 8:16	120	41490.89			head loss	58.599093
2013-08-05 15:25	2013-08-08 8:59	21.6	2013-08-05 16:07	< 4	2013-08-07 21:55					flow rate	53.802149
2013-08-08 11:01	2013-08-11 15:33	22.1	2013-08-08 11:43	< 4	2013-08-10 20:29	120	41496.63			head loss	56.752667
2013-08-11 18:06	2013-08-14 9:10	21.8	2013-08-11 20:04	< 4	2013-08-13 21:58	120	41499.58			head loss	41.917118
2013-08-14 11:26	2013-08-17 14:01	20.7	2013-08-14 12:54	< 4	2013-08-16 6:07	120	41501.95			head loss	34.000618
2013-08-17 16:05	2013-08-20 8:35	21.4	2013-08-17 16:52	< 4	2013-08-20 0:49	120	41506.03			head loss	55.884303
2013-08-20 10:52	2013-08-23 9:24	23.2	2013-08-20 11:40			120	41507.85			head loss	32.666078

2013-08-23 11:36	2013-08-26 8:02	23.7	2013-08-23 13:01	< 4	2013-08-25 5:58	120	41511.22			head loss	40.250724
2013-08-26 10:17	2013-08-28 9:16	23.4	2013-08-26 11:05	< 4	2013-08-27 19:12	120	41513.92			flow rate	32.100214
2013-08-28 11:26	2013-08-30 9:29	23.8	2013-08-28 12:19			120	41516.18			head loss	39.984044
2013-08-30 11:36	2013-09-02 19:34	24.0	2013-08-30 12:29	< 4	2013-09-01 2:20	120	41518.02			head loss	35.900414
2013-09-02 21:43	2013-09-05 9:54	22.1	2013-09-02 22:27	< 4	2013-09-04 10:34	120	41521.43			head loss	35.766229
2013-09-05 12:01	2013-09-08 13:39	19.9	2013-09-05 12:42	< 4	2013-09-07 3:01	120	41523.86			head loss	31.849642
2013-09-08 15:48	2013-09-11 10:37	20.8	2013-09-08 16:40	< 4	2013-09-10 10:07	120	41527.44	0.21	2013-09-10 13:09	flow rate	41.448382
2013-09-11 12:44	2013-09-14 7:31	21.0	2013-09-11 14:34	< 4	2013-09-13 5:55	120	41530.05	0.22	2013-09-12 15:23	turbidity	24.816667
2013-09-14 9:41	2013-09-17 10:23	18.1	2013-09-14 12:37	< 4	2013-09-16 10:03	120	41533.40			head loss	44.983768
2013-09-17 12:28	2013-09-20 9:31	18.2	2013-09-17 13:52	< 4	2013-09-19 8:17	120	41536.44			flow rate	42.415024
2013-09-20 11:30	2013-09-23 10:23	18.4	2013-09-20 12:09	< 4	2013-09-22 19:41	120	41539.77			head loss	54.199254
2013-09-23 12:33	2013-09-26 9:33	17.3	2013-09-23 13:12			120	41542.97			head loss	57.998786
2013-09-26 11:40	2013-09-29 9:40	17.8	2013-09-26 17:53	< 4	2013-09-28 21:54	120	41545.65	0.2	2013-09-29 9:13	head loss	45.651546
2013-09-29 11:47	2013-10-02 9:38	17.9	2013-09-29 12:33			120	41548.76	0.26	2013-10-01 6:54	turbidity	42.353529
2013-10-02 14:24	2013-10-05 14:52	17.8	2013-10-02 16:03	< 4	2013-10-04 23:42	120	41551.91			head loss	53.783843
2013-10-05 17:06	2013-10-08 10:54	17.1	2013-10-05 17:47	< 4	2013-10-07 19:26	120	41554.75			head loss	48.232268
2013-10-	2013-10-	15.7	2013-10-	< 4	2013-10-	120	41557			head loss	46.50109

08 13:47	11 8:17		08 14:26		10 14:05		.54				6
2013-10-11 10:27	2013-10-14 17:51	15.4	2013-10-11 11:10	< 4	2013-10-13 8:35	120	41560.50			flow rate	45.402211
2013-10-14 19:54	2013-10-17 12:06	15.8	2013-10-14 20:34	< 4	2013-10-16 2:12	120	41563.03			head loss	28.216347
2013-10-17 14:21	2013-10-20 16:52	13.8	2013-10-17 15:52	< 4	2013-10-19 18:30	120	41566.58			head loss	46.099176
2013-10-20 19:01	2013-10-23 11:03	12.1	2013-10-20 20:28			120	41570.36	0.2	2013-10-23 9:47	turbidity	61.321776
2013-10-23 13:02	2013-10-26 10:12	10.1	2013-10-23 14:39	< 4	2013-10-26 1:04	120	41572.67	0.26	2013-10-25 8:08	turbidity	41.483333
2013-10-26 12:18	2013-10-29 8:56	8.8	2013-10-26 14:05	< 4	2013-10-28 5:46	120	41575.14	1.47	2013-10-27 5:49	turbidity	15.733333
2013-10-29 12:09	2013-11-01 7:32	9.0	2013-10-29 17:09	< 4	2013-10-30 3:36	120	41578.02	0.32	2013-10-30 7:10	turbidity	14.017835
2013-11-01 10:15	2013-11-04 10:57	8.9	2013-11-01 11:51			120	41582.08	0.2	2013-11-03 3:58	turbidity	40.113324
2013-11-04 15:16	2013-11-06 10:36		2013-11-04 17:10							end of run	41.416843
2013-11-06 10:36	2013-11-08 13:02	8.9									
2013-11-08 13:02	2013-11-10 10:44	8.3	2013-11-08 13:52	< 4	2013-11-10 10:00					flow rate	44.133146
2013-11-10 12:52	2013-11-13 12:00	6.9	2013-11-10 13:29	< 4	2013-11-13 1:34	120	41590.88			head loss	55.582157
2013-11-13 14:02	2013-11-16 14:28	6.9		< 4	2013-11-15 20:48	120	41593.50				
2013-11-16 16:39	2013-11-19 7:51	6.7	2013-11-16 17:13	< 4	2013-11-18 18:45	120	41596.45			head loss	41.6174
2013-11-19 9:18	2013-11-22 10:39	6.5	2013-11-19 9:50	< 4	2013-11-21 15:15	120	41599.23			head loss	43.749108
2013-11-22 12:48	2013-11-25 12:10	4.5	2013-11-22 13:20	< 4	2013-11-24 9:28	120	41602.23			head loss	40.082824

2013-11-25 14:09	2013-11-28 15:13	2.4	2013-11-25 14:42	< 4	2013-11-27 14:39	120	41605.43			head loss	43.500747
2013-11-28 17:19	2013-12-01 17:01	1.6	2013-11-28 17:51	< 4	2013-12-01 11:21	120	41609.28	0.2	2013-12-01 6:24	turbidity	60.544954
2013-12-01 19:08	2013-12-04 14:23	1.4	2013-12-01 19:51			120	41612.15	0.2	2013-12-04 3:02	turbidity	55.183333
2013-12-04 16:19	2013-12-07 9:05	3.1	2013-12-04 18:51	< 4	2013-12-07 2:51	120	41614.64	0.24	2013-12-06 20:27	head loss	44.549193
2013-12-07 11:24	2013-12-10 10:41	1.9	2013-12-07 12:05	< 4	2013-12-10 4:21	120	41618.05			head loss	61.084181
2013-12-10 12:39	2013-12-13 10:18	1.4									
2013-12-13 12:30	2013-12-16 16:32	1.1	2013-12-13 13:50			120	41623.78	0.2	2013-12-14 21:22	turbidity	31.530706
2013-12-16 18:42	2013-12-19 13:12	1.0		< 4	2013-12-19 5:02	120	41626.73				
varied	2013-12-23 12:36	1.2	2013-12-19 14:47	< 4	2013-12-22 11:32	120	41629.90	0.2	2013-12-20 23:17	turbidity	32.499999
2013-12-23	2014-01-01 0:00	2.1									
2014-01-01 14:46	2014-01-03 13:22	1.2									
2014-01-03 15:33	2014-01-06 9:48	1.0	2014-01-03 16:19	< 4	2014-01-06 7:48	120	41644.63	0.2	2014-01-05 10:27	turbidity	42.135089
2014-01-06 12:00	2014-01-09 12:14	0.7	2014-01-06 13:00	< 4	2014-01-09 11:58	120	41648.03	0.22	2014-01-07 13:42	turbidity	24.701029
2014-01-09 15:02	2014-01-12 15:24	1.5	2014-01-09 16:22					0.27	2014-01-10 23:48	turbidity	31.434643
2014-01-12 17:51	2014-01-15 12:32	0.8	2014-01-12 19:27			120	41654.42	0.2	2014-01-14 13:53	turbidity	42.435101
2014-01-15 14:26	2014-01-18 10:29	1.4	2014-01-15 15:30					0.2	2014-01-17 16:28	turbidity	48.968707
2014-01-	2014-01-	0.5	2014-01-	< 4	2014-01-			0.2	2014-01-	turbidity	46.26859

18 12:52	21 12:09		18 13:56		21 11:57				20 12:12		4
2014-01-21 14:13	2014-01-24 9:41	1.0	2014-01-21 15:21			120	41663.23	0.23	2014-01-23 2:40	turbidity	35.331861
2014-01-24 11:47	2014-01-27 10:31	1.4	2014-01-24 12:51					0.24	2014-01-25 12:21	turbidity	23.5
2014-01-27 13:02	2014-01-30 11:26	0.5	2014-01-27 14:10			120	41669.45	0.29	2014-01-28 18:12	turbidity	28.034501
2014-01-30 13:24	2014-02-02 13:16	0.8	2014-01-30 14:08					0.28	2014-01-31 21:12	turbidity	31.067961
2014-02-02 16:13	2014-02-05 12:23	1.0	2014-02-02 17:15					0.24	2014-02-03 10:29	turbidity	17.234051
2014-02-05 14:21	2014-02-08 12:47	0.9	2014-02-05 15:11					0.27	2014-02-06 20:44	turbidity	29.565435
2014-02-08 14:54	2014-02-11 17:24	1.1	2014-02-08 15:42					0.21	2014-02-09 18:13	turbidity	26.532228
2014-02-11 19:29	2014-02-14 10:31	1.8	2014-02-11 20:11					0.22	2014-02-12 23:04	turbidity	26.898879
2014-02-14 13:13	2014-02-17 11:05	1.2	2014-02-14 13:49	< 4	2014-02-17 10:53			0.26	2014-02-16 3:55	turbidity	38.101588
2014-02-17 13:02	2014-02-20 17:02	1.4	2014-02-17 13:40					0.24	2014-02-18 15:32	turbidity	25.866667
2014-02-20 19:06	2014-02-23 10:18	2.1	2014-02-20 19:40							end of run	62.633422
2014-02-23 12:45	2014-02-26 12:12	1.0	2014-02-23 13:23	< 4	2014-02-26 11:53					flow rate	70.50294
2014-02-26 14:56	2014-03-01 13:16	1.2	2014-02-26 15:31							end of run	69.736521
2014-03-01 15:27	2014-03-04 11:08	0.7	2014-03-01 15:59	< 4	2014-03-04 10:58					flow rate	66.997204
2014-03-04 14:47	2014-03-07 15:26	1.7	2014-03-04 15:19							end of run	72.130325
2014-03-07 17:44	2014-03-10 10:41	1.2	2014-03-07 18:12							end of run	64.497136

2014-03-10 12:48	2014-03-13 9:59	1.4	2014-03-10 13:16					0.2	2014-03-13 4:26	turbidity	63.166667
2014-03-13 12:21	2014-03-16 10:31	1.4	2014-03-13 12:55					0.27	2014-03-16 0:38	turbidity	59.730844
2014-03-16 12:57	2014-03-19 8:50	0.9	2014-03-16 13:27					0.21	2014-03-19 5:25	turbidity	63.969332
2014-03-19 11:00	2014-03-22 19:17	1.0	2014-03-19 11:34			120	41720.60	0.22	2014-03-22 12:54	turbidity	73.333333
2014-03-22 21:23	2014-03-25 10:29	1.2	2014-03-22 21:53	< 4	2014-03-25 10:13					flow rate	60.336029
2014-03-25 13:24	2014-03-28 14:26	1.5	2014-03-25 14:04					0.24	2014-03-28 4:31	turbidity	62.464064
2014-03-28 16:46	2014-03-31 10:42	1.0	2014-03-28 17:22	< 4	2014-03-31 10:30			0.2	2014-03-30 7:22	turbidity	38
2014-03-31 13:55	2014-04-03 10:01	1.8	2014-03-31 14:37					0.23	2014-04-03 4:13	turbidity	61.602567
2014-04-03 12:14	2014-04-06 13:00	0.9	2014-04-03 13:14							end of run	71.769661
2014-04-06 15:24	2014-04-09 9:48	1.2	2014-04-06 16:04							end of run	65.733225
2014-04-09 12:31	2014-04-12 17:10	2.5	2014-04-09 13:13					0.22	2014-04-12 8:00	turbidity	66.797217
2014-04-12 19:21	2014-04-15 12:09	4.2	2014-04-12 20:27					0.21	2014-04-15 6:03	turbidity	57.6024
2014-04-15 14:08	2014-04-18 10:03	5.6	2014-04-15 15:18					0.26	2014-04-18 8:40	turbidity	65.36939
2014-04-18 12:18	2014-04-21 11:48	7.5	2014-04-18 13:20							end of run	70.469606
2014-04-21 14:29	2014-04-24 9:56	9.4	2014-04-21 15:19							end of run	66.630418
2014-04-24 12:18	2014-04-27 9:33	8.8	2014-04-24 13:10							end of run	68.397024
2014-04-	2014-04-	9.1	2014-04-							end of run	69.99708

27 11:38	30 10:27		27 12:28								1
2014-04-30 12:39	2014-05-03 9:29	8.7	2014-04-30 13:31							end of run	67.969603
2014-05-03 11:32	2014-05-07 10:36	9.9	2014-05-03 12:20	< 4	2014-05-07 2:56	120	41735.65	0.2	2014-05-05 2:22	turbidity	38.033333
2014-05-07 12:43	2014-05-09 12:46	12.5	2014-05-07 14:09					0.2	2014-05-08 7:27	turbidity	17.3
2014-05-09 14:45	2014-05-12 10:36	15.8	2014-05-09 21:07	< 4	2014-05-12 4:16	120	41770.79	0.21	2014-05-10 11:43	turbidity	14.600608
2014-05-12 13:38	2014-05-15 9:34	17.9	2014-05-12 15:25	< 4	2014-05-14 23:58	120	41773.62	0.2	2014-05-13 21:37	turbidity	30.198742
2014-05-15 11:58	2014-05-20 8:20	14.5	2014-05-15 16:37	< 4	2014-05-17 16:46	120	41776.34	0.26	2014-05-17 4:59	turbidity	36.365151
2014-05-20 10:27	2014-05-23 9:07	16.1	2014-05-20 17:09	< 4	2014-05-22 12:03	120	41781.15	0.2	2014-05-20 22:33	turbidity	5.4
2014-05-23 11:32	2014-05-27 10:13	19.5	2014-05-23 15:46	< 4	2014-05-25 4:51	120	41784.29	0.2	2014-05-24 12:34	turbidity	20.8
2014-05-27 12:16	2014-05-30 9:04	20.5	2014-05-28 6:34	< 4	2014-05-29 15:04	120	41788.31	0.21	2014-05-28 15:46	turbidity	9.2003833
2014-05-30 11:25	2014-06-02 11:49	21.3	2014-05-30 15:42	< 4	2014-06-02 2:39	120	41791.21	0.24	2014-05-30 23:54	turbidity	8.1996583
2014-06-02 13:55	2014-06-05 9:29	21.4	2014-06-02 18:19	< 4	2014-06-04 6:33	120	41794.14			turbidity	0
2014-06-05 12:01	2014-06-08 9:29	21.0	2014-06-05 14:01	< 4	2014-06-07 17:01	120	41797.50			head loss	46.017482
2014-06-08 12:15	2014-06-11 11:30	19.0	2014-06-08 13:13	< 4	2014-06-10 13:20					flow rate	48.131231
2014-06-12 8:12	2014-06-14 13:36	21.5								turbidity	0
2014-06-14 15:44	2014-06-17 9:58	21.6	2014-06-14 16:44	< 4	2014-06-16 21:04	120	41806.48			head loss	42.667311
2014-06-17 11:47	2014-06-20 9:41	23.5	2014-06-17 13:05	< 4	2014-06-19 12:03	120	41809.45			head loss	45.749304

2014-06-20 12:21	2014-06-23 9:54	23.5	2014-06-20 13:23	< 4	2014-06-22 8:28	120	41812.16			head loss	38.450775
2014-06-23 13:04	2014-06-26 11:26	22.5	2014-06-23 13:58	< 4	2014-06-25 4:22	120	41815.08			head loss	36.050542
2014-06-26 13:20	2014-07-02 9:18	26.5	2014-06-26 14:20	< 4	2014-06-28 3:22	120	41817.97	0.2	2014-07-01 20:15	head loss	32.949417
2014-07-02 11:34	2014-07-05 11:38	23.3	2014-07-02 12:30	< 4	2014-07-03 22:04	120	41823.78			head loss	30.133993
2014-07-05 13:57	2014-07-08 9:43	23.1	2014-07-05 14:49	< 4	2014-07-06 23:29	120	41826.80			head loss	28.416031
2014-07-08 12:32	2014-07-11 8:39	21.8	2014-07-08 13:56	< 4	2014-07-10 12:59	120	41830.42			head loss	44.217572
2014-07-11 10:56	2014-07-14 14:00	21.8	2014-07-11 11:58	< 4	2014-07-12 17:00	120	41832.69			head loss	28.699592
2014-07-14 16:09	2014-07-17 11:01	22.0	2014-07-14 16:47	< 4	2014-07-16 5:17	120	41836.13			head loss	34.316764
2014-07-17 12:59	2014-07-20 10:02	21.4	2014-07-17 13:29	< 4	2014-07-19 4:56	120	41839.15			head loss	38.033415
2014-07-20 13:30	2014-07-23 10:55	22.7	2014-07-20 14:10	< 4	2014-07-22 8:53	120	41842.18			head loss	38.034072
2014-07-23 12:50	2014-07-26 10:28	23.5	2014-07-23 13:30	< 4	2014-07-25 2:32	120	41844.93			flow rate	37.033421
2014-07-26 12:43	2014-07-29 11:05	22.7	2014-07-26 13:21	< 4	2014-07-27 23:31	120	41847.88			head loss	31.699532
2014-07-29 13:48	2014-08-01 10:47	21.0	2014-07-29 14:24	< 4	2014-07-31 5:53	120	41851.05			head loss	34.899257
2014-08-01 13:03	2014-08-04 10:31	21.7	2014-08-01 13:33	< 4	2014-08-03 1:11	120	41853.85			head loss	30.782882
2014-08-04 12:37	2014-08-07 10:40	22.6	2014-08-04 13:05	< 4	2014-08-05 17:52	120	41856.75			flow rate	28.798797
2014-08-07 12:42	2014-08-10 14:39	22.7	2014-08-07 13:14	< 4	2014-08-08 23:03	120	41859.98			flow rate	33.831764
2014-08-	2014-08-	23.2	2014-08-	< 4	2014-08-	120	41863			head loss	30.96611

10 16:57	13 9:36		10 17:23		12 4:58		.01					4
2014-08-13 12:03	2014-08-16 14:50	20.6	2014-08-13 12:39	< 4	2014-08-15 16:44	120	41866.57				head loss	49.050099
2014-08-16 17:02	2014-08-19 10:00	19.8	2014-08-16 17:26	< 4	2014-08-18 6:54	120	41869.12				head loss	33.450589
2014-08-19 11:54	2014-08-22 10:18	21.3	2014-08-19 12:22	< 4	2014-08-21 17:28	120	41872.79				head loss	54.598994
2014-08-22 12:29	2014-08-25 10:25	22.6	2014-08-22 12:53	< 4	2014-08-24 4:37	120	41875.02				head loss	35.515947
2014-08-25 12:15	2014-08-28 14:38	22.9	2014-08-25 12:49	< 4	2014-08-27 6:20	120	41878.15				head loss	38.749919
2014-08-28 16:56	2014-08-31 11:49	22.6	2014-08-28 17:22	< 4	2014-08-30 1:19	120	41880.97				head loss	29.799472
2014-08-31 13:59	2014-09-03 9:54	23.3	2014-08-31 14:21	< 4	2014-09-02 0:52	120	41883.85				head loss	30.066133
2014-09-03 11:49	2014-09-07 16:32	22.5	2014-09-03 12:17	< 4	2014-09-04 23:52	120	41887.01				flow rate	35.598514
2014-09-07 18:46	2014-09-09 10:01	21.8	2014-09-07 19:14			120	41891.00	0.21	2014-09-08 21:55		turbidity	26.698887
2014-09-09 12:02	2014-09-12 9:16	20.3	2014-09-09 12:48	< 4	2014-09-11 6:00	120	41893.04				head loss	36.150639
2014-09-12 11:28	2014-09-15 9:44	18.6	2014-09-12 11:58	< 4	2014-09-13 23:32	120	41895.78				head loss	30.850644
2014-09-15 11:52	2014-09-18 8:15	17.3	2014-09-15 12:26	< 4	2014-09-17 3:21	120	41898.76				head loss	29.882717
2014-09-18 10:25	2014-09-21 14:53	17.3	2014-09-18 10:57	< 4	2014-09-20 1:19	120	41901.78				head loss	31.882674

			F3								
				Flow Alarm		Head loss Alarm		Turbidity Alarm			
Start Date	End Date	Temperature (C°)	End of Ripening	Flow Rate (L/min)	Date	Head loss (in H2O)	Date	Turbidity (NTU)	Date	Alarm Condition	Filter Run Time (h)
2013-07-19 10:04	2013-07-23 7:46	26.3	2013-07-19 10:53	< 4	2013-07-21 15:20	120	41476.55	0.23	2013-07-22 2:27	turbidity	50.26667
2013-07-23 10:38	2013-07-25 9:04		2013-07-23 20:34							end of run	36.5
2013-07-25 11:13	2013-07-28 7:47	21.1	2013-07-25 11:56							end of run	67.85293
2013-07-28 9:57	2013-07-30 17:05		2013-07-28 11:04							end of run	54.0026
2013-07-30	2013-08-02										
2013-08-02 9:56	2013-08-05 13:18	21.1	2013-08-02 10:53							end of run	74.4199
2013-08-05 15:25	2013-08-08 8:59	21.6	2013-08-05 17:50							end of run	63.15247
2013-08-08 11:01	2013-08-11 15:33	22.1	2013-08-08 11:59							end of run	75.55348
2013-08-11 18:06	2013-08-14 9:10	21.8	2013-08-11 20:12							end of run	60.96905
2013-08-14 11:26	2013-08-17 14:01	20.7	2013-08-14 14:44							end of run	71.29682
2013-08-17 16:05	2013-08-20 8:35	21.4	2013-08-17 17:07	< 4	2013-08-20 6:53					flow rate	61.76935
2013-08-20 10:52	2013-08-23 9:24	23.2	2013-08-20 11:37	< 4	2013-08-22 23:00					flow rate	59.38592
2013-08-23 11:36	2013-08-26 8:02	23.7	2013-08-23 12:41	< 4	2013-08-26 6:40					flow rate	65.98333
2013-08-	2013-08-	23.4	2013-08-							end of run	46.03357

26 10:17	28 9:16		26 11:13								
2013-08-28 11:26	2013-08-30 9:29	23.8	2013-08-28 12:23							end of run	45.11467
2013-08-30 11:36	2013-09-02 19:34	24.0	2013-08-30 12:35	< 4	2013-09-02 4:34	120	41519.20			flow rate	63.9831
2013-09-02 21:43	2013-09-05 9:54	22.1	2013-09-02 22:57							end of run	58.94766
2013-09-05 12:01	2013-09-08 13:39	19.9	2013-09-05 12:51	< 4	2013-09-08 6:35	120	41525.25	0.21	2013-09-07 8:15	turbidity	43.39638
2013-09-08 15:48	2013-09-11 10:37	20.8	2013-09-08 16:38	< 4	2013-09-11 7:11			0.22	2013-09-10 7:11	turbidity	38.54679
2013-09-11 12:44	2013-09-14 7:31	21.0	2013-09-11 15:32	< 4	2013-09-14 5:07	120	41530.84	0.25	2013-09-12 12:15	turbidity	20.71667
2013-09-14 9:41	2013-09-17 10:23	18.1	2013-09-14 10:46	< 4	2013-09-16 18:41					flow rate	55.91643
2013-09-17 12:28	2013-09-20 9:31	18.2	2013-09-17 13:23	< 4	2013-09-20 4:51	120	41537.34			flow rate	63.46413
2013-09-20 11:30	2013-09-23 10:23	18.4	2013-09-20 12:14							end of run	70.14717
2013-09-23 12:33	2013-09-26 9:33	17.3	2013-09-23 13:24							end of run	68.15273
2013-09-26 11:40	2013-09-29 9:40	17.8	2013-09-26 17:58							end of run	63.684
2013-09-29 11:47	2013-10-02 9:38	17.9	2013-09-29 12:41					0.2	2013-10-01 0:20	turbidity	35.65297
2013-10-02 14:24	2013-10-05 14:52	17.8	2013-10-02 16:24							end of run	70.45375
2013-10-05 17:06	2013-10-08 10:54	17.1	2013-10-05 18:11							end of run	64.71924
2013-10-08 13:47	2013-10-11 8:17	15.7	2013-10-08 15:09							end of run	65.11988
2013-10-11 10:27	2013-10-14 17:51	15.4	2013-10-11 11:43	< 4	2013-10-14 17:31	120	41561.66			head loss	76.2156

2013-10-14 19:54	2013-10-17 12:06	15.8	2013-10-14 20:41							end of run	63.40294
2013-10-17 14:21	2013-10-20 16:52	13.8	2013-10-17 15:56							end of run	72.94681
2013-10-20 19:01	2013-10-23 11:03	12.1	2013-10-20 20:32					0.22	2013-10-22 23:49	turbidity	51.28761
2013-10-23 13:02	2013-10-26 10:12	10.1	2013-10-23 14:13					0.37	2013-10-25 6:23	turbidity	40.16667
2013-10-26 12:18	2013-10-29 8:56	8.8	2013-10-26 13:07	< 4	2013-10-29 8:38			0.23	2013-10-28 0:04	turbidity	34.95
2013-10-29 12:09	2013-11-01 7:32	9.0	2013-10-29 14:34					0.21	2013-10-30 16:52	turbidity	26.30219
2013-11-01 10:15	2013-11-04 10:57	8.9	2013-11-01 11:14					0.25	2013-11-02 22:38	turbidity	35.39705
2013-11-04 15:16	2013-11-06 10:36		2013-11-04 18:23							end of run	40.20028
2013-11-06 10:36	2013-11-08 13:02	8.9									
2013-11-08 13:02	2013-11-10 10:44	8.3	2013-11-08 15:29	< 4	2013-11-10 7:08					flow rate	39.64968
2013-11-10 12:52	2013-11-13 12:00	6.9	2013-11-10 13:27	< 4	2013-11-13 11:38					flow rate	70.18313
2013-11-13 14:02	2013-11-16 14:28	6.9									
2013-11-16 16:39	2013-11-19 7:51	6.7	2013-11-16 17:26					1.48	2013-11-18 13:18	turbidity	43.86667
2013-11-19 9:18	2013-11-22 10:39	6.5	2013-11-19 10:03							end of run	72.61341
2013-11-22 12:48	2013-11-25 12:10	4.5	2013-11-22 13:45							end of run	70.40023
2013-11-25 14:09	2013-11-28 15:13	2.4	2013-11-25 15:06							end of run	72.11975
2013-11-	2013-12-	1.6	2013-11-					0.2	2013-12-	turbidity	55.42871

28 17:19	01 17:01		28 18:00						01 1:26		
2013-12-01 19:08	2013-12-04 14:23	1.4	2013-12-01 19:50					0.2	2013-12-03 23:09	turbidity	50.48667
2013-12-04 16:19	2013-12-07 9:05	3.1	2013-12-04 18:08					0.21	2013-12-06 15:07	turbidity	44.36667
2013-12-07 11:24	2013-12-10 10:41	1.9	2013-12-07 12:15							end of run	70.44672
2013-12-10 12:39	2013-12-13 10:18	1.4									
2013-12-13 12:30	2013-12-16 16:32	1.1	2013-12-13 15:37					0.2	2013-12-14 14:49	turbidity	23.19807
2013-12-16 18:42	2013-12-19 13:12	1.0									
varied	2013-12-23 12:36	1.2	2013-12-19 15:21					0.21	2013-12-20 19:31	turbidity	28.16667
2013-12-23	2014-01-01 0:00	2.1									
2014-01-01 14:46	2014-01-03 13:22	1.2									
2014-01-03 15:33	2014-01-06 9:48	1.0	2014-01-03 18:59					0.23	2014-01-05 2:25	turbidity	31.43464
2014-01-06 12:00	2014-01-09 12:14	0.7	2014-01-06 15:40	< 4	2014-01-09 11:10			0.21	2014-01-07 7:02	turbidity	15.36731
2014-01-09 15:02	2014-01-12 15:24	1.5	2014-01-09 17:50					0.24	2014-01-10 16:18	turbidity	22.4676
2014-01-12 17:51	2014-01-15 12:32	0.8	2014-01-12 19:13					0.2	2014-01-14 6:53	turbidity	35.66815
2014-01-15 14:26	2014-01-18 10:29	1.4	2014-01-15 15:30					0.2	2014-01-17 9:44	turbidity	42.23509
2014-01-18 12:52	2014-01-21 12:09	0.5	2014-01-18 17:26					0.2	2014-01-20 2:44	turbidity	33.30139
2014-01-21 14:13	2014-01-24 9:41	1.0	2014-01-21 18:32					0.2	2014-01-22 18:00	turbidity	23.46569

2014-01-24 11:47	2014-01-27 10:31	1.4	2014-01-24 13:09					0.2	2014-01-25 8:07	turbidity	18.96667
2014-01-27 13:02	2014-01-30 11:26	0.5	2014-01-27 14:04	< 4	2014-01-30 11:08			0.21	2014-01-28 8:48	turbidity	18.73411
2014-01-30 13:24	2014-02-02 13:16	0.8	2014-01-30 13:56					0.26	2014-01-31 18:20	turbidity	28.40118
2014-02-02 16:13	2014-02-05 12:23	1.0	2014-02-02 17:07					0.24	2014-02-03 11:31	turbidity	18.40077
2014-02-05 14:21	2014-02-08 12:47	0.9	2014-02-05 15:19					0.23	2014-02-06 19:02	turbidity	27.73218
2014-02-08 14:54	2014-02-11 17:24	1.1	2014-02-08 15:44					0.23	2014-02-09 15:29	turbidity	23.76568
2014-02-11 19:29	2014-02-14 10:31	1.8	2014-02-11 20:11					0.2	2014-02-12 22:48	turbidity	26.63222
2014-02-14 13:13	2014-02-17 11:05	1.2	2014-02-14 13:49	< 4	2014-02-17 10:47			0.2	2014-02-15 16:21	turbidity	26.53444
2014-02-17 13:02	2014-02-20 17:02	1.4	2014-02-17 13:38					0.23	2014-02-18 17:24	turbidity	27.76667
2014-02-20 19:06	2014-02-23 10:18	2.1	2014-02-20 19:44							end of run	62.56676
2014-02-23 12:45	2014-02-26 12:12	1.0	2014-02-23 14:31	< 4	2014-02-26 12:08					flow rate	69.61652
2014-02-26 14:56	2014-03-01 13:16	1.2	2014-02-26 15:28							end of run	69.80318
2014-03-01 15:27	2014-03-04 11:08	0.7	2014-03-01 15:57	< 4	2014-03-04 11:02					flow rate	67.0972
2014-03-04 14:47	2014-03-07 15:26	1.7	2014-03-04 15:11							end of run	72.26365
2014-03-07 17:44	2014-03-10 10:41	1.2	2014-03-07 18:12							end of run	64.49714
2014-03-10 12:48	2014-03-13 9:59	1.4	2014-03-10 13:16							end of run	68.73038
2014-03-	2014-03-	1.4	2014-03-					0.21	2014-03-	turbidity	66.03058

13 12:21	16 10:31		13 12:53						16 6:54		
2014-03- 16 12:57	2014-03- 19 8:50	0.9	2014-03- 16 13:27					0.23	2014-03- 19 9:01	turbidity	67.56948
2014-03- 19 11:00	2014-03- 22 19:17	1.0	2014-03- 19 11:32							end of run	79.76325
2014-03- 22 21:23	2014-03- 25 10:29	1.2	2014-03- 22 21:55	< 4	2014-03- 25 10:17					flow rate	60.36937
2014-03- 25 13:24	2014-03- 28 14:26	1.5	2014-03- 25 13:52							end of run	72.56679
2014-03- 28 16:46	2014-03- 31 10:42	1.0	2014-03- 28 17:20	<4	2014-03- 31 10:28			0.2	2014-03- 30 7:10	turbidity	37.83333
2014-03- 31 13:55	2014-04- 03 10:01	1.8	2014-03- 31 14:35					0.2	2014-04- 03 10:09	turbidity	67.56948
2014-04- 03 12:14	2014-04- 06 13:00	0.9	2014-04- 03 12:52							end of run	72.13634
2014-04- 06 15:24	2014-04- 09 9:48	1.2	2014-04- 06 15:56							end of run	65.86656
2014-04- 09 12:31	2014-04- 12 17:10	2.5	2014-04- 09 12:59					0.22	2014-04- 12 14:32	turbidity	73.5636
2014-04- 12 19:21	2014-04- 15 12:09	4.2	2014-04- 12 19:53					0.22	2014-04- 15 11:55	turbidity	64.036
2014-04- 15 14:08	2014-04- 18 10:03	5.6	2014-04- 15 14:38					0.2	2014-04- 18 6:32	turbidity	63.90266
2014-04- 18 12:18	2014-04- 21 11:48	7.5	2014-04- 18 12:54							end of run	70.90296
2014-04- 21 14:29	2014-04- 24 9:56	9.4	2014-04- 21 15:15							end of run	66.69708
2014-04- 24 12:18	2014-04- 27 9:33	8.8	2014-04- 24 12:48							end of run	68.76369
2014-04- 27 11:38	2014-04- 30 10:27	9.1	2014-04- 27 12:12							end of run	70.26374
2014-04- 30 12:39	2014-05- 03 9:29	8.7	2014-04- 30 13:17							end of run	68.20294

2014-05-03 11:32	2014-05-07 10:36	9.9	2014-05-03 12:06					0.32	2014-05-04 22:24	turbidity	34.3
2014-05-07 12:43	2014-05-09 12:46	12.5	2014-05-07 15:03					0.23	2014-05-08 7:23	turbidity	16.33333
2014-05-09 14:45	2014-05-12 10:36	15.8	2014-05-09 21:25					0.22	2014-05-10 9:31	turbidity	12.1005
2014-05-12 13:38	2014-05-15 9:34	17.9	2014-05-12 15:59					0.35	2014-05-13 17:01	turbidity	25.03229
2014-05-15 11:58	2014-05-20 8:20	14.5	2014-05-15 15:29	< 4	2014-05-18 22:54	120	41777.92	0.21	2014-05-17 0:17	turbidity	32.79863
2014-05-20 10:27	2014-05-23 9:07	16.1	2014-05-20 14:03					0.2	2014-05-21 2:27	turbidity	12.4
2014-05-23 11:32	2014-05-27 10:13	19.5	2014-05-23 13:48	< 4	2014-05-27 2:33	120	41785.65	0.22	2014-05-24 9:36	turbidity	19.8
2014-05-27 12:16	2014-05-30 9:04	20.5	2014-05-27 19:04			120	41789.36	0.2	2014-05-28 14:42	turbidity	19.63415
2014-05-30 11:25	2014-06-02 11:49	21.3	2014-05-30 17:40	< 4	2014-06-02 5:27	120	41792.12	0.21	2014-05-31 17:28	turbidity	23.79901
2014-06-02 13:55	2014-06-05 9:29	21.4	2014-06-02 17:23					0.21	2014-06-03 14:37	turbidity	21.23333
2014-06-05 12:01	2014-06-08 9:29	21.0	2014-06-05 13:55							end of run	67.5696
2014-06-08 12:15	2014-06-11 11:30	19.0	2014-06-08 14:41							end of run	68.83031
2014-06-12 8:12	2014-06-14 13:36	21.5	2014-06-12 8:51							end of run	52.73723
2014-06-14 15:44	2014-06-17 9:58	21.6	2014-06-14 16:18							end of run	65.66941
2014-06-17 11:47	2014-06-20 9:41	23.5	2014-06-17 12:17			120	41810.26			head loss	66.04895
2014-06-20 12:21	2014-06-23 9:54	23.5	2014-06-20 12:53	< 4	2014-06-23 6:50	120	41813.05			head loss	60.20111
2014-06-	2014-06-	22.5	2014-06-	< 4	2014-06-	120	41816			head loss	59.70095

23 13:04	26 11:26		23 13:34		26 1:30		.05				
2014-06-26 13:20	2014-07-02 9:18	26.5	2014-06-26 13:50	< 4	2014-06-28 4:58	120	41818.91	0.2	2014-06-28 20:51	flow rate	39.14863
2014-07-02 11:34	2014-07-05 11:38	23.3	2014-07-02 14:07	< 4	2014-07-04 21:56	120	41824.87	0.22	2014-07-04 11:31	turbidity	45.39811
2014-07-05 13:57	2014-07-08 9:43	23.1	2014-07-05 15:27	< 4	2014-07-08 0:41	120	41827.82	0.21	2014-07-06 19:59	turbidity	28.53452
2014-07-08 12:32	2014-07-11 8:39	21.8	2014-07-08 14:49							end of run	65.83059
2014-07-11 10:56	2014-07-14 14:00	21.8	2014-07-11 11:54	< 4	2014-07-14 9:24	120	41834.11			head loss	62.84902
2014-07-14 16:09	2014-07-17 11:01	22.0	2014-07-14 16:47			120	41837.09			head loss	57.31676
2014-07-17 12:59	2014-07-20 10:02	21.4	2014-07-17 13:31			120	41839.96			head loss	57.58342
2014-07-20 13:30	2014-07-23 10:55	22.7	2014-07-20 14:10			120	41843.31			head loss	65.28453
2014-07-23 12:50	2014-07-26 10:28	23.5	2014-07-23 13:34	< 4	2014-07-26 0:54	120	41845.87			head loss	55.30105
2014-07-26 12:43	2014-07-29 11:05	22.7	2014-07-26 13:19	< 4	2014-07-29 0:49	120	41848.62			head loss	49.64923
2014-07-29 13:48	2014-08-01 10:47	21.0	2014-07-29 14:20			120	41851.74			head loss	51.38232
2014-08-01 13:03	2014-08-04 10:31	21.7	2014-08-01 13:29							end of run	69.03343
2014-08-04 12:37	2014-08-07 10:40	22.6	2014-08-04 12:59	< 4	2014-08-07 4:42					flow rate	63.73
2014-08-07 12:42	2014-08-10 14:39	22.7	2014-08-07 13:02							end of run	73.63012
2014-08-10 16:57	2014-08-13 9:36	23.2	2014-08-10 17:27							end of run	64.1639
2014-08-13 12:03	2014-08-16 14:50	20.6	2014-08-13 12:23							end of run	74.46356

2014-08-16 17:02	2014-08-19 10:00	19.8	2014-08-16 17:24							end of run	64.60269
2014-08-19 11:54	2014-08-22 10:18	21.3	2014-08-19 12:12							end of run	70.09994
2014-08-22 12:29	2014-08-25 10:25	22.6	2014-08-22 12:51	< 4	2014-08-24 12:23					flow rate	47.53532
2014-08-25 12:15	2014-08-28 14:38	22.9	2014-08-25 12:33	< 4	2014-08-27 23:58	120	41879.36			flow rate	59.43071
2014-08-28 16:56	2014-08-31 11:49	22.6	2014-08-28 17:16			120	41882.23			head loss	60.14897
2014-08-31 13:59	2014-09-03 9:54	23.3	2014-08-31 14:25			120	41885.05	0.21	2014-09-03 5:01	head loss	58.83232
2014-09-03 11:49	2014-09-07 16:32	22.5	2014-09-03 12:21	< 4	2014-09-06 12:28	120	41888.12	0.21	2014-09-06 0:02	turbidity	59.69751
2014-09-07 18:46	2014-09-09 10:01	21.8	2014-09-07 20:47					0.28	2014-09-09 1:29	turbidity	28.6988
2014-09-09 12:02	2014-09-12 9:16	20.3	2014-09-09 12:40							end of run	68.60295
2014-09-12 11:28	2014-09-15 9:44	18.6	2014-09-12 12:12							end of run	69.53644
2014-09-15 11:52	2014-09-18 8:15	17.3	2014-09-15 12:34							end of run	67.69708
2014-09-18 10:25	2014-09-21 14:53	17.3	2014-09-18 10:59			120	41903.49			head loss	72.76532

			F4								
				Flow Alarm		Head loss Alarm		Turbidity Alarm			
Start Date	End Date	Temperature (C°)	End of Ripening	Flow Rate (L/min)	Date	Head loss (in H2O)	Date	Turbidity (NTU)	Date	Alarm Condition	Filter Run Time (h)
2013-07-19 10:04	2013-07-23 7:46	26.3	2013-07-19 10:51	< 4	2013-07-20 18:10	120	41475.63	0.31	2013-07-20 22:13	head loss	28.300001
2013-07-23 10:38	2013-07-25 9:04		2013-07-23 20:25							end of run	36.650001
2013-07-25 11:13	2013-07-28 7:47	21.1	2013-07-25 11:43							end of run	68.069594
2013-07-28 9:57	2013-07-30 17:05		2013-07-28 10:30							end of run	54.569224
2013-07-30	2013-08-02										
2013-08-02 9:56	2013-08-05 13:18	21.1	2013-08-02 10:42							end of run	74.603221
2013-08-05 15:25	2013-08-08 8:59	21.6	2013-08-05 15:57							end of run	65.035957
2013-08-08 11:01	2013-08-11 15:33	22.1	2013-08-08 11:33							end of run	75.986781
2013-08-11 18:06	2013-08-14 9:10	21.8	2013-08-11 18:45							end of run	62.419174
2013-08-14 11:26	2013-08-17 14:01	20.7	2013-08-14 12:07							end of run	73.913482
2013-08-17 16:05	2013-08-20 8:35	21.4	2013-08-17 16:40							end of run	63.919425
2013-08-20 10:52	2013-08-23 9:24	23.2	2013-08-20 11:33	< 4	2013-08-23 1:30	120	41508.95			head loss	59.365635
2013-08-23 11:36	2013-08-26 8:02	23.7	2013-08-23 12:16	< 4	2013-08-26 4:28	120	41512.14			head loss	63.084425
2013-08-	2013-08-	23.4	2013-08-							end of run	46.40020

26 10:17	28 9:16		26 10:51								1
2013-08-28 11:26	2013-08-30 9:29	23.8	2013-08-28 12:03							end of run	45.448001
2013-08-30 11:36	2013-09-02 19:34	24.0	2013-08-30 12:11	< 4	2013-09-01 18:44	120	41518.87			flow rate	54.549797
2013-09-02 21:43	2013-09-05 9:54	22.1	2013-09-02 22:24			120	41522.25			head loss	55.565896
2013-09-05 12:01	2013-09-08 13:39	19.9	2013-09-05 12:40	< 4	2013-09-07 20:27	120	41524.73	0.22	2013-09-08 1:41	head loss	52.79929
2013-09-08 15:48	2013-09-11 10:37	20.8	2013-09-08 16:55	< 4	2013-09-10 23:19	120	41528.04	0.21	2013-09-10 12:50	turbidity	43.913007
2013-09-11 12:44	2013-09-14 7:31	21.0	2013-09-11 14:07	< 4	2013-09-13 20:31	120	41530.75	0.23	2013-09-12 16:47	turbidity	26.666667
2013-09-14 9:41	2013-09-17 10:23	18.1	2013-09-14 11:19	< 4	2013-09-16 19:03	120	41533.89			flow rate	55.73305
2013-09-17 12:28	2013-09-20 9:31	18.2	2013-09-17 13:18	< 4	2013-09-20 4:11	120	41536.93			head loss	57.034535
2013-09-20 11:30	2013-09-23 10:23	18.4	2013-09-20 11:59	< 4	2013-09-23 8:13	120	41540.39			flow rate	68.230576
2013-09-23 12:33	2013-09-26 9:33	17.3	2013-09-23 13:05							end of run	68.469425
2013-09-26 11:40	2013-09-29 9:40	17.8	2013-09-26 17:26			120	41546.17			head loss	58.685051
2013-09-29 11:47	2013-10-02 9:38	17.9	2013-09-29 12:20	< 4	2013-10-02 8:54	120	41549.15	0.22	2013-10-01 9:17	turbidity	44.953746
2013-10-02 14:24	2013-10-05 14:52	17.8	2013-10-02 15:56			120	41552.60			head loss	70.4005
2013-10-05 17:06	2013-10-08 10:54	17.1	2013-10-05 17:35							end of run	65.319292
2013-10-08 13:47	2013-10-11 8:17	15.7	2013-10-08 14:17	< 4	2013-10-11 7:55					flow rate	65.619789
2013-10-11 10:27	2013-10-14 17:51	15.4	2013-10-11 11:47	< 4	2013-10-13 20:29	120	41560.70			head loss	52.899329

2013-10-14 19:54	2013-10-17 12:06	15.8	2013-10-14 20:25	< 4	2013-10-17 3:44	120	41563.87			head loss	48.449333
2013-10-17 14:21	2013-10-20 16:52	13.8	2013-10-17 15:42	< 4	2013-10-20 11:00	120	41567.30			head loss	63.598888
2013-10-20 19:01	2013-10-23 11:03	12.1	2013-10-20 20:21					0.2	2013-10-23 9:02	turbidity	60.68839
2013-10-23 13:02	2013-10-26 10:12	10.1	2013-10-23 14:23					0.21	2013-10-25 10:49	turbidity	44.433333
2013-10-26 12:18	2013-10-29 8:56	8.8	2013-10-26 13:44					0.25	2013-10-28 3:25	turbidity	37.683333
2013-10-29 12:09	2013-11-01 7:32	9.0	2013-10-29 13:44					0.23	2013-10-30 20:57	turbidity	31.219268
2013-11-01 10:15	2013-11-04 10:57	8.9	2013-11-01 10:55					0.37	2013-11-03 4:02	turbidity	41.11324
2013-11-04 15:16	2013-11-06 10:36		2013-11-04 21:35							end of run	37.000544
2013-11-06 10:36	2013-11-08 13:02	8.9									
2013-11-08 13:02	2013-11-10 10:44	8.3	2013-11-08 13:29	< 4	2013-11-10 8:06					flow rate	42.616511
2013-11-10 12:52	2013-11-13 12:00	6.9	2013-11-10 13:13							end of run	70.783056
2013-11-13 14:02	2013-11-16 14:28	6.9									
2013-11-16 16:39	2013-11-19 7:51	6.7	2013-11-16 17:01							end of run	62.833335
2013-11-19 9:18	2013-11-22 10:39	6.5	2013-11-19 9:38							end of run	73.030107
2013-11-22 12:48	2013-11-25 12:10	4.5	2013-11-22 13:13							end of run	70.933519
2013-11-25 14:09	2013-11-28 15:13	2.4	2013-11-25 14:35							end of run	72.636417
2013-11-	2013-12-	1.6	2013-11-					0.2	2013-12-	turbidity	63.79468

28 17:19	01 17:01		28 17:45						01 9:33		3
2013-12-01 19:08	2013-12-04 14:23	1.4	2013-12-01 19:37					0.21	2013-12-04 6:16	turbidity	58.65
2013-12-04 16:19	2013-12-07 9:05	3.1	2013-12-04 16:50					0.22	2013-12-06 21:44	turbidity	52.683333
2013-12-07 11:24	2013-12-10 10:41	1.9	2013-12-07 11:51							end of run	70.846756
2013-12-10 12:39	2013-12-13 10:18	1.4									
2013-12-13 12:30	2013-12-16 16:32	1.1	2013-12-13 12:58					0.2	2013-12-14 18:42	turbidity	29.730856
2013-12-16 18:42	2013-12-19 13:12	1.0									
varied	2013-12-23 12:36	1.2	2013-12-19 15:27					0.2	2013-12-21 2:29		35.033333
2013-12-23	2014-01-01 0:00	2.1									
2014-01-01 14:46	2014-01-03 13:22	1.2									
2014-01-03 15:33	2014-01-06 9:48	1.0	2014-01-03 17:05					0.2	2014-01-05 10:07	turbidity	41.035043
2014-01-06 12:00	2014-01-09 12:14	0.7	2014-01-06 12:42	< 4	2014-01-09 11:58			0.21	2014-01-07 12:36	turbidity	23.900996
2014-01-09 15:02	2014-01-12 15:24	1.5	2014-01-09 15:52					0.2	2014-01-11 3:10	turbidity	35.301471
2014-01-12 17:51	2014-01-15 12:32	0.8	2014-01-12 18:53					0.21	2014-01-14 13:59	turbidity	43.101796
2014-01-15 14:26	2014-01-18 10:29	1.4	2014-01-15 15:30					0.2	2014-01-17 14:58	turbidity	47.468644
2014-01-18 12:52	2014-01-21 12:09	0.5	2014-01-18 14:24					0.24	2014-01-20 9:38	turbidity	43.235135
2014-01-21 14:13	2014-01-24 9:41	1.0	2014-01-21 15:52					0.22	2014-01-23 1:00	turbidity	33.131953

2014-01-24 11:47	2014-01-27 10:31	1.4	2014-01-24 12:31					0.22	2014-01-25 16:27	turbidity	27.933333
2014-01-27 13:02	2014-01-30 11:26	0.5	2014-01-27 13:52	< 4	2014-01-30 11:14			0.36	2014-01-28 15:58	turbidity	26.101088
2014-01-30 13:24	2014-02-02 13:16	0.8	2014-01-30 14:06					0.21	2014-02-01 0:52	turbidity	34.768115
2014-02-02 16:13	2014-02-05 12:23	1.0	2014-02-02 17:01	< 4	2014-02-05 12:10			0.2	2014-02-03 10:25	turbidity	17.400725
2014-02-05 14:21	2014-02-08 12:47	0.9	2014-02-05 15:13					0.27	2014-02-06 22:16	turbidity	31.065372
2014-02-08 14:54	2014-02-11 17:24	1.1	2014-02-08 15:50					0.25	2014-02-09 17:29	turbidity	25.665597
2014-02-11 19:29	2014-02-14 10:31	1.8	2014-02-11 20:09					0.29	2014-02-12 21:18	turbidity	25.165618
2014-02-14 13:13	2014-02-17 11:05	1.2	2014-02-14 13:55	< 4	2014-02-17 10:53			0.21	2014-02-15 14:15	turbidity	24.334347
2014-02-17 13:02	2014-02-20 17:02	1.4	2014-02-17 13:58					0.2	2014-02-18 15:36	turbidity	25.633333
2014-02-20 19:06	2014-02-23 10:18	2.1	2014-02-20 19:48							end of run	62.500094
2014-02-23 12:45	2014-02-26 12:12	1.0	2014-02-23 13:21	< 4	2014-02-26 12:08					flow rate	70.783233
2014-02-26 14:56	2014-03-01 13:16	1.2	2014-02-26 15:29							end of run	69.769853
2014-03-01 15:27	2014-03-04 11:08	0.7	2014-03-01 15:57	< 4	2014-03-04 10:58					flow rate	67.030536
2014-03-04 14:47	2014-03-07 15:26	1.7	2014-03-04 15:19							end of run	72.130325
2014-03-07 17:44	2014-03-10 10:41	1.2	2014-03-07 18:14							end of run	64.463801
2014-03-10 12:48	2014-03-13 9:59	1.4	2014-03-10 13:18					0.21	2014-03-13 1:38	turbidity	60.333333
2014-03-	2014-03-	1.4	2014-03-					0.22	2014-03-	turbidity	59.36419

13 12:21	16 10:31		13 12:55						16 0:16		3
2014-03-16 12:57	2014-03-19 8:50	0.9	2014-03-16 13:27					0.22	2014-03-18 23:19	turbidity	57.869078
2014-03-19 11:00	2014-03-22 19:17	1.0	2014-03-19 11:34					0.2	2014-03-22 10:46	turbidity	71.2
2014-03-22 21:23	2014-03-25 10:29	1.2	2014-03-22 21:59	< 4	2014-03-25 10:19					flow rate	60.336038
2014-03-25 13:24	2014-03-28 14:26	1.5	2014-03-25 14:02					0.2	2014-03-28 9:05	turbidity	67.063872
2014-03-28 16:46	2014-03-31 10:42	1.0	2014-03-28 17:22	< 4	2014-03-31 10:36			0.27	2014-03-30 4:28	turbidity	35.1
2014-03-31 13:55	2014-04-03 10:01	1.8	2014-03-31 15:25					0.2	2014-04-03 2:47	turbidity	59.36914
2014-04-03 12:14	2014-04-06 13:00	0.9	2014-04-03 13:44							end of run	71.26964
2014-04-06 15:24	2014-04-09 9:48	1.2	2014-04-06 16:06							end of run	65.69989
2014-04-09 12:31	2014-04-12 17:10	2.5	2014-04-09 13:17					0.2	2014-04-12 6:26	turbidity	65.163951
2014-04-12 19:21	2014-04-15 12:09	4.2	2014-04-12 21:25					0.2	2014-04-15 4:49	turbidity	55.402308
2014-04-15 14:08	2014-04-18 10:03	5.6	2014-04-15 15:12					0.24	2014-04-18 8:30	turbidity	65.302721
2014-04-18 12:18	2014-04-21 11:48	7.5	2014-04-18 13:26							end of run	70.369601
2014-04-21 14:29	2014-04-24 9:56	9.4	2014-04-21 15:15	< 4	2014-04-24 9:52					flow rate	66.630421
2014-04-24 12:18	2014-04-27 9:33	8.8	2014-04-24 13:30							end of run	68.06369
2014-04-27 11:38	2014-04-30 10:27	9.1	2014-04-27 12:16							end of run	70.197072
2014-04-30 12:39	2014-05-03 9:29	8.7	2014-04-30 13:33							end of run	67.936269

2014-05-03 11:32	2014-05-07 10:36	9.9	2014-05-03 12:40			120	41736.27	0.2	2014-05-04 22:06	turbidity	33.433333
2014-05-07 12:43	2014-05-09 12:46	12.5	2014-05-07 15:07					0.2	2014-05-08 6:17	turbidity	15.166667
2014-05-09 14:45	2014-05-12 10:36	15.8	2014-05-09 21:31					0.21	2014-05-10 7:07	turbidity	9.6004
2014-05-12 13:38	2014-05-15 9:34	17.9	2014-05-12 17:37							turbidity	0
2014-05-15 11:58	2014-05-20 8:20	14.5	2014-05-15 12:32	< 4	2014-05-18 9:14	120	41777.30			turbidity	0
2014-05-20 10:27	2014-05-23 9:07	16.1	2014-05-20 13:25			120	41782.31			turbidity	0
2014-05-23 11:32	2014-05-27 10:13	19.5	2014-05-23 12:00	< 4	2014-05-26 13:27	120	41784.89			turbidity	0
2014-05-27 12:16	2014-05-30 9:04	20.5	2014-05-27 14:28	< 4	2014-05-30 2:42	120	41788.93			turbidity	0
2014-05-30 11:25	2014-06-02 11:49	21.3	2014-05-30 14:30	< 4	2014-06-02 4:11	120	41792.18			turbidity	0
2014-06-02 13:55	2014-06-05 9:29	21.4	2014-06-02 17:17							turbidity	0
2014-06-05 12:01	2014-06-08 9:29	21.0	2014-06-05 14:31			120	41798.04			turbidity	0
2014-06-08 12:15	2014-06-11 11:30	19.0	2014-06-08 16:49	< 4	2014-06-10 23:46			0.32	2014-06-10 16:41	turbidity	47.866667
2014-06-12 8:12	2014-06-14 13:36	21.5	2014-06-12 10:05							end of run	51.503953
2014-06-14 15:44	2014-06-17 9:58	21.6	2014-06-14 16:24	< 4	2014-06-17 6:04	120	41807.13			head loss	58.750921
2014-06-17 11:47	2014-06-20 9:41	23.5	2014-06-17 12:29	< 4	2014-06-20 0:11	120	41809.72			head loss	52.849171
2014-06-20 12:21	2014-06-23 9:54	23.5	2014-06-20 13:55	< 4	2014-06-22 22:14	120	41812.71			head loss	51.167685
2014-06-	2014-06-	22.5	2014-06-	< 4	2014-06-	120	41815	0.21	2014-06-	head loss	47.86741

23 13:04	26 11:26		23 13:44		25 22:06		.57		25 23:08		1
2014-06-26 13:20	2014-07-02 9:18	26.5	2014-06-26 14:05	< 4	2014-06-28 21:46	120	41818.69	0.21	2014-06-27 15:51	turbidity	25.767481
2014-07-02 11:34	2014-07-05 11:38	23.3	2014-07-02 19:11	< 4	2014-07-04 19:08	120	41824.61	0.21	2014-07-04 10:11	turbidity	38.998375
2014-07-05 13:57	2014-07-08 9:43	23.1	2014-07-05 16:09	< 4	2014-07-07 16:35	120	41827.61	0.27	2014-07-06 16:37	turbidity	24.467686
2014-07-08 12:32	2014-07-11 8:39	21.8	2014-07-08 16:09							end of run	64.49731
2014-07-11 10:56	2014-07-14 14:00	21.8	2014-07-11 12:22	< 4	2014-07-13 14:30	120	41833.57			head loss	49.299258
2014-07-14 16:09	2014-07-17 11:01	22.0	2014-07-14 17:07	< 4	2014-07-16 22:43	120	41836.96			flow rate	53.60246
2014-07-17 12:59	2014-07-20 10:02	21.4	2014-07-17 13:39	< 4	2014-07-19 20:40	120	41839.82			head loss	54.116756
2014-07-20 13:30	2014-07-23 10:55	22.7	2014-07-20 15:02	< 4	2014-07-22 19:35	120	41842.99			flow rate	52.564472
2014-07-23 12:50	2014-07-26 10:28	23.5	2014-07-23 13:40	< 4	2014-07-24 18:48					flow rate	29.133428
2014-07-26 12:43	2014-07-29 11:05	22.7	2014-07-26 13:49	< 4	2014-07-29 1:01					flow rate	59.202704
2014-07-29 13:48	2014-08-01 10:47	21.0	2014-07-29 14:48	< 4	2014-07-31 19:53					flow rate	53.097519
2014-08-01 13:03	2014-08-04 10:31	21.7	2014-08-01 13:59	< 4	2014-08-04 1:51	120	41854.91			head loss	55.849142
2014-08-04 12:37	2014-08-07 10:40	22.6	2014-08-04 13:13	< 4	2014-08-07 2:30	120	41857.95			head loss	57.701086
2014-08-07 12:42	2014-08-10 14:39	22.7	2014-08-07 13:32	< 4	2014-08-10 6:29	120	41860.80			head loss	53.650839
2014-08-10 16:57	2014-08-13 9:36	23.2	2014-08-10 17:39			120	41864.01			head loss	54.532383
2014-08-13 12:03	2014-08-16 14:50	20.6	2014-08-13 13:38	< 4	2014-08-16 12:16	120	41867.22			head loss	63.633474

2014-08-16 17:02	2014-08-19 10:00	19.8	2014-08-16 17:54	< 4	2014-08-19 9:06	120	41870.25			head loss	60.067603
2014-08-19 11:54	2014-08-22 10:18	21.3	2014-08-19 12:54			120	41873.24			head loss	64.898792
2014-08-22 12:29	2014-08-25 10:25	22.6	2014-08-22 13:13	< 4	2014-08-25 2:43	120	41875.58			head loss	48.599043
2014-08-25 12:15	2014-08-28 14:38	22.9	2014-08-25 13:17	< 4	2014-08-28 1:02	120	41879.02			head loss	59.116567
2014-08-28 16:56	2014-08-31 11:49	22.6	2014-08-28 17:34	< 4	2014-08-30 20:13	120	41881.57			head loss	44.182562
2014-08-31 13:59	2014-09-03 9:54	23.3	2014-08-31 14:33	< 4	2014-09-02 20:10	120	41884.47	0.21	2014-09-02 19:43	head loss	44.615887
2014-09-03 11:49	2014-09-07 16:32	22.5	2014-09-03 12:21	< 4	2014-09-05 21:54	120	41887.47	0.22	2014-09-05 9:00	turbidity	44.664806
2014-09-07 18:46	2014-09-09 10:01	21.8	2014-09-07 19:28					0.23	2014-09-09 8:21	turbidity	36.898462
2014-09-09 12:02	2014-09-12 9:16	20.3	2014-09-09 12:50			120	41893.99			head loss	59.034354
2014-09-12 11:28	2014-09-15 9:44	18.6	2014-09-12 21:53	< 4	2014-09-15 0:56	120	41896.60			head loss	40.584719
2014-09-15 11:52	2014-09-18 8:15	17.3	2014-09-15 12:36	< 4	2014-09-18 1:37	120	41899.62			head loss	50.382365
2014-09-18 10:25	2014-09-21 14:53	17.3	2014-09-18 10:57	< 4	2014-09-21 3:39	120	41902.84			head loss	57.132253

			F5								
				Flow Alarm		Head loss Alarm		Turbidity Alarm			
Start Date	End Date	Temperature (C°)	End of Ripening	Flow Rate (L/min)	Date	Head loss (in H2O)	Date	Turbidity (NTU)	Date	Alarm Condition	Filter Run Time (h)
2014-01-03 15:33	2014-01-06 9:48	1.0	2014-01-03 14:37			120	2014-01-05 9:03	0.2	2014-01-05 11:23	head loss	42.449239
2014-01-06 12:00	2014-01-09 12:14	0.7	2014-01-06 11:00			120	2014-01-08 16:59	0.21	2014-01-07 15:50	turbidity	28.834535
2014-01-09 15:02	2014-01-12 15:24	1.5	2014-01-09 13:12			120	2014-01-11 23:45	0.22	2014-01-11 2:16	turbidity	37.068211
2014-01-12 17:51	2014-01-15 12:32	0.8	2014-01-12 16:53			120	2014-01-14 22:56	0.2	2014-01-14 16:57	turbidity	48.068669
2014-01-15 14:26	2014-01-18 10:29	1.4	2014-01-15 13:20			120	2014-01-18 6:11	0.23	2014-01-17 19:32	turbidity	54.202258
2014-01-18 12:52	2014-01-21 12:09	0.5	2014-01-18 11:58			120	2014-01-21 9:02	0.2	2014-01-20 13:48	turbidity	49.83541
2014-01-21 14:13	2014-01-24 9:41	1.0	2014-01-21 13:05			120	2014-01-24 2:23	0.22	2014-01-23 5:42	turbidity	40.63164
2014-01-24 11:47	2014-01-27 10:31	1.4	2014-01-24 11:05			120	2014-01-27 9:23	0.2	2014-01-25 17:29	turbidity	30.4
2014-01-27 13:02	2014-01-30 11:26	0.5	2014-01-27 13:10			120	2014-01-30 8:04	0.8	2014-01-28 10:42	turbidity	21.534231
2014-01-	2014-02-	0.8	2014-01-					0.2	2014-	turbidity	31.101296

30 13:24	02 13:16		30 12:22						01-31 19:28		
2014-02-02 16:13	2014-02-05 12:23	1.0	2014-02-02 15:49					0.2	2014-02-03 11:41	turbidity	19.87
2014-02-05 14:21	2014-02-08 12:47	0.9	2014-02-05 13:25					0.24	2014-02-06 19:26	turbidity	30.032082
2014-02-08 14:54	2014-02-11 17:24	1.1	2014-02-08 14:18					0.2	2014-02-09 18:53	turbidity	28.598808
2014-02-11 19:29	2014-02-14 10:31	1.8	2014-02-11 18:59					0.2	2014-02-12 22:36	turbidity	27.632182
2014-02-14 13:13	2014-02-17 11:05	1.2	2014-02-14 12:53					0.2	2014-02-15 20:47	turbidity	31.901329
2014-02-17 13:02	2014-02-20 17:02	1.4	2014-02-17 12:08					0.23	2014-02-18 17:14	turbidity	29.1
2014-02-20 19:06	2014-02-23 10:18	2.1	2014-02-20 18:24							end of run	63.900036
2014-02-23 12:45	2014-02-26 12:12	1.0	2014-02-23 11:49							end of run	72.3833
2014-02-26 14:56	2014-03-01 13:16	1.2	2014-02-26 13:10							end of run	72.103089
2014-03-01 15:27	2014-03-04 11:08	0.7	2014-03-01 14:33							end of run	68.597138
2014-03-04 14:47	2014-03-07 15:26	1.7	2014-03-04 12:47							end of run	74.663553
2014-03-07 17:44	2014-03-10 10:41	1.2	2014-03-07 17:16							end of run	65.430508
2014-03-	2014-03-	1.4	2014-03-					0.2	2014-	turbidity	66.266667

10 12:48	13 9:59		10 11:56						03-13 6:12		
2014-03-13 12:21	2014-03-16 10:31	1.4	2014-03-13 11:19					0.21	2014-03-16 3:38	turbidity	64.330653
2014-03-16 12:57	2014-03-19 8:50	0.9	2014-03-16 12:07							end of run	68.730385
2014-03-19 11:00	2014-03-22 19:17	1.0	2014-03-19 10:08			120	41720.65	0.23	2014-03-22 18:10	head loss	77.432032
2014-03-22 21:23	2014-03-25 10:29	1.2	2014-03-22 20:31							end of run	61.969317
2014-03-25 13:24	2014-03-28 14:26	1.5	2014-03-25 11:34			120	41726.58			head loss	74.282115
2014-03-28 16:46	2014-03-31 10:42	1.0	2014-03-28 17:24					0.2	2014-03-30 9:28	turbidity	40.066667
2014-03-31 13:55	2014-04-03 10:01	1.8	2014-03-31 11:53							end of run	70.136258
2014-04-03 12:14	2014-04-06 13:00	0.9	2014-04-03 12:50			120	41735.19			head loss	63.61656
2014-04-06 15:24	2014-04-09 9:48	1.2	2014-04-06 14:14							end of run	67.566635
2014-04-09 12:31	2014-04-12 17:10	2.5	2014-04-09 13:52							end of run	75.29686
2014-04-12 19:21	2014-04-15 12:09	4.2	2014-04-12 18:45							end of run	65.39996
2014-04-15 14:08	2014-04-18 10:03	5.6	2014-04-15 13:18					0.21	2014-04-18 9:06	turbidity	67.802825
2014-04-18 12:18	2014-04-21 11:48	7.5	2014-04-18 11:22							end of run	72.436354
2014-04-	2014-04-	9.4	2014-04-							end of run	68.830418

21 14:29	24 9:56		21 13:07								
2014-04-24 12:18	2014-04-27 9:33	8.8	2014-04-24 11:26							end of run	70.130357
2014-04-27 11:38	2014-04-30 10:27	9.1	2014-04-27 11:04							end of run	71.397022
2014-04-30 12:39	2014-05-03 9:29	8.7	2014-04-30 11:35							end of run	69.902936
2014-05-03 11:32	2014-05-07 10:36	9.9	2014-05-03 10:42			120	41735.18	0.2	2014-05-05 0:36	turbidity	37.9
2014-05-07 12:43	2014-05-09 12:46	12.5	2014-05-07 12:35					0.21	2014-05-08 8:05	turbidity	19.5
2014-05-09 14:45	2014-05-12 10:36	15.8	2014-05-09 14:31			120	41770.71	0.2	2014-05-10 11:55	turbidity	21.400892
2014-05-12 13:38	2014-05-15 9:34	17.9	2014-05-12 14:41			120	41773.37	0.2	2014-05-13 19:25	turbidity	28.732136
2014-05-15 11:58	2014-05-20 8:20	14.5	2014-05-15 13:51	< 4	2014-05-18 22:04	120	41776.24	0.22	2014-05-16 20:45	turbidity	30.898712
2014-05-20 10:27	2014-05-23 9:07	16.1	2014-05-20 9:45	< 4	2014-05-22 10:43	120	41780.95	0.23	2014-05-21 5:07	turbidity	19.366667
2014-05-23 11:32	2014-05-27 10:13	19.5	2014-05-23 10:46	< 4	2014-05-25 11:57	121	41784.00	0.2	2014-05-24 13:28	turbidity	26.7
2014-05-27 12:16	2014-05-30 9:04	20.5	2014-05-27 12:00	< 4	2014-05-29 17:02	123	41788.05	0.2	2014-05-28 21:24	turbidity	33.401392
2014-05-30 11:25	2014-06-02 11:49	21.3	2014-05-30 13:50	< 4	2014-06-02 10:59	120	41790.98	0.2	2014-05-31	turbidity	33.43194

									23:16		
2014-06-02 13:55	2014-06-05 9:29	21.4	2014-06-02 12:47			121	41794.28	2	2014-06-05 10:31	head loss	41.899999
2014-06-05 12:01	2014-06-08 9:29	21.0	2014-06-05 12:45			122	41797.16			head loss	39.034011
2014-06-08 12:15	2014-06-11 11:30	19.0	2014-06-08 11:25	< 4	2014-06-11 3:22	121	41799.92	0.32	2014-06-10 17:15	turbidity	53.833333
2014-06-12 8:12	2014-06-14 13:36	21.5	2014-06-12 8:51							end of run	52.737235
2014-06-14 15:44	2014-06-17 9:58	21.6	2014-06-14 14:50			121	41806.50	0.31	2014-06-17 9:08	head loss	45.067399
2014-06-17 11:47	2014-06-20 9:41	23.5	2014-06-17 10:51	< 4	2014-06-20 8:55	120	41809.23	0.22	2014-06-19 23:34	head loss	42.732632
2014-06-20 12:21	2014-06-23 9:54	23.5	2014-06-20 11:27	< 4	2014-06-22 21:14	120	41811.96	0.25	2014-06-22 14:46	head loss	35.550614
2014-06-23 13:04	2014-06-26 11:26	22.5	2014-06-23 12:28	< 4	2014-06-25 3:32	120	41814.74	0.2	2014-06-25 23:56	head loss	29.383801
2014-06-26 13:20	2014-07-02 9:18	26.5	2014-06-26 14:50	< 4	2014-06-28 12:48	121	41817.69	0.25	2014-06-28 7:37	head loss	25.782861
2014-07-02 11:34	2014-07-05 11:38	23.3	2014-07-02 10:46	< 4	2014-07-04 8:24	122	41823.53	0.21	2014-07-04 2:11	head loss	25.867154
2014-07-05 13:57	2014-07-08 9:43	23.1	2014-07-05 12:59	< 4	2014-07-06 21:39	120	41826.53	0.21	2014-07-06 22:35	head loss	23.666217
2014-07-	2014-07-	21.8	2014-07-	< 4	2014-07-	120	41830			head loss	39.317358

08 12:32	11 8:39		08 11:40		10 16:25		.12				
2014-07- 11 10:56	2014-07- 14 14:00	21.8	2014-07- 11 9:52	< 4	2014-07- 12 22:42	120	41832 .53			head loss	26.799571
2014-07- 14 16:09	2014-07- 17 11:01	22.0	2014-07- 14 15:33	< 4	2014-07- 16 7:31	120	41835 .81			head loss	27.883379
2014-07- 17 12:59	2014-07- 20 10:02	21.4	2014-07- 17 12:23	< 4	2014-07- 19 20:54	120	41838 .71			head loss	28.716703
2014-07- 20 13:30	2014-07- 23 10:55	22.7	2014-07- 20 13:06	< 4	2014-07- 22 12:29	120	41842 .04			head loss	35.767306
2014-07- 23 12:50	2014-07- 26 10:28	23.5	2014-07- 23 12:44	< 4	2014-07- 25 5:24	126	41844 .52			head loss	23.633804
2014-07- 26 12:43	2014-07- 29 11:05	22.7	2014-07- 26 12:07	< 4	2014-07- 29 2:37	122	41847 .79			head loss	30.766183
2014-07- 29 13:48	2014-08- 01 10:47	21.0	2014-07- 29 12:18			121	41851 .05			head loss	36.999417
2014-08- 01 13:03	2014-08- 04 10:31	21.7	2014-08- 01 12:25	< 4	2014-08- 04 7:43	121	41853 .91			head loss	33.332811
2014-08- 04 12:37	2014-08- 07 10:40	22.6	2014-08- 04 11:57	< 4	2014-08- 07 9:20	121	41856 .79			head loss	31.050568
2014-08- 07 12:42	2014-08- 10 14:39	22.7	2014-08- 07 12:06	< 4	2014-08- 08 20:49	128	41859 .02	0.28	2014- 08-10 11:25	head loss	12.333519
2014-08- 10 16:57	2014-08- 13 9:36	23.2	2014-08- 10 16:35			120	41862 .93			head loss	29.766147
2014-08- 13 12:03	2014-08- 16 14:50	20.6	2014-08- 13 10:57	< 4	2014-08- 16 10:18	121	41866 .42			head loss	47.166694
2014-08- 16 17:02	2014-08- 19 10:00	19.8	2014-08- 16 16:20			124	41869 .07			head loss	33.300529
2014-08- 19 11:54	2014-08- 22 10:18	21.3	2014-08- 19 11:28			120	41872 .36			head loss	45.082539
2014-08- 22 12:29	2014-08- 25 10:25	22.6	2014-08- 22 11:47	< 4	2014-08- 25 6:17	120	41874 .93			head loss	34.449363

2014-08-25 12:15	2014-08-28 14:38	22.9	2014-08-25 11:35	< 4	2014-08-28 6:32	120	41877.95	0.29	2014-08-27 16:05	head loss	35.233304
2014-08-28 16:56	2014-08-31 11:49	22.6	2014-08-28 16:16	< 4	2014-08-31 1:19	120	41880.83	0.23	2014-08-30 10:56	head loss	27.649526
2014-08-31 13:59	2014-09-03 9:54	23.3	2014-08-31 13:31	< 4	2014-09-02 10:14	120	41883.87	0.22	2014-09-02 18:49	head loss	31.48279
2014-09-03 11:49	2014-09-07 16:32	22.5	2014-09-03 11:25	< 4	2014-09-05 8:54	120	41886.78	0.2	2014-09-05 20:24	head loss	31.183903
2014-09-07 18:46	2014-09-09 10:01	21.8	2014-09-07 17:54			120	41890.93	0.23	2014-09-09 2:59	head loss	28.300517
2014-09-09 12:02	2014-09-12 9:16	20.3	2014-09-09 11:22			120	41892.98			head loss	36.250617
2014-09-12 11:28	2014-09-15 9:44	18.6	2014-09-12 10:42	< 4	2014-09-13 13:18	121	41895.52			head loss	25.783819
2014-09-15 11:52	2014-09-18 8:15	17.3	2014-09-15 11:06	< 4	2014-09-17 19:49	120	41898.67			head loss	28.882811
2014-09-18 10:25	2014-09-21 14:53	17.3	2014-09-18 9:41	< 4	2014-09-20 22:25	120	41901.67			head loss	30.482771

Appendix B

Nutrient Data

	INF										
Sampling Date	TOC (mg/L)	DOC (mg/L)	POC (mg/L)	UV_{254}	SUVA	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/l)	SRP (mg/L)	NH3-N (mg/L)
2013-10-03	4.96	5.204						0.0030	0.0012	0.0041	
2013-10-30	4.087	3.964	0.123	0.038577	0.973174	7.72	1.17	0.0092	0.0046	0.0074	0.0746
2013-11-18	5.225	4.14	1.085	0.064059	1.547309	7.95	0.351	0.0016	0.0008	0.0045	0.0621
2013-11-20	4.944	4.907	0.037	0.062022	1.263945	8.07	0.378	0.0026		0.0040	0.0821
2013-12-11	4.583	4.123	0.46	0.053925	1.307912		0.675	0.0047	0.0030	0.0057	0.374
2014-01-10	3.42	3.245	0.175	0.055281	1.703575	8	0.73	0.0053	0.0019	0.0046	0.463
2014-01-20	3.29	3.418	0	0.04483	1.311597	7.87	0.626	0.0141	0.0098	0.0052	0.2965
2014-02-07	3.639	3.289	0.35	0.043506	1.322785	7.57		0.0096		0.0017	0.3325
2014-02-12	3.73	3.448	0.282	0.047212	1.369252	7.86	0.519	0.0111		0.0010	0.424
2014-02-16	3.713	3.532	0.181	0.051791	1.466331	7.76	0.391	0.0098		0.0018	0.4045
2014-02-18	3.947	3.562	0.385	0.052956	1.486687	7.92	0.762	0.0085		0.0009	0.395
2014-02-21	3.468	3.439	0.029	0.04423	1.286124	7.73	0.396	0.0013		0.0007	0.513
2014-02-25	3.325	3.117	0.208	0.069273	2.222419	7.52	0.55	0.0027		0.0015	0.4415
2014-03-14	4.206	3.924	0.282	0.051754	1.318909	7.77	0.53	0.0072		0.0012	0.4605
2014-03-20	3.721	3.527	0.194	0.04783	1.35611	7.42	0.411	0.0104		0.0044	0.493
2014-03-23	3.617	3.463	0.154	0.046389	1.339567	7.4	0.481	0.0132		0.0030	0.4585
2014-03-26	3.615	3.421	0.1943333	0.046422	1.35711	7.4	0.486	0.0127		0.0031	0.4235
2014-04-01	3.508	3.260	0.2476666	0.039557	1.213281	7.39	0.818	0.0176		0.0045	0.444
2014-04-04	3.073	2.944	0.1286666	0.035	1.188717	7.33	0.765	0.0193		0.0039	0.3775
2014-04-07	3.220	3.003	0.2173333	0.034288	1.141785	7.4	0.992	0.0156		0.0033	0.2865
2014-04-16	2.590	2.476	0.1143333	0.025198	1.017827	7.27	0.533	0.0111		0.0042	0.112
2014-04-22	2.605	2.532	0.0733333	0.028974	1.144479	7.45	0.491	0.0043		0.0039	0.144
2014-06-03	3.674	3.430	0.2436666	0.037465	1.092162	7.76	0.182	0.0003		0.0011	0.0304
2014-06-18	3.646	3.501	0.1453333	0.043449	1.241152	7.35	0.088	0.0000		0.0006	0.015
2014-06-21	3.660	3.420	0.2396666	0.0444	1.298125	7.67	0.559	0.0000		0.0012	0.029
2014-07-03	4.107	3.841	0.2656666	0.043811	1.140505	7.4	0.364	0.0005		0.0023	0.024

2014-07-09	3.9	3.554	0.346	0.059946	1.686708	7.63	0.518	0.0026		0.0009	0.049
2014-07-15	3.611	3.455	0.156	0.038	1.099849	7.7		0.0073		0.0015	0.0079
2014-07-18	3.808	3.439	0.3686666	0.044615	1.297187	7.45	0.295	0.0088		0.0047	0.046
2014-07-27	3.967	4.064	0	0.050929	1.253067	7.62	0.139	0.0000		0.0049	0.039
2014-07-30	3.915	3.846	0.0683333	0.04626	1.202704	7.55	0.167	0.0006		0.0033	0.059
2014-08-05	4.053	4.036	0.0173333	0.053052	1.314578	7.24		0.0000		0.0052	0.046
2014-08-23	4.079	3.949	0.1296666	0.050373	1.275486	7.68	0.233	0.0000		0.0049	0.0276
2014-08-26	4.417	4.425	0	0.053694	1.522808	7.5	0.345	0.0000		0.0047	0.03
2014-08-29	4.775	4.496	0.2793333	0.053247	1.184398	7.54	0.41	0.0000		0.0049	0.013
2014-09-13	4.959	4.805	0.1536666	0.066611	1.386181	7.4	0.306	0.0000		0.0054	0.039
2014-09-16	4.684	4.721	0	0.065267	1.382584	7.35	0.315	0.0005		0.0053	0.015

	EFF-F1										
Sampling Date	TOC (mg/L)	DOC (mg/L)	POC (mg/L)	UV_{254}	SUVA	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/l)	SRP (mg/L)	NH3-N (mg/L)
2013-10-03	3.37	3.565	0					0.0021	0.0003	0.0054	
2013-10-30	4.521	4.51	0.011	0.036965	1.036893	7.77	0.124	0.0022	0.0007	0.0058	0.245
2013-11-18	3.675	4.569	0	0.060117	1.332967	8.01	0.075	0.0007	0.0005	0.0042	0.0551
2013-11-20			0	0.060082	1.314988	8.09	0.076	0.0004	0.0023	0.0043	0.0454
2013-12-11	4.005	3.997	0.008					< 0.5		< 0.04	0.24
2014-01-10	4.229	3.073	1.156	0.051355	1.349142		0.09	0.0003	0.0002	0.0050	0.388
2014-01-20	2.92	2.999	0	0.053276	1.733689	7.96	0.122	0.0027	0.0064	0.0035	0.456
2014-02-07	3.087	3.093	0	0.043627	1.454718	8.03	0.184	0.0085	0.0051	0.0024	0.267
2014-02-12	3.258	3.263	0	0.041348	1.336819	7.8	0.17	0.0037		0.0014	0.413
2014-02-16	3.215	3.186	0.029	0.05802	1.778106	7.71	0.06	0.0038		0.0006	0.413
2014-02-18	3.236	3.35	0	0.045798	1.437476	7.84	0.211	0.0054		0.0012	0.4745
2014-02-21	3.077	3.116	0	0.043999	1.313391	7.94	0.071	0.0013		0.0009	0.387
2014-02-25	2.925	2.911	0.014	0.041908	1.344936	7.73	0.057	0.0035		0.0005	0.525
2014-03-14	3.672	3.579	0.093	0.062188	2.136311	7.66	0.05	0.0012		0.0011	0.491
2014-03-20	3.297	3.275	0.022	0.049214	1.375082	7.81	0.072	0.0034		0.0012	0.4055
2014-03-23	3.115	3.09	0.025	0.045548	1.390785	7.48	0.076	0.0035		0.0036	0.498
2014-03-26	3.114	3.045	0.069	0.041725	1.350311	7.55	0.076	0.0040		0.0029	0.468
2014-04-01	3.387	3.12	0.267	0.042812	1.405961	7.44	0.069	0.0036		0.0032	0.4145
2014-04-04	2.592	2.628	0	0.037044	1.187295	7.48	0.063	0.0094		0.0035	0.419
2014-04-07	2.693	2.739	0	0.033614	1.279087	7.45	0.072	0.0003		0.0032	0.4275
2014-04-16	2.239	2.131	0.108	0.03719	1.357788	7.41	0.071	0.0000		0.0032	0.313
2014-04-22	2.207	2.238	0	0.022431	1.052623	7.52	0.077	0.0003		0.0049	0.1085
2014-06-03	2.773	2.767	0.006	0.026746	1.195103	7.6	0.083	0.0000		0.0038	0.1635
2014-06-18	2.883	2.921	0	0.03413	1.233451	7.72	0.968	0.0000		0.0012	0.014
2014-06-21	2.905	2.884	0.021	0.037982	1.300322	7.71		0.0000		0.0007	0.006

2014-07-03	3.003	3.036	0	0.041347	1.433669	7.72		0.0000		0.0010	0.0013
2014-07-09	3.129	3.054	0.075	0.039738	1.308887	7.71	0.1	0.0000		0.0009	0
2014-07-15	2.903	2.806	0.097	0.043462	1.42313	7.65	0.06	0.0000		0.0005	0
2014-07-18	3.488	3.276	0.212	0.032821	1.169686	7.78	0.06	0.0000		0.0041	0
2014-07-27	3.465	3.448	0.017	0.041525	1.267546	7.63	0.06	0.0000		0.0051	0.022
2014-07-30	3.293	3.283	0.01	0.046998	1.363057	7.7	0.06	0.0000		0.0043	0.024
2014-08-05	3.466	3.476	0	0.042336	1.289552	7.68	0.055	0.0000		0.0038	0.024
2014-08-23	3.228	3.246	0	0.049009	1.409925	7.7	0.06	0.0000		0.0066	0.025
2014-08-26	3.536	3.706	0	0.045162	1.391325	7.75	0.054	0.0000		0.0053	0
2014-08-29	3.756	3.829	0	0.047645	1.285607	7.49	0.086	0.0000		0.0046	0.013
2014-09-13	4.119	4.082	0.037	0.04954	1.293821	7.56	0.053	0.0000		0.0045	0.013
2014-09-16	4.047	4.153	0	0.060021	1.470382	7.52	0.077	0.0000		0.0052	0.01

	EFF-F2										
Sampling Date	TOC (mg/L)	DOC (mg/L)	POC (mg/L)	UV_{254}	SUVA	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/l)	SRP (mg/L)	NH3-N (mg/L)
2013-10-03	4.098	4.395						0.0020	0.0003	0.0046	
2013-10-30	3.448	3.568	0	0.036994	1.036822	7.75	0.326	0.0020	0.0015	0.0076	0.103
2013-11-18	4.441	4.393	0.048	0.060461	1.376303	8.16	0.054	0.0004	0.0000	0.0038	0.0516
2013-11-20	4.598	4.6	0	0.058445	1.270535	8.12	0.056	0.0008	0.0022	0.0043	0.0504
2013-12-11			0					< 0.5		< 0.04	0.24
2014-01-10	3.951	3.936	0.015	0.051249	1.302063		0.07	0.0000	0.0008	0.0048	0.352
2014-01-20	2.995	3.051	0	0.052618	1.724598	7.95	0.083	0.0002	0.0032	0.0031	0.458
2014-02-07	2.91	2.954	0	0.043514	1.47306	8.04	0.164	0.0055	0.0048	0.0028	0.266
2014-02-12	3.077	3.044	0.033	0.040587	1.333338	7.72	0.21	0.0036		0.0010	0.4235
2014-02-16	3.224	3.113	0.111	0.049548	1.591635	7.73	0.039	0.0177		0.0094	0.48
2014-02-18	3.183	3.135	0.048	0.044533	1.420498	7.82	0.168	0.0144		0.0074	0.502
2014-02-21	3.215	3.194	0.021	0.046035	1.441309	7.84	0.129	0.0136		0.0101	0.38
2014-02-25	3.136	3.152	0	0.043037	1.365381	7.73	0.041	0.0348		0.0198	0.506
2014-03-14	2.88	N/A	#VALUE!	0.062445	#VALUE !	7.65	0.032	0.0103		0.0058	0.518
2014-03-20	3.648	3.56	0.088	0.050334	1.413882	7.7	0.043	0.0376		0.0290	0.4335
2014-03-23	3.303	3.251	0.052	0.04493	1.382024	7.51	0.03	0.1280		0.0936	0.8445
2014-03-26	3.094	3.122	0	0.040663	1.302473	7.58	0.057	0.1090		0.0950	0.8155
2014-04-01	3.136	3.155	0	0.044402	1.40736	7.4	0.059	0.1080		0.1020	0.753
2014-04-04	2.963	2.982	0	0.034862	1.169081	7.47	0.065	0.0822		0.0880	0.704
2014-04-07	2.598	2.628	0	0.032398	1.232801	7.52	0.076	0.0696		0.0914	0.7685
2014-04-16	2.656	2.844	0	0.038181	1.342525	7.43	0.077	0.0816	0.0758	0.0816	0.712
2014-04-22	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2014-06-03	2.222	2.264	0	0.026672	1.178101	7.53	0.087	0.0028		0.0080	0.1585
2014-06-18	2.905	3.016	0	0.035306	1.17061	7.67	0.216	0.0000		0.0008	0.017

2014-06-21	2.804	2.849	0	0.037882	1.329653	7.67	0.088	0.0000		0.0009	0.0027
2014-07-03	2.89	2.854	0.036	0.041205	1.443756	7.66	0.088	0.0000		0.0011	0.0003
2014-07-09	3.02	3.058	0	0.040876	1.336678	7.7	0.071	0.0000		0.0008	0
2014-07-15	3.489	3.421	0.068	0.047782	1.396714	7.47	0.079	0.0167		0.0134	0
2014-07-18	2.943	2.925	0.018	0.034635	1.184096	7.67	0.07	0.0166		0.0167	0
2014-07-27	2.953	4.826	-1.873	0.042462	0.879867	7.55	0.07	0.0094		0.0088	0.021
2014-07-30	3.478	4.33	-0.852	0.046723	1.079044	7.58	0.07	0.0405		0.0167	0.021
2014-08-05	3.728	3.339	0.389	0.043215	1.294244	7.62	0.06	0.0575		0.0365	0.024
2014-08-23	3.455	3.449	0.006	0.049035	1.421711	7.63	0.07	0.0384		0.0424	0.021
2014-08-26	3.245	3.293	0	0.045009	1.366796	7.67	0.067	0.0835		0.1220	0
2014-08-29	3.665	3.678	0	0.048132	1.308657	7.42	0.065	0.0805		0.1010	0.0092
2014-09-13	4.211	4.254	0	0.050341	1.18338	7.42	0.059	0.0752		0.1040	0.014
2014-09-16	4.047	4.184	0	0.059957	1.433016	7.44	0.082	0.1060		0.1440	0.0076

	EFF-F3										
Sampling Date	TOC (mg/L)	DOC (mg/L)	POC (mg/L)	UV_{254}	SUVA	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/l)	SRP (mg/L)	NH3-N (mg/L)
2013-10-03	4.074	4.534						0.0010	0.0001	0.0051	
2013-10-30	3.485	3.553	0	0.036336	1.022679	7.77	0.253	0.0012	0.0012	0.0070	0.0676
2013-11-18	4.59	4.358	0.232	0.063269	1.451794	8	0.053	0.0006	0.0000	0.0038	0.0526
2013-11-20	4.512	4.611	0	0.058023	1.258356	8.11	0.084	0.0003	0.0019	0.0047	0.048
2013-12-11			0					< 0.5		< 0.04	0.25
2014-01-10	3.925	3.94	0	0.051356	1.303462		0.1	0.0009	0.0009	0.0047	0.357
2014-01-20	2.995	3.032	0	0.053	1.748013	8.04	0.138	0.0003	0.0030	0.0031	0.476
2014-02-07	2.973	3.14366	0	0.044073	1.401949	8.01	0.29	0.0015	0.0041	0.0030	0.275
2014-02-12	3.13	3.028	0.102	0.040215	1.328118	7.66	0.23	0.0029		0.0013	0.4075
2014-02-16	3.265	3.203	0.062	0.04963	1.549479	7.74	0.043	0.0028		0.0006	0.404
2014-02-18	3.555	3.117	0.438	0.044053	1.413321	7.92	0.162	0.0086		0.0013	0.456
2014-02-21	3.241	3.293	0	0.044968	1.365551	7.91	0.138	0.0012		0.0009	0.384
2014-02-25	3.085	3.081	0.004	0.042665	1.384765	7.8	0.0446	0.0026		0.0008	0.501
2014-03-14	2.896	3.053	0	0.062701	2.05375	7.69	0.036	0.0019		0.0011	0.509
2014-03-20	3.628	3.553	0.075	0.051321	1.444436	7.7	0.042	0.0037		0.0010	0.405
2014-03-23	3.39	3.314	0.076	0.044857	1.353561	7.61	0.046	0.0042		0.0031	0.5145
2014-03-26	3.108	3.388	0	0.044179	1.303973	7.6	0.049	0.0033		0.0033	0.47
2014-04-01	3.108	3.067	0.041	0.044061	1.436622	7.47	0.047	0.0034		0.0031	0.432
2014-04-04	3.005	2.964	0.041	0.033912	1.144116	7.45	0.048	0.0038		0.0032	0.42
2014-04-07	2.648	2.634	0.014	0.034013	1.291321	7.44	0.053	0.0000		0.0034	0.4245
2014-04-16	2.739	2.676	0.063	0.03745	1.399484	7.39	0.052	0.0017		0.0036	0.319
2014-04-22	2.104	2.119	0	0.022737	1.073016	7.41	0.055	0.0007		0.0023	0.108
2014-06-03	2.202	2.258	0	0.026085	1.155226	7.68	0.06	0.0000		0.0034	0.163
2014-06-18	2.872	2.901	0	0.036692	1.264798	7.72	0.259	0.0000		0.0010	0.0165
2014-06-21	3.458	3.124	0.334	0.037966	1.215307	7.54	0.09	0.0000		0.0011	0.00825

2014-07-03	2.885	2.867	0.018	0.041472	1.446522	7.8	0.127	0.0000		0.0012	0.0092
2014-07-09	3.065	3.088	0	0.04074	1.319294	7.74	0.137	0.0000		0.0011	0
2014-07-15	3.444	3.199	0.245	0.051686	1.615699	7.68	0.136	0.0000		0.0005	0
2014-07-18	2.897	2.868	0.029	0.033868	1.180886	7.76	0.06	0.0002		0.0056	0
2014-07-27	3.122	4.44	-1.318	0.041451	0.933572	7.69	0.07	0.0000		0.0043	0.02
2014-07-30	3.583	3.543	0.04	0.046692	1.317855	7.75	0.06	0.0000		0.0040	0.02
2014-08-05	3.343	3.174	0.169	0.042761	1.347234	7.65	0.053	0.0000		0.0038	0.022
2014-08-23	3.376	3.478	0	0.049294	1.417297	7.73	0.07	0.0000		0.0057	0.018
2014-08-26	3.266	3.298	0	0.049269	1.493905	7.71	0.062	0.0000		0.0062	0
2014-08-29	3.66	3.735	0	0.048856	1.30807	7.62	0.064	0.0000		0.0042	0.0095
2014-09-13	3.812	3.898	0	0.049958	1.281621	7.66	0.063	0.0000		0.0041	0.013
2014-09-16	4.195	4.204	0	0.060598	1.441427	7.53	0.099	0.0000		0.0056	0.01

	EFF-F4										
Sampling Date	TOC (mg/L)	DOC (mg/L)	POC (mg/L)	UV_{254}	SUVA	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/l)	SRP (mg/L)	NH3-N (mg/L)
2013-10-03	4.351	4.503						0.0011	0.0002	0.0036	
2013-10-30	3.494	3.569	0	0.036863	1.032866	7.68	0.113	0.0011	0.0008	0.0064	0.0693
2013-11-18	4.485	4.556	0	0.060954	1.337875	8.1	0.04	0.0003	0.0000	0.0037	0.0546
2013-11-20	4.554	4.569	0	0.057951	1.268343	8.12	0.054	0.0008	0.0020	0.0054	0.053
2013-12-11			0					< 0.5		< 0.04	0.26
2014-01-10	3.867	4.09	0	0.051258	1.253257		0.05	0.0002	0.0014	0.0046	0.375
2014-01-20	3.111	3.058	0.053	0.052399	1.713506	8.02	0.073	0.0078	0.0031	0.0033	0.409
2014-02-07	2.87	2.93	0	0.04366	1.490116	8.01	0.177	0.0032	0.0015	0.0030	0.295
2014-02-12	3.118	3.085	0.033	0.040055	1.298366	7.73	0.2	0.0041		0.0012	0.4295
2014-02-16	3.252	3.218	0.034	0.05426	1.686134	7.79	0.042	0.0235		0.0123	0.546
2014-02-18	3.544	3.445	0.099	0.045707	1.326758	7.89	0.235	0.0425		0.0189	0.533
2014-02-21	3.519	3.361	0.158	0.048166	1.433097	7.86	0.178	0.0330		0.0155	0.384
2014-02-25	3.104	3.105	0	0.043844	1.412052	7.83	0.049	0.0348		0.0173	0.518
2014-03-14	2.858	2.905	0	0.063432	2.183532	7.64	0.037	0.0331		0.0210	0.509
2014-03-20	3.615	3.521	0.094	0.051837	1.472212	7.56	0.049	0.0368		0.0296	0.4265
2014-03-23	3.35	3.255	0.095	0.046033	1.414224	7.53	0.052	0.1290		0.0966	0.891
2014-03-26	3.122	3.12	0.002	0.042196	1.352423	7.59	0.056	0.1100		0.1010	0.8125
2014-04-01	3.155	3.037	0.118	0.043691	1.438632	7.51	0.055	0.1100		0.0877	0.7695
2014-04-04	2.971	2.957	0.014	0.037374	1.263916	7.51	0.069	0.0835		0.0670	0.7335
2014-04-07	2.738	2.577	0.161	0.033199	1.288265	7.53	0.075	0.0823		0.0965	0.79
2014-04-16	2.665	2.667	0	0.040925	1.534511	7.47	0.074	0.0902		0.0962	0.87
2014-04-22	2.166	2.207	0	0.023079	1.045727	7.48	0.102	0.0104		0.0104	0.108
2014-06-03	2.228	2.194	0.034	0.025651	1.169125	7.74	0.09	0.0024		0.0061	0.166
2014-06-18	3.176	3.1	0.076	0.03764	1.214187	7.71	0.248	0.0000		0.0010	0.0053
2014-06-21	2.849	2.91	0	0.037702	1.295588	7.7	0.053	0.0000		0.0005	0.033

2014-07-03	2.877	3.022	-0.145	0.041605	1.376744	7.7	0.058	0.0000		0.0009	0.0027
2014-07-09	3.074	3.084	0	0.04037	1.309027	7.75	0.108	0.0000		0.0008	0
2014-07-15	3.246	3.35	0	0.052492	1.566919	7.7	0.182	0.0031		0.0041	0.18
2014-07-18	3.921	3.016	0.905	0.034286	1.13681	7.69	0.1	0.0160		0.0141	0
2014-07-27	3.112	3	0.112	0.041169	1.372287	7.61	0.1	0.0143		0.0081	0.022
2014-07-30	3.473	4.012	-0.539	0.045978	1.146002	7.55	0.1	0.0357		0.0137	0.019
2014-08-05	3.287	3.237	0.05	0.042455	1.311566	7.49	0.092	0.0370		0.0342	0.019
2014-08-23	3.444	3.528	0	0.048797	1.383135	7.67	0.11	0.0430		0.0339	0.018
2014-08-26	3.265	3.304	0	0.038951	1.17889	7.78	0.143	0.0720		0.0938	0
2014-08-29	3.642	3.684	0	0.048473	1.315767	7.54	0.184	0.0721		0.0987	0.0095
2014-09-13	3.773	3.799	0	0.049715	1.308639	7.53	0.232	0.0730		0.0747	0.011
2014-09-16	4.081	4.104	0	0.059747	1.455824	7.42	0.188	0.1130		0.1280	0.0045

	EFF-F5										
Sampling Date	TOC (mg/L)	DOC (mg/L)	POC (mg/L)	UV_{254}	SUVA	pH	Turbidity (NTU)	TP (mg/L)	TDP (mg/l)	SRP (mg/L)	NH3-N (mg/L)
2013-10-03	4.025	4.416						0.0016	0.0001	0.0047	
2013-10-30	3.433	3.35	0.083	0.036746	1.096884			0.0016	0.0010	0.0066	0.075
2013-11-18	4.307	4.232	0.075	0.058758	1.388431	8.12		0.0005	NA	0.0037	0.028
2013-11-20	4.413	4.475	0	0.056977	1.273238	8.14		0.0008	0.0009	0.0050	0.0336
2013-12-11			0					< 0.5		< 0.04	0.22
2014-01-10	3.947	3.915	0.032	0.050947	1.301333			0.0007	0.0008	0.0049	0.359
2014-01-20	3.053	3.016	0.037	0.052399	1.737367	7.96	0.05	0.0104		0.0033	0.39
2014-02-07	2.921	2.964	0	0.043779	1.477011	7.98	0.163	0.0050	0.0031	0.0029	0.315
2014-02-12	3.169	2.992	0.177	0.040327	1.347841	7.96	0.06	0.0053		0.0014	0.434
2014-02-16	3.316	3.274	0.042	0.055871	1.706494	7.75	0.043	0.0025		0.0010	0.439
2014-02-18	3.288	3.201	0.087	0.045037	1.406973	7.82	0.267	0.0071		0.0015	0.429
2014-02-21	3.519	3.353	0.166	0.042339	1.262732	7.77	0.129	0.0018		0.0017	0.366
2014-02-25	3.03	3.189	0	0.043482	1.363487	7.77	0.046	0.0032		0.0009	0.527
2014-03-14	2.973	2.937	0.036	0.060266	2.051958	7.57	0.042	0.0008		0.0013	0.527
2014-03-20	3.69	3.593	0.097	0.049726	1.383958	7.66	0.044	0.0051		0.0016	0.432
2014-03-23	3.366	3.251	0.115	0.04466	1.373743	7.57	0.043	0.0047		0.0028	0.531
2014-03-26	3.109	3.202	0	0.041397	1.292861	7.52	0.047	0.0033		0.0031	0.482
2014-04-01	3.085	3.063	0.022	0.043131	1.408116	7.46	0.043	0.0034		0.0026	0.4475
2014-04-04	2.949	2.961	0	0.033626	1.135623	7.44	0.048	0.0039		0.0031	0.429
2014-04-07	2.613	2.604	0.009	0.031398	1.205753	7.49	0.05	0.0000		0.0039	0.443
2014-04-16	2.709	2.712	0	0.03711	1.368355	7.36	0.049	0.0014		0.0035	0.3285
2014-04-22	2.092	2.107	0	0.022169	1.052178	7.4	0.052	0.0005		0.0028	0.1095
2014-06-03	2.245	2.228	0.017	0.025901	1.162531	7.64	0.059	0.0000		0.0029	0.1615
2014-06-18	2.866	2.849	0.017	0.035757	1.255058	7.57	0.121	0.0000		0.0010	0.012
2014-06-21	2.825	2.822	0.003	0.037256	1.320198	7.57	0.064	0.0000		0.0008	0.00315

2014-07-03	2.862	2.87	0	0.040836	1.422843	7.61	0.074	0.0000		0.0017	0.0084
2014-07-09	3.155	3.16	0	0.040381	1.277873	7.64	0.056	0.0000		0.0008	0
2014-07-15	3.238	3.285	0	0.052422	1.595793	7.68	0.172	0.0000		0.0005	0
2014-07-18	3.387	2.995	0.392	0.034615	1.15576	7.65	0.09	0.0003		0.0064	0
2014-07-27	3.066	3.4	-0.334	0.040981	1.205312	7.58	0.09	0.0000		0.0049	0.02
2014-07-30	3.536	3.547	0	0.04582	1.291807	7.57	0.09	0.0000		0.0036	0.019
2014-08-05	3.193	3.304	0	0.042683	1.291858	7.67	0.081	0.0000		0.0056	0.018
2014-08-23	3.446	3.522	0	0.050861	1.444083	7.57	0.09	0.0000		0.0051	0.017
2014-08-26	3.309	3.307	0.002	0.045988	1.390626	7.69	0.093	0.0000		0.0054	0
2014-08-29	3.66	3.666	0	0.048082	1.311555	7.56	0.093	0.0000		0.0043	0.012
2014-09-13	3.777	3.907	-0.13	0.048615	1.244295	7.59	0.091	0.0000		0.0041	0.012
2014-09-16	4.088	4.092	0	0.058683	1.434096	7.51	0.119	0.0000		0.0048	0.003

Appendix C

Equations Used in Statistical Analyses

ANOVA outcomes dictate the type of t-test that is used to evaluate the difference in means of two data sets. The F-ratio (f_o) is determined using **Equation C.1**:

$$f_o = \frac{s_1^2}{s_2^2} \qquad \textbf{Equation C.1}$$

where, s_1^2 is the sample variance of data set one, and s_2^2 is the variance of data set two. If the F-ratio is not statistically significant, it is concluded that differences in the variances are not statistically significant, though the population variances are unknown. In this case, the t-test described in **Equation C.2** is used to determine if the differences in sample means are statistically significant:

$$\bar{x}_1 - \bar{x}_2 - t_{\frac{\alpha}{2},n_1+n_2-2} s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \leq \mu_1 - \mu_2 \leq \bar{x}_1 - \bar{x}_2 + t_{\frac{\alpha}{2},n_1+n_2-2} s_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}} \qquad \textbf{Equation C.2}$$

where $\bar{x}_1$ and $\bar{x}_2$ are the sample means of data set one and two respectively, t is the value of the random variable T, α is the significance level, n_1 and n_2 are the number of sample points in data set one and two respectively, s_p is the pooled variance, and μ_1 and μ_2 are the true means of data set one and two respectively. s_p is calculated using **Equation C.3**.

$$s_p = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \qquad \textbf{Equation C.3}$$

If the F-ratio is statistically significant, differences in the population variances are also statistically significant, but unknown. In this case, the t-test described in **Equation C.4** is used to determine if the differences in the means are statistically significant:

$$\bar{x}_1 - \bar{x}_2 - t_{\frac{\alpha}{2},v} \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \leq \mu_1 - \mu_2 \leq \bar{x}_1 - \bar{x}_2 + t_{\frac{\alpha}{2},v} \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}} \qquad \textbf{Equation C.4}$$

where v is the number of degrees of freedom and is calculated using **Equation C.5**.

$$v = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{(s_1^2/n_1)^2}{n_1 + 1} + \frac{(s_2^2/n_2)^2}{n_2 + 1}} - 2 \qquad \textbf{Equation C.5}$$

Appendix D

Summary Data and Statistical Analysis

Mean rate of head loss accumulation at cold water conditions without nutrient amendments

Table D.1: Summary of the mean pilot plant head loss accumulation rate at cold water conditions without nutrient amendments

	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of runs, n	20	20	20	20	12
Mean rate of head loss accumulation (inH_2O/day)	39.35	45.86	29.35	33.94	41.72
Standard Deviation (inH_2O/day)	5.75	9.94	4.62	5.21	10.29

The F-test indicated that differences in the variances of the rate of head loss accumulation data collected from Filters 2 and 5 were not statistically significant (p = 0.5693). The t-test indicated that differences in the means of the rate of head loss accumulation of Filters 2 and 5 also were not statistically significant (p = 0.1344), at cold water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from Filters 1 and 4 were not statistically significant (p = 0.3368). The paired t-test indicated that the differences in the means of the rate of head loss accumulation from Filters 1 and 4 were statistically significant (p = 0.0017) at cold water conditions.

Table D.2: Summary of the mean pilot plant head loss accumulation rate data categorized by filter configuration at cold water conditions without nutrient amendments

	Filter 2 + 5	Filter 1 + 4	Filter 3
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of runs, n	32	40	20
Mean rate of head loss accumulation (inH_2O/day)	44.31	36.64	29.35
Standard Deviation (inH_2O/day)	10.11	6.07	4.62

The F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from the pooled EC capped and GAC filter data sets were not statistically significant (p = 0.9986). The t-test indicated that the differences in the means of the rate of head loss accumulation of the EC capped filters and the GAC filters were statistically significant (p < 0.001).

The F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from the plastic capped filter and pooled GAC filter data sets were not statistically significant (p = 0.9996). The t-test indicated that the differences in the means of the rate of head loss accumulation of the plastic capped filters and the GAC filters were statistically significant (p < 0.001).

The F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from the plastic and pooled EC capped filter data sets were not statistically significant (p = 0.9264). The t-test indicated that the differences in the means of the rate of head loss accumulation of the plastic and EC capped filters were statistically significant (p < 0.001).

Mean rate of head loss accumulation at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.3: Summary of the mean pilot plant head loss accumulation rate at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	12	12	12	12	12
Mean rate of head loss accumulation (inH_2O/day)	27.85	32.18	22.76	25.91	30.87
Standard Deviation (inH_2O/day)	4.02	3.59	2.43	3.06	2.75

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant (p = 0.1821). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant (p = 0.1634), at cold water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 1 and 4 were not statistically significant (p = 0.1883). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 1 and 4 were not statistically significant (p = 0.0992), at cold water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 2 were not statistically significant (p = 0.8946). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 2 were statistically significant (p < 0.0001).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 4 were not statistically significant (p = 0.7708). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 4 were statistically significant (p = 0.0053).

Mean rate of head loss accumulation at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.4: Summary of the mean pilot plant head loss accumulation rate at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	9	10	10	9	10
Mean rate of head loss accumulation (inH_2O/day)	32.48	37.70	28.38	28.93	36.22
Standard Deviation (inH_2O/day)	4.67	3.93	4.25	4.97	4.26

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant (p = 0.5938). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant (p = 0.2142), at cold water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 1 and 4 were not statistically significant (p = 0.5678). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 1 and 4 were not statistically significant (p = 0.0689), at cold water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 2 were not statistically significant (p = 0.5678). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 2 were statistically significant ($p < 0.0001$).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 4 were not statistically significant ($p = 0.6751$). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 4 were not statistically significant ($p = 0.6008$).

Mean rate of head loss accumulation at the transitional temperature range without nutrient amendments

Table D.5: Summary of the mean pilot plant head loss accumulation rate at transitional water temperatures

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of runs, n	16	16	17	17	7
Mean rate of head loss accumulation (inH_2O/day)	35.45	43.88	21.59	29.34	31.56
Standard Deviation (inH_2O/day)	10.30	15.51	6.23	7.18	10.20

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant ($p = 0.1541$). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant ($p = 0.0346$), at transitional water temperatures.

The F-test indicates that the differences in the variances of the rate of head loss accumulation of Filters 1 and 4 were not significant ($p = 0.0815$). The paired t-test indicated that the differences in the means of the rate of head loss accumulation from Filters 1 and 4 were not statistically significant ($p = 0.0556$), at transitional water temperatures.

Table D.6: Summary of the mean pilot plant head loss accumulation rate data categorized by filter configuration at transitional water temperatures

	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of runs, n	23	33	17
Mean rate of head loss accumulation (inH_2O/day)	40.13	32.30	21.59
Standard Deviation (inH_2O/day)	15.03	9.23	6.23

The F-test indicated that the differences in the variances of the rate of head loss accumulation of the pooled EC capped and GAC filters data sets were not statistically significant (p = 0.9941). The t-test indicated that the differences in the means of the rate of head loss accumulation of the EC capped filters and the GAC filters were statistically significant (p = 0.0096).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of the plastic capped filter and pooled GAC filter data sets were not statistically significant (p = 0.9996). The t-test indicated that the differences in the means of the rate of head loss accumulation of the plastic capped filters and the GAC filters were statistically significant (p < 0.001).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of the plastic and pooled EC capped filter data sets were not statistically significant (p = 0.9440). The t-test indicated that the differences in the means of the rate of head loss accumulation of the plastic capped filters and the GAC filters were statistically significant (p < 0.001).

Mean rate of head loss accumulation at warm water temperatures without nutrient amendments

Table D.7: Summary of the mean pilot plant head loss accumulation rate at warm water conditions without nutrient amendments

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of runs, n	36	40	40	40	15
Mean rate of head loss accumulation (inH_2O/day)	55.52	66.57	36.54	52.26	75.62
Standard Deviation (inH_2O/day)	11.34	13.13	7.21	8.08	14.92

The F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from Filters 2 and 5 were not statistically significant (p = 0.7435). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 2 and 5 were statistically significant (p = 0.0.163), at warm water conditions.

Using the data summarized in Table 4.3, F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from Filters 2 and 5 were not statistically significant (p = 0.8496). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 2 and 5 were statistically significant (p = 0.8534), at warm water conditions from 9 May 2014 to 5 July 2014.

Using the data summarized in Table 4.3, the F-test indicates that the differences in the variances of the rate of head loss accumulation data collected from Filters 1 and 4 were not significant (p = 0.9796). The paired t-test indicated that the differences in the means of the rate of head loss accumulation from Filters 1 and 4 were not statistically significant (p = 0.0664), at warm water conditions.

Table D.8: Summary of the mean pilot plant head loss accumulation rate data categorized by filter configuration at warm water conditions without nutrient amendments

	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of runs, n	30	76	40
Mean rate of head loss accumulation (inH_2O/day)	73.04	53.80	36.54
Standard Deviation (inH_2O/day)	13.24	9.83	7.21

The F-test indicated that the differences in the variances of the rate of head loss accumulation of the pooled EC capped and GAC filters were not statistically significant (p = 0.9790). The t-test indicated that the differences in the means of the rate of head loss accumulation of the EC capped filters and the GAC filters were statistically significant ($p < 0.0001$).

The F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from the plastic capped filter and pooled GAC filter data sets were not statistically significant (p = 0.9998). The t-test indicated that the differences in the means of the rate of head loss accumulation of the plastic capped and the GAC filters were statistically significant ($p < 0.001$).

The F-test indicated that the differences in the variances of the rate of head loss accumulation data collected from the palstic and pooled EC capped filter data sets were not statistically significant (p = 0.9821). The t-test indicated that the differences in the means of the rate of head loss accumulation of the plastic and EC capped filters were statistically significant ($p < 0.001$).

Mean rate of head loss accumulation at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.9: Summary of the mean pilot plant head loss accumulation rate at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	14	14	14	14	13
Mean rate of head loss accumulation (inH_2O/day)	63.08	84.50	39.91	59.47	90.16
Standard Deviation (inH_2O/day)	7.74	10.87	6.57	6.39	16.50

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant (p = 0.9251). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant (p = 0.8502), at warm water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 1 and 4 were not statistically significant (p = 0.2494). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 1 and 4 were not statistically significant (p = 0.0947), at warm water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 2 were not statistically significant (p = 0.9596). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 2 were statistically significant ($p <$ 0.0001).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 4 were not statistically significant (p = 0.4598). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 4 were statistically significant ($p < 0.0001$).

Mean rate of head loss accumulation at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.10: Summary of the mean pilot plant head loss accumulation rate at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	12	12	12	12	12
Mean rate of head loss accumulation (inH_2O/day)	67.13	83.16	37.58	57.07	87.61
Standard Deviation (inH_2O/day)	12.29	8.83	6.52	6.53	11.77

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant ($p = 0.8223$). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 2 and 5 were not statistically significant ($p = 0.8467$), at warm water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filters 1 and 4 were not statistically significant ($p = 0.9767$). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filters 1 and 4 were statistically significant ($p = 0.0101$), at warm water conditions.

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 2 were not statistically significant ($p = 0.8356$). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 2 were statistically significant ($p < 0.0001$).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of Filter 3 and 4 were not statistically significant ($p = 0.5015$). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 4 were statistically significant ($p < 0.0001$).

Mean filter run time at cold water conditions without nutrient amendments

Table D.11: Summary of the mean pilot plant filter run time at cold water conditions without nutrient amendments

	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of runs, n	20	20	20	20	12
Mean filter run time (hours)	39.63	38.48	36.54	42.94	36.17
Standard Deviation (hours)	15.38	12.13	18.37	16.81	11.05

The F-test indicated that the differences in the variances of the filter run time data collected from Filters 2 and 5 were not statistically significant (p = 0.6136). The t-test indicated that the differences in the means of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.7033), at cold water conditions.

The F-test indicated that the differences in the variances of the filter run time data collected from Filters 1 and 4 were not statistically significant (p = 0.6490). The t-test indicated that the differences in the means of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.7402) at cold water conditions.

Table D.12: Summary of the mean pilot plant filter run time data categorized by filter configuration at cold water conditions without nutrient amendments

	Filter 2 + 5	Filter 1 + 4	Filter 3
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of runs, n	32	40	20
Mean filter run time (hours)	37.62	41.28	36.54
Standard Deviation (hours)	11.61	15.99	18.37

The F-test indicated that the differences in the variances of the filter run time data collected from the pooled EC capped and GAC filter data sets were not statistically significant (p = 0.9655). The t-test indicated that the differences in the means of the filter run time of the EC capped filters and the GAC filters were not statistically significant (p = 0.1403).

The F-test indicated that the differences in the variances of the filter run time data collected from the plastic capped and pooled GAC filter data sets were not statistically significant (p = 0.9887). The t-test indicated that the differences in the means of the filter run time of the plastic capped filter and the GAC filters were not statistically significant (p = 0.3979).

The F-test indicated that the differences in the variances of the filter run time data collected from the plastic and pooled EC capped filter data sets were not statistically significant (p = 0.7733). The t-test indicated that the differences in the means of the filter run time of the plastic and EC capped filters were not statistically significant (p = 0.1535).

Mean filter run time at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

Table D.13: Summary of the mean pilot plant filter run time at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	12	12	12	12	12
Mean filter run time (hours)	59.65	53.90	53.78	52.27	55.41
Standard Deviation (hours)	14.79	18.71	20.56	20.37	19.58

The F-test indicated that the differences in the variances of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.5582). The t-test indicated that the differences in the means of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.5757), at cold water conditions.

The F-test indicated that the differences in the variances of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.8482). The t-test indicated that the differences in the means of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.1601), at cold water conditions.

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 2 were not statistically significant (p = 0.3804). The t-test indicated that the differences in the means of the filter run times of Filter 3 and 2 not were statistically significant (p = 0.5061).

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 4 were not statistically significant (p = 0.4878). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 4 were statistically significant (p = 0.4291).

Mean filter run time at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

Table D.14: Summary of the mean pilot plant filter run time at cold water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	10	10	10	10	10
Mean filter run time (hours)	66.83	62.16	66.13	60.85	66.45
Standard Deviation (hours)	6.14	9.79	11.36	10.54	10.57

The F-test indicated that the differences in the variances of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.5882). The t-test indicated that the differences in the means of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.8205), at cold water conditions.

The F-test indicated that the differences in the variances of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.9386). The t-test indicated that the differences in the means of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.0691), at cold water conditions.

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 2 were not statistically significant (p = 0.3328). The t-test indicated that the differences in the means of the filter run times of Filter 3 and 2 not were statistically significant (p = 0.2069).

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 4 were not statistically significant (p = 0.4141). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 4 were statistically significant (p = 0.1478).

Mean filter run time at transitional temperature without nutrient amendments

Table D.15: Summary of the mean pilot plant filter run time at transitional water temperatures

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of runs, n	18	19	19	19	8
Mean filter run time (hours)	52.20	47.87	51.94	53.80	59.74
Standard Deviation (hours)	19.13	18.48	18.40	17.42	19.83

The F-test indicated that the differences in the variances of the filter run time data collected from Filters 2 and 5 were not statistically significant (p = 0.3769). The t-test indicated that the differences in the means of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.0740), at transitional water temperatures.

The F-test indicated that the differences in the variances of the filter run time data collected from Filters 1 and 4 were not statistically significant (p = 0.3475). The t-test indicated that the differences in the means of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.6036), at transitional water temperatures.

Table D.16: Summary of the mean pilot plant filter run time data categorized by filter configuration at transitional water temperatures

	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of runs, n	27	37	19
Mean filter run time (hours)	51.38	53.02	51.94
Standard Deviation (hours)	19.31	18.03	18.40

The F-test indicated that the differences in the variances of the filter run time data collected from the pooled EC capped and GAC filter data sets were not statistically significant (p = 0.6533). The t-test indicated that the differences in the means of the filter run time of the EC capped filters and the GAC filters were not statistically significant (p = 0.3644).

The F-test indicated that the differences in the variances of the filter run time data collected from the plastic capped and pooled GAC filter data sets were not statistically significant (p = 0.5762). The t-test indicated that the differences in the means of the filter run time of the plastic capped filter and the GAC filters were not statistically significant (p = 0.4608).

The F-test indicated that the differences in the variances of the filter run time data collected from the plastic and pooled EC capped filter data sets were not statistically significant (p = 0.4424). The t-test indicated that the differences in the means of the filter run time of the plastic and EC capped filters were not statistically significant (p = 0.5828).

Mean filter run time at warm water conditions without nutrient amendments

Table D.17: Summary of the mean pilot plant filter run time at warm water conditions without nutrient amendments

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of runs, n	37	37	37	37	14
Mean filter run time (hours)	44.33	36.72	51.68	43.57	32.39
Standard Deviation (hours)	18.12	14.80	19.94	26.25	7.87

The F-test indicated that the differences in the variances of the filter run time data collected from Filters 2 and 5 were not statistically significant (p = 0.9911). The t-test indicated that the differences in the means of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.8474), at warm water conditions.

The F-test indicated that the differences in the variances of the filter run time data collected from Filters 1 and 4 were not statistically significant (p = 0.9855). The t-test indicated that the differences in the means of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.4431) at warm water conditions.

Table D.18: Summary of the mean pilot plant filter run time data categorized by filter configuration at warm water conditions without nutrient amendments

	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of runs, n	51	74	37
Mean rate of head loss accumulation (inH_2O/day)	35.53	43.95	51.68
Standard Deviation (inH_2O/day)	13.33	22.40	19.94

The F-test indicated that the differences in the variances of the filter run time data collected from the pooled EC capped and GAC filters data sets were not statistically significant (p = 0.9790). The t-test indicated that the differences in the means of the filter run time of the EC capped filters and the GAC filters were statistically significant (p = 0.9912).

The F-test indicated that the differences in the variances of the filter run time data collected from the pooled plastic capped and GAC filters data sets were not statistically significant (p = 0.9957). The t-test indicated that the differences in the means of the filter run time of the plastic capped filter and the GAC filters were statistically significant (p < 0.0001).

The F-test indicated that the differences in the variances of the filter run time data collected from the pooled plastic and EC capped filter data sets were not statistically significant (p = 0.7768). The t-test indicated that the differences in the means of the filter run time of the plastic and EC capped filters were not statistically significant (p = 0.0394).

Mean filter run time at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

Table D.19: Summary of the mean pilot plant filter run time at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:10:1

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	14	14	14	14	14
Mean filter run time (hours)	44.19	34.91	59.91	51.81	30.51
Standard Deviation (hours)	7.67	6.03	11.7	11.42	8.24

The F-test indicated that the differences in the variances of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.8628). The t-test indicated that the differences in the means of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.0595), at warm water conditions.

The F-test indicated that the differences in the variances of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.9111). The t-test indicated that the differences in the means of the filter run time of Filters 1 and 4 was statistically significant (p = 0.9755), at warm water conditions.

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 2 were not statistically significant (p = 0.9884). The t-test indicated that the differences in the means of the filter run times of Filter 3 and 2 was statistically significant (p < 0.0001).

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 4 were not statistically significant (p = 0.4642). The t-test indicated that the differences in the means of the filter run times of Filter 3 and 4 were not statistically significant (p = 0.0377).

Mean filter run time at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

Table D.20: Summary of the mean pilot plant filter run time at warm water conditions with the influent of Filters 2 and 4 nutrient-amended to a C:N:P ratio of 100:20:2

	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of runs, n	11	11	11	11	11
Mean filter run time (hours)	42.53	35.14	63.54	52.12	32.71
Standard Deviation (hours)	7.76	7.12	7.28	8.20	5.22

F-test indicated that the differences in the variances of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.1710). The t-test indicated that the differences in the means of the filter run time of Filters 2 and 5 were not statistically significant (p = 0.1858), at warm water conditions.

The F-test indicated that the differences in the variances of the filter run time of Filters 1 and 4 were not statistically significant (p = 0.5665). The t-test indicated that the differences in the means of the filter run time of Filters 1 and 4 were statistically significant (*p* = 0.9947), at warm water conditions.

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 2 were not statistically significant (*p* = 0.4730). The t-test indicated that the differences in the means of the filter run times of Filter 3 and 2 were statistically significant (*p* < 0.0001).

The F-test indicated that the differences in the variances of the filter run times of Filter 3 and 4 were not statistically significant (*p* = 0.6429). The t-test indicated that the differences in the means of the rate of head loss accumulation of Filter 3 and 4 were statistically significant (*p* = 0.0012).

Mean TOC and DOC removal at cold water conditions without nutrient amendments

Table D.21: Summary of the mean pilot plant effluent TOC and DOC removal at cold water conditions without nutrient amendments

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of TOC samples, n	4	4	4	4	4
Mean TOC Removed (mg/L)	0.500	0.500	0.477	0.492	0.461
TOC Standard Deviation (mg/L)	0.113	0.117	0.144	0.173	0.126
TOC Percent Removed (%)	13.4	13.4	12.8	13.2	12.3
Number of DOC samples, n	4	4	4	4	4
Mean DOC Removed (mg/L)	0.228	0.273	0.233	0.228	0.297
DOC Standard Deviation (mg/L)	0.130	0.130	0.042	0.190	0.111
DOC Percent Removed (%)	6.5	7.8	6.6	6.5	8.4

The F-test indicated that the differences in the variances of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant (*p* = 0.4522). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant (*p* = 0.3326), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (*p* = 0.5987). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (*p* = 0.6077), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.6854). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.5278), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.7227). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.5008), at cold water conditions.

Table D.22: Summary of the mean effluent TOC and DOC removal categorized by filter configuration at cold water conditions without nutrient amendments

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of TOC samples, n	8	7	4
Mean TOC Removed (mg/L)	0.480	0.495	0.477
TOC Standard Deviation (mg/L)	0.115	0.139	0.144
Number of DOC samples, n	8	8	4
Mean DOC Removed (mg/L)	0.285	0.228	0.233
DOC Standard Deviation (mg/L)	0.113	0.151	0.042

The F-test indicated that the differences in the variances of the TOC removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.6855). The t-test indicated that the differences in the means of the TOC removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.4110), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.7677). The t-test indicated that the differences in the means of the DOC removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.7953), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of pooled plastic capped and GAC filters were not statistically significant (p = 0.7196). The t-test indicated that the differences in the means of the TOC removed at the effluent of pooled plastic capped and GAC filters were not statistically significant (p = 0.5147), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at effluent of pooled plastic capped and GAC filters were not statistically significant (p = 0.0677). The t-test indicated that the differences in the means of the DOC removed at the effluent of pooled plastic capped and GAC filters were not statistically significant (p = 0.7980), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of pooled plastic and EC capped filters were not statistically significant (p = 0.5182). The t-test indicated that the differences in the means of the TOC removed at the effluent of pooled plastic and EC capped filters were not statistically significant (p = 0.4217), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at effluent of pooled palstic and EC filters were not statistically significant (p = 0.9967). The t-test indicated that the differences in the means of the DOC removed at the effluent of pooled plastic and EC filters were not statistically significant (p = 0.5233), at cold water conditions.

Table D.23: Summary of the mean fraction of the total TOC and DOC removed at sample port S2 at cold water conditions without nutrient amendments

	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Fraction of TOC removed at sample port S2 (%)	22.1	46.1	36.9
Fraction of DOC removed at sample port S2 (%)	56.8	78.1	57.5

Mean TOC and DOC removal at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.24: Summary of the mean pilot plant effluent TOC and DOC removal at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of TOC samples, n	6	6	6	6	6
Mean TOC Removed (mg/L)	0.501	0.532	0.453	0.416	0.429
TOC Standard Deviation (mg/L)	0.117	0.143	0.186	0.142	0.053
TOC Percent Removed (%)	13.4	14.2	12.1	11.2	11.5
Number of DOC samples, n	6	5	6	6	6
Mean DOC Removed (mg/L)	0.270	0.350	0.287	0.245	0.250
DOC Standard Deviation (mg/L)	0.076	0.042	0.127	0.111	0.071
DOC Percent Removed (%)	7.7	10.0	8.2	6.7	7.1

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.9681). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.0798), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.1597). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 5 were statistically significant (p = 0.0110), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.6604). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.8575), at cold water conditions.

The F-test indicated that the differences in the variances of the effluent DOC removed by Filters 1 and 4 were not statistically significant (p = 0.7847). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (*p* = 0.6711), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 4 were not statistically significant (*p* = 0.5032). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 2 and 4 were not statistically significant (*p* = 0.0952), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 4 were not statistically significant (*p* = 0.3728). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 4 were not statistically significant (*p* = 0.0378), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 3 were not statistically significant (*p* = 0.7621). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 3 were not statistically significant (*p* = 0.7463), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 3 were not statistically significant (*p* = 0.9746). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant (*p* = 0.8417), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant (*p* = 0.2858). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant (*p* = 0.6468), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant *p* = 0.3858). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 4 and 3 were not statistically significant (*p* = 0.7251), at cold water conditions.

Mean TOC and DOC removal at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.25: Summary of the mean pilot plant effluent TOC and DOC removal at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of TOC samples, n	6	6	6	6	6
Mean TOC Removed (mg/L)	0.426	0.501	0.459	0.459	0.487
TOC Standard Deviation (mg/L)	0.153	0.054	0.070	0.089	0.072
TOC Percent Removed (%)	12.3	14.5	13.3	13.3	14.1
Number of DOC samples, n	6	5	6	6	6
Mean DOC Removed (mg/L)	0.287	0.273	0.263	0.334	0.304
DOC Standard Deviation (mg/L)	0.089	0.063	0.103	0.041	0.037
DOC Percent Removed (%)	8.8	8.3	8.0	10.2	9.3

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.7348). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.6392), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.1424). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.1576), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.1294). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.3301), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent Filters 1 and 4 were not statistically significant (p = 0.0582). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (*p* = 0.1316), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 4 were not statistically significant (*p* = 0.1458). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (*p* = 0.1742), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 4 were not statistically significant (*p* = 0.8113). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 4 were not statistically significant (*p* = 0.9640), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 3 were not statistically significant (*p* = 0.2849). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 3 were not statistically significant (*p* = 0.1399), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 3 were not statistically significant (*p* = 0.1471). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant *p* = 0.3979), at cold water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant (*p* = 0.6920). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant (*p* = 0.4958), at cold water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent Filters 1 and 4 were not statistically significant (*p* = 0.9680). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 4 and 3 were not statistically significant (*p* = 0.9271), at cold water conditions.

Mean TOC and DOC removal at the transitional temperature range without nutrient amendments

Table D.26: Summary of the mean pilot plant effluent TOC and DOC removal at transitional water temperatures

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of TOC samples, n	5	4	5	5	5
Mean TOC Removed (mg/L)	0.688	0.538	0.512	0.505	0.592
TOC Standard Deviation (mg/L)	0.366	0.209	0.103	0.157	0.210
TOC Percent Removed (%)	17.7	13.8	13.2	13.0	15.2
Number of DOC samples, n	4	3	4	4	4
Mean DOC Removed (mg/L)	0.344	0.324	0.334	0.335	0.430
DOC Standard Deviation (mg/L)	0.043	0.066	0.062	0.052	0.134
DOC Percent Removed (%)	9.5	9.0	9.3	9.3	11.9

The F-test indicated that the differences in the variances of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.5190). The t-test indicated that the differences in the means of the TOC removed at effluent of Filters 2 and 5 were not statistically significant (p = 0.6442), at transitional water temperatures.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.2010). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.8657), at transitional water temperatures.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.0654). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.8327), at transitional water temperatures.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.6127). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.6009), at transitional water temperatures.

Table D.27: Summary of the mean effluent TOC and DOC removal categorized by filter configuration at transitional water temperatures

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of TOC samples, n	9	10	5
Mean TOC Removed (mg/L)	0.568	0.596	0.512
TOC Standard Deviation (mg/L)	0.198	0.283	0.103
Number of DOC samples, n	7	8	4
Mean DOC Removed (mg/L)	0.384	0.339	0.334
DOC Standard Deviation (mg/L)	0.117	0.044	0.062

The F-test indicated that the differences in the variances of the TOC removed at effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.1656). The t-test indicated that the differences in the means of the TOC removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.5967), at transitional water temperatures.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.9888). The t-test indicated that the differences in the means of the DOC removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.1651), at transitional water temperatures.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.1096). The t-test indicated that the differences in the means of the TOC removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.7161), at transitional water temperatures.

The F-test indicated that the differences in the variances of the DOC removed at effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.1637). The t-test indicated that the differences in the means of the DOC removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.7728), at transitional water temperatures.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.4098). The t-test indicated that the differences in the means of the TOC removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.7330), at transitional water temperatures.

The F-test indicated that the differences in the variances of the DOC removed at effluent of the plastic and pooled EC filters were not statistically significant (p = 0.5415). The t-test indicated that the differences in the means of the DOC removed at the effluent of the plastic and EC filters were not statistically significant (p = 0.5629), at transitional water temperatures.

Table D.28: Summary of the mean fraction of the total TOC and DOC removed at sample port S2 at transitional water temperatures

	Filter 2 + 5	Filter 1 + 4	Filter 3
Media Configuration	GAC	EC and GAC	Plastic and GAC
Fraction of TOC removed at sample port S2 (%)	54.9	33.6	40.8
Fraction of DOC removed at sample port S2 (%)	60.4	56.6	74.3

Mean TOC and DOC removal at warm water conditions without nutrient amendments

Table D.29: Summary of the mean pilot plant effluent TOC and DOC removal at warm water conditions without nutrient amendments

	Effluent				
	Filter 1	Filter 2	Filter 3	Filter 4	Filter 5
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of TOC samples, n	4	4	4	3	4
Mean TOC Removed (mg/L)	0.881	0.867	0.702	0.776	0.845
TOC Standard Deviation (mg/L)	0.163	0.151	0.363	0.268	0.072
TOC Percent Removed (%)	23.4	23.0	18.6	20.6	22.4
Number of DOC samples, n	4	4	4	3	4
Mean DOC Removed (mg/L)	0.646	0.604	0.553	0.559	0.623
DOC Standard Deviation (mg/L)	0.118	0.155	0.155	0.215	0.067
DOC Percent Removed (%)	18.2	17.0	15.6	15.8	17.6

The F-test indicated that the differences in the variances of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.8712). The t-test indicated that the differences in the means of the TOC removed at effluent of Filters 2 and 5 were not statistically significant (p = 0.3994), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.8982). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.5854), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.7864). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.7273), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant p = 0.8253). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.7400), at warm water conditions.

Table D.30: Summary of the mean effluent TOC and DOC removal categorized by filter configuration at warm water conditions without nutrient amendments

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of TOC samples, n	8	7	4
Mean TOC Removed (mg/L)	0.856	0.836	0.702
TOC Standard Deviation (mg/L)	0.110	0.201	0.363
Number of DOC samples, n	8	7	4
Mean DOC Removed (mg/L)	0.613	0.609	0.553
DOC Standard Deviation (mg/L)	0.111	0.157	0.155

The F-test indicated that the differences in the variances of the TOC removed at effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.9302). The t-test indicated that the differences in the means of the TOC removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.4055), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.8074). The t-test indicated that the differences in the means of the DOC removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.4751), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.9950). The t-test indicated that the differences in the means of the TOC removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.8614), at warm water conditions.

The F-test indicated that the variances of the DOC removed at effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.7892). The t-test indicated that the means of the DOC removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.7741), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.1800). The t-test indicated that the differences in the means of the TOC removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.8614), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at effluent of the plastic and pooled EC filters were not statistically significant (p = 0.5557). The t-test indicated that the differences in the means of the DOC removed at the effluent of the plastic and EC filters were not statistically significant (p = 0.2911), at warm water conditions.

Table D.31: Summary of the mean fraction of the total TOC and DOC removed at sample port S2 at warm water conditions without nutrient amendments

	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Fraction of TOC removed at sample port S2 (%)	63.9	54.1	56.3
Fraction of DOC removed at sample port S2 (%)	70.8	63.2	60.0

Mean TOC and DOC removal at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.32: Summary of the mean pilot plant effluent TOC and DOC removal at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of TOC samples, n	6	4	5	5	5
Mean TOC Removed (mg/L)	0.585	0.466	0.561	0.647	0.529
TOC Standard Deviation (mg/L)	0.160	0.215	0.141	0.038	0.202
TOC Percent Removed (%)	15.1	12.0	14.5	16.7	13.7
Number of DOC samples, n	6	4	5	5	5
Mean DOC Removed (mg/L)	0.509	0.439	0.539	0.440	0.460
DOC Standard Deviation (mg/L)	0.177	0.207	0.117	0.149	0.111
DOC Percent Removed (%)	13.6	11.8	14.4	11.8	12.3

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 5 were not statistically significant ($p = 0.5647$). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant ($p = 0.6679$), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant ($p = 0.8693$). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant ($p = 0.5758$), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant ($p = 0.9809$). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant ($p = 0.7607$), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at sample S2 by Filters 1 and 4 were not statistically significant ($p = 0.3820$). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.7456), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 4 were not statistically significant (p = 0.9914). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.9253), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 4 were not statistically significant p = 0.7328). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.5020), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 3 were not statistically significant (p = 0.7559). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 3 were not statistically significant (p = 0.7695), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 3 were not statistically significant (p = 0.8507). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.8051), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant p = 0.9721). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant (p = 0.1392), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 4 and 3 were not statistically significant (p = 0.6761). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 4 and 3 were not statistically significant (p = 0.8614), at warm water conditions.

Mean TOC and DOC removal at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.33: Summary of the mean pilot plant effluent TOC and DOC removal at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of TOC samples, n	5	5	5	5	4
Mean TOC Removed (mg/L)	0.846	0.733	0.779	0.677	0.763
TOC Standard Deviation (mg/L)	0.137	0.149	0.130	0.054	0.089
TOC Percent Removed (%)	18.5	16.0	17.0	14.8	16.6
Number of DOC samples, n	5	5	5	5	4
Mean DOC Removed (mg/L)	0.676	0.580	0.630	0.677	0.684
DOC Standard Deviation (mg/L)	0.065	0.195	0.040	0.054	0.063
DOC Percent Removed (%)	15.1	12.9	14.1	15.1	15.3

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.7883). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.6338), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.9531). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.8283), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.9498). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 1 and 4 were statistically significant (p = 0.0169), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.3718). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.4877), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 4 were not statistically significant (p = 0.9619). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 1 and 4 were not statistically significant (p = 0.2273), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 4 were not statistically significant (p = 0.9854). The t-test indicated that the differences in the means of the DOC removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.8430), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 2 and 3 were not statistically significant (p = 0.5963). The t-test indicated that the differences in the means of the TOC removed at the effluent of Filters 2 and 3 were not statistically significant (p = 0.6930), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 2 and 3 were not statistically significant (p = 0.9952). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 2 and 5 were not statistically significant (p = 0.7041), at warm water conditions.

The F-test indicated that the differences in the variances of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant (p = 0.9414). The t-test indicated that the differences in the means of the TOC removed at the effluent by Filters 4 and 3 were not statistically significant (p = 0.0726), at warm water conditions.

The F-test indicated that the differences in the variances of the DOC removed at the effluent by Filters 3 and 4 were not statistically significant (p = 0.7137). The t-test indicated that the differences in the means of the DOC removed at the effluent by Filters 4 and 3 were not statistically significant (p = 0.0765), at warm water conditions.

Mean NH_3-N removal at cold water conditions without nutrient amendments

Table D.34: Summary of the mean pilot plant effluent NH_3-N removal at cold water conditions without nutrient amendments

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of samples, n	4	4	4	4	4
Mean NH_3-N Removed (mg/L)*	-0.015	-0.008	-0.012	-0.011	-0.008
NH_3-N Standard Deviation (mg/L)	0.047	0.056	0.044	0.063	0.073
NH_3-N Percent Removed (%)*	-4.1	-2.2	-3.2	-3.0	-2.2
* Negative values signify an increase in the concentration from the influent stream					

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.3387). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.5031), at cold water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.6728). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant p = 0.4624), at cold water conditions.

Table D.35: Summary of the mean effluent NH_3-N removal categorized by filter configuration at cold water conditions without nutrient amendments

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of samples, n	8	8	4
Mean NH_3-N Removed (mg/L)*	-0.008	-0.013	-0.012
NH_3-N Standard Deviation (mg/L)	0.060	0.052	0.044
* Negative values signify an increase in the concentration from the influent stream			

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.3475). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.5609), at cold water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.3333). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.5474), at cold water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.4399). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the BioFill® and EC capped filters were not statistically significant (p = 0.4976), at cold water conditions.

Mean NH_3-N removal at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.36: Summary of the mean effluent pilot plant NH_3-N removal at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of samples, n	6	4	6	4	6
Mean NH_3-N Removed (mg/L)*	-0.010	-0.007	-0.003	-0.007	-0.014
NH_3-N Standard Deviation (mg/L)	0.045	0.047	0.047	0.043	0.042
NH_3-N Percent Removed (%)*	-2.3	-1.6	-0.7	-1.6	-3.2
* Negative values signify an increase in the concentration from the influent stream					

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.6155). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.4098), at cold water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.5092). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.4636), at cold water conditions.

Mean NH_3-N removal at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.37: Summary of the mean pilot plant effluent NH_3-N removal at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:20:2)	No	Yes	No	Yes	No
Number of samples, n	6	6	6	6	6
Mean NH_3-N Removed (mg/L)*	-0.009	-0.016	-0.016	-0.061	-0.030
NH_3-N Standard Deviation (mg/L)	0.026	0.056	0.024	0.060	0.027
NH_3-N Percent Removed (%)*	-2.2	-2.1	-2.1	-8.1	-7.3
* Negative values signify an increase in the concentration from the influent stream					

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.9339). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.3033), at cold water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant p = 0.9525). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.9585), at cold water conditions.

Mean NH_3-N removal at transitional water temperatures without nutrient amendments

Table D.38: Summary of the mean pilot plant effluent NH_3-N removal at transitional water temperatures

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of samples, n	4	4	5	5	5
Mean NH_3-N Removed (mg/L)	0.007	0	0.007	0.005	0.013
NH_3-N Standard Deviation (mg/L)	0.023	0.027	0.019	0.018	0.027
NH_3-N Percent Removed (%)	7.4	0	7.4	5.3	13.7

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.5113). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.7626), at transitional water temperatures.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.6807). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.4399), at transitional water temperatures.

Table D.39: Summary of the mean effluent NH_3-N removal categorized by filter configuration at transitional water temperatures

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of samples, n	9	9	5
Mean NH_3-N Removed (mg/L)	0.007	0.006	0.007
NH_3-N Standard Deviation (mg/L)	0.026	0.019	0.019

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.1972). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.5608), at transitional water temperatures.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.2767). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.5079), at transitional water temperatures.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the plastic and pooled EC filters were not statistically significant (p = 0.5501). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.5509), at transitional water temperatures.

Mean NH_3-N removal at warm water conditions without nutrient amendments

Table D.40: Summary of the mean pilot plant effluent NH_3-N removal at warm water conditions from without nutrient amendments

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number of samples, n	4	4	4	4	4
Mean NH_3-N Removed (mg/L)	0.019	0.020	0.016	0.014	0.019
NH_3-N Standard Deviation (mg/L)	0.008	0.008	0.007	0.022	0.005
NH_3-N Percent Removed (%)	76.0	80.0	64.0	56.0	76.0

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.7608). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.4292), at warm water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.9244). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.6575), at warm water conditions.

Table D.41: Summary of the mean effluent NH_3-N removal categorized by filter configuration at warm water conditions without nutrient amendments

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of samples, n	8	8	4
Mean NH_3-N Removed (mg/L)	0.019	0.017	0.016
NH_3-N Standard Deviation (mg/L)	0.006	0.015	0.007

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.9849). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.6522), at warm water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.6879). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.7639), at warm water conditions.

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of the plastic and pooled EC filters were not statistically significant (p = 0.1325). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.5329), at warm water conditions.

Mean NH_3-N removal at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.42: Summary of the mean pilot plant effluent NH_3-N removal at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of samples, n	6	6	6	6	6
Mean NH_3-N Removed (mg/L)	0.025	0.426	0.028	0.397	0.029
NH_3-N Standard Deviation (mg/L)	0.015	0.011	0.014	0.078	0.018
NH_3-N Percent Removed (%)	63.3	96.7	69.5	90.2	72.0

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.9994). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.8339), at warm water conditions.

Table D.43: Summary of the mean pilot plant effluent NH_3-N concentration at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of samples, n	6	6	6	6	6
Mean NH_3-N concentration (mg/L)	0.016	0.015	0.013	0.043	0.012
NH_3-N Standard Deviation (mg/L)	0.012	0.011	0.010	0.068	0.010

The F-test indicated that the differences in the variances of the mean effluent NH_3-N concentration of Filters 2 and 5 were not statistically significant (p = 0.6344). The t-test indicated that the differences in the means of the effluent NH_3-N concentrations of Filters 2 and 5 were not statistically significant (p = 0.5083), at warm water conditions.

The F-test indicated that the differences in the variances of the mean effluent NH_3-N concentration of Filters 1 and 4 were not statistically significant (p = 0.9766). The t-test indicated that the differences in the means of the effluent NH_3-N concentrations of Filters 1 and 4 were not statistically significant (p = 0.4913), at warm water conditions.

Mean NH_3-N removal at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.44: Summary of the mean pilot plant effluent NH_3-N removal at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:20:2)	No	Yes	No	Yes	No
Number of samples, n	5	5	5	5	5
Mean NH_3-N Removed (mg/L)	0.017	1.037	0.018	1.038	0.020
NH_3-N Standard Deviation (mg/L)	0.012	0.005	0.012	0.004	0.013
NH_3-N Percent Removed (%)	66.6	99.3	70.3	99.4	78.1

The F-test indicated that the differences in the variances of the NH_3-N removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.3913). The t-test indicated that the differences in the means of the NH_3-N removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.3284), at warm water conditions.

Table D.45: Summary of the mean pilot plant effluent NH_3-N concentration at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	No	Yes	No
Number of samples, n	5	5	5	5	5
Mean NH_3-N concentration (mg/L)	0.008	0.007	0.007	0.006	0.005
NH_3-N Standard Deviation (mg/L)	0.006	0.005	0.005	0.004	0.006

The F-test indicated that the differences in the variances of the mean effluent NH_3-N concentration of Filters 2 and 5 were not statistically significant (p = 0.7080). The t-test indicated that the differences in the means of the effluent NH_3-N concentrations of Filters 2 and 5 were not statistically significant (p = 0.5173), at warm water conditions.

The F-test indicated that the differences in the variances of the mean effluent NH_3-N concentration of Filters 1 and 4 were not statistically significant (p = 0.2578). The t-test indicated that the differences in the means of the effluent NH_3-N concentrations of Filters 1 and 4 were not statistically significant (p = 0.4968), at warm water conditions.

Mean TP and SRP removal at cold water conditions without nutrient amendments

Table D.46: Summary of the mean pilot plant effluent TP and SRP removal at cold water conditions from without nutrient amendments

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number TP of samples, n	4	4	4	4	4
Mean TP Removed (µg/L)	4.6	6.1	7.0	4.6	3.1
TP Standard Deviation (µg/L)	1.5	1.8	3.9	5.5	5.9
TP Percent Removed (%)	54.8	72.6	83.3	54.8	36.9
Number SRP of samples, n	4	4	4	4	4
Mean SRP Removed (µg/L)	0.3	0.4	0.2	0.5	0.2
SRP Standard Deviation (µg/L)	0.7	0.8	0.7	0.6	0.9
SRP Percent Removed (%)	7.0	9.3	4.7	11.6	4.7

The F-test indicated that the differences in the variances of the TP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.9608). The t-test indicated that the differences in the means of the TP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.8190), at cold water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.4236). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.3523), at cold water conditions.

The F-test indicated that the differences in the variances of the TP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.9720). The t-test indicated that the differences in the means of the TP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.4991), at cold water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.2653). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.4691), at cold water conditions.

Table D.47: Summary of the mean effluent TP and SRP removal categorized by filter configuration at cold water conditions without nutrient amendments

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of TP samples, n	8	7	4
Mean TP Removed (µg/L)	4.6	4.6	7.0
TP Standard Deviation (µg/L)	4.4	3.7	3.9
Number of SRP samples, n	8	8	4
Mean SRP Removed (µg/L)	1.3	1.2	1.3
SRP Standard Deviation (µg/L)	0.8	0.9	0.8

The F-test indicated that the differences in the variances of the TP removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.3442). The t-test indicated that the differences in the means of the TP removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.4902), at cold water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.6245). The t-test indicated that the differences in the means of the SRP removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.5451), at cold water conditions.

The F-test indicated that the differences in the variances of the TP removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.4756). The t-test indicated that the differences in the means of the TP removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.1832), at cold water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.5764). The t-test indicated that the differences in the means of the SRP removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.4895), at cold water conditions.

The F-test indicated that the variances of the TP removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.5959). The t-test indicated that the means of the TP removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.1623), at cold water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.4812). The t-test indicated that the differences in the means of the SRP removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.4550), at cold water conditions.

Mean SRP removal at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.48: Summary of the mean pilot plant effluent SRP removal at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

	Effluent			
	Filter 1	**Filter 2**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	Yes	No
Number of samples, n	6	6	6	6
Mean SRP Removed (µg/L)*	0.2	76.9	71.4	0.1
SRP Standard Deviation (mg/L)	0.3	9.0	5.9	0.4
SRP Percent Removed (%)*	16.7	85.0	78.9	8.3

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.1910). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.8810), at cold water conditions.

Mean SRP removal at cold water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.49: Summary of the mean pilot plant effluent SRP removal at cold water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

	Effluent			
	Filter 1	**Filter 2**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	EC and GAC	GAC
Nutrient-amended (100:20:2)	No	Yes	Yes	No
Number of samples, n	6	6	6	6
Mean SRP Removed (µg/L)	0.5	73.6	74.7	0.5
SRP Standard Deviation (mg/L)	0.5	6.9	12.5	0.8
SRP Percent Removed (%)	13.5	44.5	45.1	13.5

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.8911). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.4268), at cold water conditions.

Mean TP and SRP removal at transitional water temperatures without nutrient amendments

Table D.50: Summary of the mean pilot plant effluent TP and SRP removal at transitional water temperatures

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number TP of samples, n	5	4	5	5	5
Mean TP Removed (µg/L)	5.0	2.9	5.2	2.8	5.1
TP Standard Deviation (µg/L)	4.0	2.9	3.9	3.0	4.0
TP Percent Removed (%)	76.9	44.6	80.0	43.1	78.5
Number SRP of samples, n	5	4	5	5	5
Mean SRP Removed (µg/L)*	0.2	-1.0	0.6	-1.6	0.6
SRP Standard Deviation (µg/L)	0.9	2.1	0.9	2.9	0.9
SRP Percent Removed (%)*	4.2	-20.8	12.5	-33.3	12.5
* Negative values signify an increase in the concentration from the influent stream					

The F-test indicated that the differences in the variances of the TP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.3062). The t-test indicated that the differences in the means of the TP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.8035), at transitional water temperatures.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.9335). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.9181), at transitional water temperatures.

The F-test indicated that the variances of the TP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.3015). The t-test indicated that the means of the TP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.1683), at transitional water temperatures.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.9803). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.1110), at transitional water temperatures.

Table D.51: Summary of the mean effluent TP and SRP removal categorized by filter configuration at transitional water temperatures

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of TP samples, n	9	10	5
Mean TP Removed (μg/L)	4.1	3.9	5.2
TP Standard Deviation (μg/L)	3.5	3.5	3.9
Number of SRP samples, n	9	10	5
Mean SRP Removed (μg/L)*	-0.1	-0.7	0.6
SRP Standard Deviation (μg/L)	1.7	2.2	0.9
* Negative values signify an increase in the concentration from the influent stream			

The F-test indicated that the differences in the variances of the TP removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.4964). The t-test indicated that the differences in the means of the TP removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.5526), at transitional water temperatures.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.7991). The t-test indicated that the differences in the means of the SRP removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.7430), at transitional water temperatures.

The F-test indicated that the differences in the variances of the TP removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.6363). The t-test indicated that the differences in the means of the TP removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.3075), at transitional water temperatures.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.1215). The t-test indicated that the differences in the means of the SRP removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.2106), at transitional water temperatures.

The F-test indicated that the differences in the variances of the TP removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.4465). The t-test indicated that the differences in the means of the TP removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.7319), at transitional water temperatures.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.9900). The t-test indicated that the differences in the means of the SRP removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.8761), at transitional water temperatures.

Mean TP and SRP removal at warm water conditions without nutrient amendments

Table D.52: Summary of the mean pilot plant effluent TP and SRP removal at warm water conditions from without nutrient amendments

	Effluent				
	Filter 1	**Filter 2**	**Filter 3**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	Plastic and GAC	EC and GAC	GAC
Number TP of samples, n	4	4	4	4	4
Mean TP Removed (µg/L)	0.2	0.2	0.2	0.2	0.2
TP Standard Deviation (µg/L)	0.2	0.2	0.2	0.2	0.2
TP Percent Removed (%)	100.0	100.0	100.0	100.0	100.0
Number SRP of samples, n	4	4	4	4	4
Mean SRP Removed (µg/L)	0.3	0.3	0.2	0.5	0.2
SRP Standard Deviation (µg/L)	0.7	0.8	0.7	0.6	0.9
SRP Percent Removed (%)	23.1	23.1	15.4	38.5	15.4

The F-test indicated that the differences in the variances of the TP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.5000). The t-test indicated that the differences in the means of the TP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.5000), at warm water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.4150). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 2 and 5 were not statistically significant (p = 0.4101), at warm water conditions.

The F-test indicated that the differences in the variances of the TP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.5000). The t-test indicated that the differences in the means of the TP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.5000), at warm water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.4063). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 1 and 4 were not statistically significant (p = 0.3692), at warm water conditions.

Table D.53: Summary of the mean effluent TP and SRP removal categorized by filter configuration at warm water conditions without nutrient amendments

	Effluent		
	Filter 2 + 5	**Filter 1 + 4**	**Filter 3**
Media Configuration	GAC	EC and GAC	Plastic and GAC
Number of TP samples, n	8	8	4
Mean TP Removed (µg/L)	0.2	0.2	0.2
TP Standard Deviation (µg/L)	0.2	0.2	0.2
Number of SRP samples, n	8	8	4
Mean SRP Removed (µg/L)	0.3	0.4	0.2
SRP Standard Deviation (µg/L)	0.8	0.6	0.7

The F-test indicated that the differences in the variances of the TP removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.5000). The t-test indicated that the differences in the means of the TP removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.5000), at warm water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the pooled EC capped and GAC filters were not statistically significant (p = 0.3363). The t-test indicated that the differences in the means of the SRP removed at the effluent of the EC capped and GAC filters were not statistically significant (p = 0.3798), at warm water conditions.

The F-test indicated that the differences in the variances of the TP removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.6119). The t-test indicated that the differences in the means of the TP removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.5000), at warm water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the plastic capped and pooled GAC filters were not statistically significant (p = 0.4981). The t-test indicated that the differences in the means of the SRP removed at the effluent of the plastic capped and GAC filters were not statistically significant (p = 0.5763), at warm water conditions.

The F-test indicated that the variances of the TP removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.6119). The t-test indicated that the means of the TP removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.5000), at warm water conditions.

The F-test indicated that the differences in the variances of the SRP removed at the effluent of the plastic and pooled EC capped filters were not statistically significant (p = 0.6248). The t-test indicated that the differences in the means of the SRP removed at the effluent of the plastic and EC capped filters were not statistically significant (p = 0.6834), at warm water conditions.

Mean SRP removal at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:10:1

Table D.54: Summary of the mean pilot plant effluent SRP removal at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:10:1

	Effluent			
	Filter 1	**Filter 2**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	EC and GAC	GAC
Nutrient-amended (100:10:1)	No	Yes	Yes	No
Number of samples, n	6	6	6	6
Mean SRP Removed (µg/L)*	-0.6	74.0	78.4	-0.9
SRP Standard Deviation (mg/L)	1.2	13.6	13.0	2.3
SRP Percent Removed (%)*	-18.3	76.7	81.3	-26.6
* Negative values signify an increase in the concentration from the influent stream				

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.4579). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.2893), at warm water conditions.

Mean SRP removal at warm water conditions while amending the influent C:N:P ratio of Filters 2 and 4 to 100:20:2

Table D.55: Summary of the mean pilot plant effluent SRP removal at warm water conditions while amending the influent of Filters 2 and 4 to a C:N:P ratio of 100:20:2

	Effluent			
	Filter 1	**Filter 2**	**Filter 4**	**Filter 5**
Media Configuration	EC and GAC	GAC	EC and GAC	GAC
Nutrient-amended (100:20:2)	No	Yes	Yes	No
Number of samples, n	5	5	5	5
Mean SRP Removed (µg/L)	0.1	110.3	129.1	0.3
SRP Standard Deviation (mg/L)	0.3	18.6	20.6	0.5
SRP Percent Removed (%)	2.3	47.7	55.8	5.4

The F-test indicated that the differences in the variances of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.5745). The t-test indicated that the differences in the means of the SRP removed at the effluent of Filters 2 and 4 were not statistically significant (p = 0.0845), at warm water conditions.

Appendix E

Temperature Dependence Data Comparison

Table E.1: Rate of head loss accumulation based on filter configuration and temperature range without nutrient addition

	GAC		EC Capped		Plastic Capped	
Temperature conditions	Cold	Warm	Cold	Warm	Cold	Warm
Number of filter runs, n	32	30	40	76	20	40
Mean rate of head loss accumulation (inH_2O/day)	44.31	73.04	36.64	53.80	29.35	36.54
Standard deviation (inH_2O/day)	10.11	13.24	6.07	9.83	4.62	7.21

The F-test indicated that the differences in the variances of the rate of head loss accumulation of the GAC filters at cold and warm water conditions were not statistically significant (p = 0.9280). The t-test indicated that the differences in the means of the rate of head loss accumulation of GAC filters at cold and warm water conditions were statistically significant (p < 0.0001).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of the EC capped filters at cold and warm water conditions were not statistically significant (p = 0.9993). The t-test indicated that the differences in the means of the rate of head loss accumulation of EC capped filters at cold and warm water conditions were statistically significant (p < 0.0001).

The F-test indicated that the differences in the variances of the rate of head loss accumulation of the plastic capped filter at cold and warm water conditions were not statistically significant (p = 0.9800). The t-test indicated that the differences in the means of the rate of head loss accumulation of plastic capped filter at cold and warm water conditions were statistically significant (p < 0.0001).

Table E.2: Effluent percent DOC removed based on filter configuration and temperature range without nutrient addition

	GAC		EC Capped		Plastic Capped	
Temperature conditions	Cold	Warm	Cold	Warm	Cold	Warm
Number of samples, n	20	17	20	17	16	14
Mean percent of effluent DOC removed (%)	8.20	15.28	7.61	15.96	7.77	14.56
Standard deviation (%)	2.61	3.18	3.31	2.86	2.96	2.71

The F-test indicated that the differences in the variances of the percent effluent DOC removed by the GAC filters at cold and warm water conditions were not statistically significant (p = 0.7982). The t-test indicated that the percent effluent DOC removed by the GAC filters at cold and warm water conditions were statistically significant ($p < 0.0001$).

The F-test indicated that the differences in the variances of the percent effluent DOC removed by the EC capped filters at cold and warm water conditions were not statistically significant ($p = 0.2810$). The t-test indicated that the differences in the means of the percent effluent DOC removed by the EC capped filters at cold and warm water conditions were statistically significant ($p < 0.0001$).

The F-test indicated that the differences in the variances of the percent effluent DOC removed by the plastic capped filter at cold and warm water conditions were not statistically significant ($p = 0.3787$). The t-test indicated that the differences in the means of the percent effluent DOC removed by the plastic capped filter at cold and warm water conditions were statistically significant ($p < 0.0001$).

Appendix F

Quality Control Data

DOC and TOC Quality Control Data

Sample	Measured Value (mg/L)	Carousel Position	Analysis Time		
FIL-EFF-F3-20140110	3.023	12	2014-01-16 16:35		
FIL-EFF-F3-20140110	3.034	17	2014-01-16 18:19	Average	Std Dev
FIL-EFF-F3-20140110	3.039	21	2014-01-16 19:55	3.032	0.008185
FIL-EFF-F3-20140120	3.148	12	2014-01-24 22:24		
FIL-EFF-F3-20140120	3.129	16	2014-01-24 23:53	Average	Std Dev
FIL-EFF-F3-20140120	3.154	21	2014-01-25 1:44	3.143667	0.013051
FIL-S2-F5-20140207	3.128	12	2014-02-07 21:41		
FIL-S2-F5-20140207	3.164	16	2014-02-07 23:09	Average	Std Dev
FIL-S2-F5-20140207	3.251	21	2014-02-08 0:55	3.181	0.063238
FIL-S2-F3-20140212	3.351	10	2014-02-12 21:13		
FIL-S2-F3-20140212	3.354	14	2014-02-12 22:44	Average	Std Dev
FIL-S2-F3-20140212	3.252	26	2014-02-13 2:09	3.319	0.058043
EFF-F1-20140212	3.224	30	2014-02-13 3:57		
EFF-F1-20140212	3.273	35	2014-02-13 5:47	Average	Std Dev
EFF-F1-20140212	3.277	37	2014-02-13 6:12	3.258	0.029513
FIL-S2-F2-20140216	3.38	9	2014-02-16 22:11		
FIL-S2-F2-20140216	3.376	14	2014-02-16 23:54	Average	Std Dev
FIL-S2-F2-20140216	3.343	25	2014-02-17 3:13	3.366333	0.020306
FIL-S2-F1-20140218	3.392	8	2014-02-19 18:16		
FIL-S2-F1-20140218	3.386	17	2014-02-19 20:54	Average	Std Dev
FIL-S2-F1-20140218	3.338	26	2014-02-19 23:37	3.372	0.029597
FIL-S2-F4-20140221	3.161	11	2014-02-21 19:58		
FIL-S2-F4-20140221	3.209	14	2014-02-21 21:14	Average	Std Dev
FIL-S2-F4-20140221	3.217	22	2014-02-21 23:41	3.195667	0.030288
FIL-EFF-F2-20140225	4.274	8	2014-02-27 16:22		
FIL-EFF-F2-20140225	4.065	17	2014-02-27 19:00	Average	Std Dev
FIL-EFF-F2-20140225	6.267	26	2014-02-27 21:39	4.868667	1.215493
FIL-INF-20140314	3.882	7	2014-03-14 18:47		
FIL-INF-20140314	3.92	16	2014-03-14 21:30	Average	Std Dev
FIL-INF-20140314	3.97	25	2014-03-15 0:12	3.924	0.044136
FIL-S2-F4-20140320	3.401	11	2014-03-20 21:28		
FIL-S2-F4-20140320	3.363	14	2014-03-20 22:49	Average	Std Dev
FIL-S2-F4-20140320	3.412	23	2014-03-21 1:30	3.392	0.02571

FIL-INF-20140323	3.399	7	2014-03-26 15:46		
FIL-INF-20140323	3.373	16	2014-03-26 18:28	Average	Std Dev
FIL-INF-20140323	3.367	25	2014-03-26 21:06	3.379667	0.01701
FIL-INF-20140326	3.324	7	2014-03-27 20:54		
FIL-INF-20140326	3.323	16	2014-03-27 23:32	Average	Std Dev
FIL-INF-20140326	3.344	26	2014-03-28 2:24	3.330333	0.011846
FIL-INF-20140401	3.285	7	2014-04-01 19:17		
FIL-INF-20140401	3.249	16	2014-04-01 21:56	Average	Std Dev
FIL-INF-20140401	3.247	24	2014-04-02 0:27	3.260333	0.021385
FIL-INF-20140404	2.966	7	2014-04-04 22:30		
FIL-INF-20140404	2.904	16	2014-04-05 1:12	Average	Std Dev
FIL-INF-20140404	2.963	25	2014-04-05 3:53	2.944333	0.034962
INF-20140407	3.227	12	2014-04-08 18:28		
INF-20140407	3.236	16	2014-04-08 20:04	Average	Std Dev
INF-20140407	3.198	22	2014-04-08 22:02	3.220333	0.019858
FIL-INF-20140416	2.488	7	2014-04-16 21:03		
FIL-INF-20140416	2.482	16	2014-04-16 23:44	Average	Std Dev
FIL-INF-20140416	2.457	26	2014-04-17 2:43	2.475667	0.016442
FIL-INF-20140422	2.564	7	2014-04-22 21:36		
FIL-INF-20140422	2.531	16	2014-04-23 0:12	Average	Std Dev
FIL-INF-20140422	2.5	26	2014-04-23 3:07	2.531667	0.032005
FIL-INF-20140603	3.366	7	2014-06-04 19:16		
FIL-INF-20140603	3.506	16	2014-06-04 22:01	Average	Std Dev
FIL-INF-20140603	3.419	25	2014-06-05 0:45	3.430333	0.070685
FIL-INF-20140618	3.443	7	2014-06-18 19:56		
FIL-INF-20140618	3.477	16	2014-06-18 22:41	Average	Std Dev
FIL-INF-20140618	3.582	25	2014-06-19 1:20	3.500667	0.072459
FIL-INF-20140621	3.4	7	2014-06-23 15:20		
FIL-INF-20140621	3.4	16	2014-06-23 18:00	Average	Std Dev
FIL-INF-20140621	3.461	25	2014-06-23 20:51	3.420333	0.035218
FIL-INF-20140703	3.766	7	2014-07-03 21:57		
FIL-INF-20140703	3.883	16	2014-07-04 0:42	Average	Std Dev
FIL-INF-20140703	3.875	25	2014-07-04 3:28	3.841333	0.065363
FIL-INF-20140709	3.611	7	2014-07-27 1:03		
FIL-INF-20140709	3.507	16	2014-07-27 3:48	Average	Std Dev
FIL-INF-20140709	3.544	25	2014-07-27 6:33	3.554	0.052716

S2-F5-20140709	3.586	28	2014-07-27 8:05		
S2-F5-20140709	3.845	37	2014-07-27 10:51	Average	Std Dev
S2-F5-20140709	4.373	40	2014-07-27 11:35	3.934667	0.401089
FIL-EFF-F2-20140715	2.903	10	2014-08-03 20:57		
FIL-EFF-F2-20140715	2.947	15	2014-08-03 22:45	Average	Std Dev
FIL-EFF-F2-20140715	2.755	26	2014-08-04 2:05	2.868333	0.100585
FIL-INF-20140718	3.465	7	2014-08-17 17:06		
FIL-INF-20140718	3.468	20	2014-08-17 20:49	Average	Std Dev
FIL-INF-20140718	3.385	32	2014-08-18 0:28	3.439333	0.047078
FIL-INF-20140727	4.034	34	2014-08-18 1:34		
FIL-INF-20140727	4.12	47	2014-08-18 5:32	Average	Std Dev
FIL-INF-20140727	4.039	59	2014-08-18 8:54	4.064333	0.048274
INF-20140730	3.918	30	2014-08-15 6:50		
INF-20140730	3.9	35	2014-08-15 8:31	Average	Std Dev
INF-20140730	3.926	40	2014-08-15 9:41	3.914667	0.013317
FIL-INF-20140805	4.047	7	2014-08-14 23:18		
FIL-INF-20140805	3.999	16	2014-08-15 2:05	Average	Std Dev
FIL-INF-20140805	4.061	25	2014-08-15 4:50	4.035667	0.032517
FIL-INF-20140730	3.813	7	2014-08-18 15:32		
FIL-INF-20140730	3.869	16	2014-08-18 18:16	Average	Std Dev
FIL-INF-20140730	3.857	24	2014-08-18 20:51	3.846333	0.029484
FIL-INF-20140823	3.916	7	2014-08-23 18:49		
FIL-INF-20140823	3.904	16	2014-08-23 21:36	Average	Std Dev
FIL-INF-20140823	4.028	25	2014-08-24 0:17	3.949333	0.068391
FIL-INF-20140826	4.376	7	2014-08-27 16:21		
FIL-INF-20140826	4.47	18	2014-08-27 19:29	Average	Std Dev
FIL-INF-20140826	4.429	23	2014-08-27 21:22	4.425	0.047127
FIL-INF-20140829	4.523	7	2014-08-29 22:38		
FIL-INF-20140829	4.558	16	2014-08-30 1:25	Average	Std Dev
FIL-INF-20140829	4.406	25	2014-08-30 4:09	4.495667	0.079601
FIL-INF-20140913	4.708	7	2014-09-13 23:34		
FIL-INF-20140913	4.858	16	2014-09-14 2:17	Average	Std Dev
FIL-INF-20140913	4.85	25	2014-09-14 5:00	4.805333	0.084388
FIL-INF-20140916	4.722	7	2014-09-17 15:36		
FIL-INF-20140916	4.712	16	2014-09-17 18:21	Average	Std Dev
FIL-INF-20140916	4.728	25	2014-09-17 21:13	4.720667	0.008083

FIL-INF-20140924	4.237	7	2014-10-01 0:37		
FIL-INF-20140924	4.28	16	2014-10-01 3:29	Average	Std Dev
FIL-INF-20140924	3.918	25	2014-10-01 6:18	4.145	0.19776
INF-20140927	4.299	30	2014-10-01 8:24		
INF-20140927	4.366	36	2014-10-01 10:32	Average	Std Dev
INF-20140927	4.349	45	2014-10-01 13:24	4.338	0.034828
FIL-INF-20141003	5.333	11	2014-10-06 19:13		
FIL-INF-20141003	5.361	14	2014-10-06 20:28	Average	Std Dev
FIL-INF-20141003	5.297	23	2014-10-06 23:13	5.330333	0.032083

SRP Quality Control Data

Sample	Dilution Factor	Concentration (µg P/L)		
FIL-S2-F4-20131003	1	6.35		
FIL-S2-F4-20131003	1	5.04	Average	Std Dev
FIL-S2-F4-20131003	1	5.55	5.65	0.660328
INF-20140314	1	1.39		
INF-20140314	1	1.47	Average	Std Dev
INF-20140314	1	0.64	1.17	0.459008
S2-F5-20140225	1	1.03		
S2-F5-20140225	1	0.83	Average	Std Dev
S2-F5-20140225	1	0.63	0.83	0.202502
INF-20140218	1	0.95		
INF-20140218	1	0.99	Average	Std Dev
INF-20140218	1	0.81	0.92	0.091526
S2-F5-20140216	1	1.39		
S2-F5-20140216	1	1.12	Average	Std Dev
S2-F5-20140216	1	0.80	1.10	0.293301
S2-F2-20140110	1	3.92		
S2-F2-20140110	1	3.77	Average	Std Dev
S2-F2-20140110	1	4.05	3.91	0.140119
S2-F2-20140314	13.92	129.00		
S2-F2-20140314	16.005	132.00	Average	Std Dev
S2-F2-20140314	15.571	134.00	131.67	2.516611
INF-20140320	1	4.12		
INF-20140320	1	4.70	Average	Std Dev
INF-20140320	1	4.41	4.41	0.29
S2-F5-20140323	1	2.79		
S2-F5-20140323	1	3.01	Average	Std Dev
S2-F5-20140323	1	2.46	2.75	0.276827
S2-F5-20140326	1	2.94		
S2-F5-20140326	1	3.35	Average	Std Dev
S2-F5-20140326	1	2.94	3.08	0.236714
S2-F3-20140404	1	5.70		
S2-F3-20140404	1	5.72	Average	Std Dev
S2-F3-20140404	1	5.87	5.76	0.092916
EFF-F3-20140407	1	3.55		
EFF-F3-20140407	1	3.98	Average	Std Dev

EFF-F3-20140407	1	3.40	3.64	0.301054
S2-F4-20140422	1	5.06		
S2-F4-20140422	1	5.64	Average	Std Dev
S2-F4-20140422	1	5.06	5.25	0.334863
S2-F2-20140603	1	0.97		
S2-F2-20140603	1	1.02	Average	Std Dev
S2-F2-20140603	1	1.19	1.06	0.114936
EFF-F5-20140621	1	1.78		
EFF-F5-20140621	1	1.74	Average	Std Dev
EFF-F5-20140621	1	1.44	1.65	0.185831
EFF-F5-20140703	1	0.70		
EFF-F5-20140703	1	0.58	Average	Std Dev
EFF-F5-20140703	1	1.03	0.77	0.235663
S2-F5-20140715	1	5.36		
S2-F5-20140715	1	4.67	Average	Std Dev
S2-F5-20140715	1	4.54	4.86	0.440719
EFF-F5-20140718	1	4.73		
EFF-F5-20140718	1	5.29	Average	Std Dev
EFF-F5-20140718	1	4.34	4.79	0.477528
20	1	17.50		
20	1	19.40	Average	Std Dev
20	1	17.80	18.23	1.021437
S2-F3-20140730	1	4.98		
S2-F3-20140730	1	4.13	Average	Std Dev
S2-F3-20140730	1	5.01	4.71	0.499633
EFF-F5-20140805	1	4.87		
EFF-F5-20140805	1	6.36	Average	Std Dev
EFF-F5-20140805	1	4.06	5.10	1.166633
20	1	19.60		
20	1	19.50	Average	Std Dev
20	1	19.90	19.67	0.208167
S2-F1-20140913	1	5.02		
S2-F1-20140913	1	4.75	Average	Std Dev
S2-F1-20140913	1	4.65	4.81	0.191398
EFF-F2-20140924	13.991	83.60		
EFF-F2-20140924	15.281	79.50	Average	Std Dev
EFF-F2-20140924	11.294	89.70	84.27	5.132576

TP Quality Control Data

Sample	Dilution Factor	Concentration (µg P/L)		
FIL-S2-F1-20131030	1	3.88		
FIL-S2-F1-20131030	1	3.96	Average	Std Dev
FIL-S2-F1-20131030	1	3.64	3.83	0.166533
EFF-F5-20131118	1	0.50		
EFF-F5-20131118	1	0.44	Average	Std Dev
EFF-F5-20131118	1	0.64	0.53	0.103549
S2-F4-20131120	1	0.97		
S2-F4-20131120	1	1.05	Average	Std Dev
S2-F4-20131120	1	1.00	1.01	0.039247
EFF-F1-20131211	1	0.32		
EFF-F1-20131211	1	0.25	Average	Std Dev
EFF-F1-20131211	1	0.26	0.27	0.037287
INF-20140110	1	5.66		
INF-20140110	1	5.18	Average	Std Dev
INF-20140110	1	5.15	5.33	0.286182
FIL-S2-F4-20140110	1	4.08		
FIL-S2-F4-20140110	1	3.62	Average	Std Dev
FIL-S2-F4-20140110	1	3.64	3.78	0.26
FIL-EFF-F5-20140110	1	3.74		
FIL-EFF-F5-20140110	1	3.31	Average	Std Dev
FIL-EFF-F5-20140110	1	3.43	3.49	0.221886
FIL-EFF-F2-20140120	1	4.63		
FIL-EFF-F2-20140120	1	5.17	Average	Std Dev
FIL-EFF-F2-20140120	1	4.57	4.79	0.330454
S2-F1-20140320	1	6.38		
S2-F1-20140320	1	7.22	Average	Std Dev
S2-F1-20140320	1	6.69	6.76	0.424774
INF-F2-20140401	25.934	146.00		
INF-F2-20140401	26.492	144.00	Average	Std Dev
INF-F2-20140401	47.123	129.00	139.67	9.291573
S2-F3-20140404	1	9.33		
S2-F3-20140404	1	9.13	Average	Std Dev
S2-F3-20140404	1	9.10	9.19	0.125033
EFF-F2-20140407	28.626	71.90		
EFF-F2-20140407	26.034	75.10	Average	Std Dev
EFF-F2-20140407	28.164	80.40	75.80	4.293018

5	1	4.29		
5	1	4.27	Average	Std Dev
5	1	4.29	4.28	0.011547
INF-20140603	1	0.40		
INF-20140603	1	0.37	Average	Std Dev
INF-20140603	1	0.00	0.26	0.222027
EFF-F1-20140618	1	-0.90		
EFF-F1-20140618	1	-0.81	Average	Std Dev
EFF-F1-20140618	1	-1.10	-0.94	0.147412
INF-20140703	1	0.13		
INF-20140703	1	1.30	Average	Std Dev
INF-20140703	1	0.13	0.52	0.675789
INF-20140709	1	2.59		
INF-20140709	1	2.60	Average	Std Dev
INF-20140709	1	2.60	2.60	0.005774
S2-F3-20140715	1	4.12		
S2-F3-20140715	1	4.26	Average	Std Dev
S2-F3-20140715	1	3.75	4.04	0.263502
EFF-F1-20140718	1	-1.60		
EFF-F1-20140718	1	-1.59	Average	Std Dev
EFF-F1-20140718	1	-0.50	-1.23	0.632796
EFF-F4-20140727	7.266	35.00		
EFF-F4-20140727	7.489	37.20	Average	Std Dev
EFF-F4-20140727	7.521	35.00	35.73	1.270171
FIL-S2-F1-20131030	1	3.88		
FIL-S2-F1-20131030	1	3.96	Average	Std Dev
FIL-S2-F1-20131030	1	3.64	3.83	0.166533
EFF-F5-20131118	1	0.50		
EFF-F5-20131118	1	0.44	Average	Std Dev
EFF-F5-20131118	1	0.64	0.53	0.103549
S2-F4-20131120	1	0.97		
S2-F4-20131120	1	1.05	Average	Std Dev
S2-F4-20131120	1	1.00	1.01	0.039247
EFF-F1-20131211	1	0.32		
EFF-F1-20131211	1	0.25	Average	Std Dev
EFF-F1-20131211	1	0.26	0.27	0.037287

5	1	4.64		
5	1	4.66	Average	Std Dev
5	1	4.83	4.71	0.104403
S2-F2-20140823	7.179	114.00		
S2-F2-20140823	6.971	113.00	Average	Std Dev
S2-F2-20140823	6.955	109.00	112.00	2.645751
EFF-F2-20140826	7.075	80.80		
EFF-F2-20140826	8.325	80.90	Average	Std Dev
EFF-F2-20140826	9.923	79.70	80.47	0.665833
EFF-F4-20140829	8.754	73.90		
EFF-F4-20140829	9.699	68.60	Average	Std Dev
EFF-F4-20140829	9.096	76.40	72.97	3.98288
S2-F2-20140916	6.978	138.00		
S2-F2-20140916	8.265	141.00	Average	Std Dev
S2-F2-20140916	7.6	149.00	142.67	5.686241
EFF-F2-20140927	7.967	60.50		
EFF-F2-20140927	8.808	60.60	Average	Std Dev
EFF-F2-20140927	8.801	60.10	60.40	0.264575

Appendix G

Filtration Media Specification Sheets

PRODUCT BULLETIN

CALGON
CALGON CARBON CORPORATION

FILTRASORB® 816 & 820

GRANULAR ACTIVATED CARBONS FOR POTABLE WATER

DESCRIPTION

Filtrasorb 816 and Filtrasorb 820 are two high activity granular activated carbons developed by Calgon Carbon Corporation for the removal of taste and odor compounds and dissolved organic compounds in potable water treatment.

These activated carbons are manufactured from select grades of bituminous coal to produce a high activity, durable granular product capable of withstanding the abrasion associated with repeated backwashing, air scouring, and hydraulic transport. Activation is carefully controlled to produce an exceptionally high internal surface area with optimum pore size for effective adsorption of a broad range of high and low molecular weight organic contaminants. The product is also designed to comply with all the applicable provisions of the AWWA Standard for Granular Activated Carbon edition B604-90, the stringent extractable metals requirements of ANSI/NSF Standard 61 and Food Chemicals Codex.

APPLICATIONS

Filtrasorb 816 and 820 are used primarily to treat surface water sources for the production of drinking water. These carbons are coarser mesh media and are generally used in deep bed filters where pressure drop may be a concern. Filtrasorb 816 and 820 carbons function as dual purpose media, providing both filtration and adsorption.

DESIGN CONSIDERATIONS

As a replacement for existing filter media, the conversion to Filtrasorb 816 or 820 activated carbon imposes no major changes to a plant's normal filtration operations. If more contact time is required, the height of the backwash troughs can be increased. Calgon Carbon Corporation can also provide complete modular adsorption systems as an add-on treatment stage if required.

PACKAGING

55 Pound (25 kg) 5 Ply Bag
1,000 Pound (453.7 kg) Super Sack
Bulk Trucks

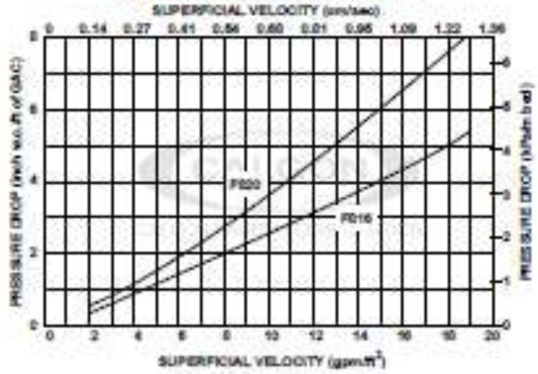
MANUFACTURING

Catlettsburg, KY
Pearlington, MS

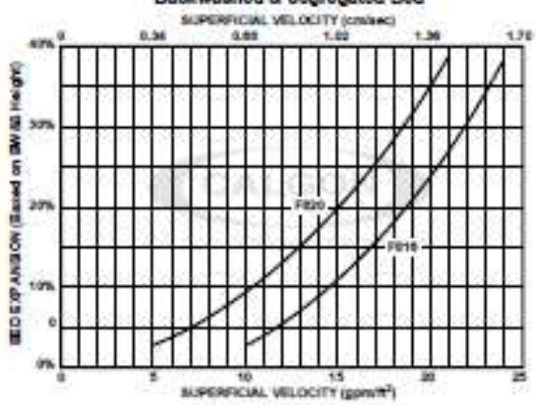
SPECIFICATIONS

	F816	F820
Iodine Number, mg/g (Min.)	900	900
Moisture, weight % (Max. %)	2	2
Abrasion Number (Min.)	75	75
Effective Size, mm	1.3-1.5	1.0-1.2
Uniformity Coefficient (Max.)	1.4	1.5
Ash, weight % (Max.)	8	8
Apparent Density, g/cc (Min.)	.50-.57	.50-.57
Water Soluble Ash, weight % (Max.)	-	0.5
Sieve Size, U.S. Sieve Series, weight %		
Larger than No. 8 (Max.)	15	5
Smaller than No. 16 (Max.)	5	-
Smaller than No. 20 (Max.)	-	4

Down Flow Pressure Drop at 55°F
Backwashed & Segregated Bed



Bed Expansion During Backwash at 55°F
Backwashed & Segregated Bed



CALGON CARBON CORPORATION • P.O. BOX 717 • PITTSBURGH, PA 15230-717 • PHONE 1-800-4CARBON

CALGON
CALGON CARBON CORPORATION

Calgon Carbon Corporation 500 Calgon Carbon Drive, Pittsburgh, PA 15205

Certificate of Analysis

Date: 04/08/2013
Customer Order: 45405061
Delivery / Item: 80510461 / 900003
Sales Order: 10368736
Ship Date: 03/14/2013
Page: 1 of 3

Customer Number: 8019850

CONTINENTAL CARBON
C/O MUN OF WATERLOO MANNHEIM WATER
2069 OTTAWA STREET SOUTH
KITCHENER ON N2E 3K3

Attention: Sir / Madam

Customer Specific Information
Material:

NSF®

This Carbon is Tested and Certified by NSF International against NSF/ANSI Standard 61 for material requirements only.

Material: 21301030 / FILTRASORB 816 - 1000LB-SS/C/NL

Batch S12C20DA / Quantity 18,000.000 LB / Manufacture Date 12/20/2012

Specification	Unit	Value	Lower Limit	Upper Limit
IODINE NUMBER TM4/ASTM D4607	mg/g	917	900	---
MOISTURE TM1 / ASTM D2867	%	1	---	2
ABRASION NUMBER TM9	Unit	91	75	---
APPARENT DENSITY TM7	g/cc	0.53	0.50	---
EFFECTIVE SIZE TM47/ASTMD2862	mm	1.4	1.3	1.5
UNIFORMITY COEFFICIENT TM47	Unit	1.3	---	1.4
US SIEVE SERIES ON 8 MESH	%	1	---	15
US SIEVE SERIES <16 MESH	%	2	---	5

Batch S13118EQ / Quantity 10,000.000 LB / Manufacture Date 01/18/2013

Specification	Unit	Value	Lower Limit	Upper Limit
IODINE NUMBER TM4/ASTM D4607	mg/g	936	900	---
MOISTURE TM1 / ASTM D2867	%	2	---	2
ABRASION NUMBER TM9	Unit	87	75	---
APPARENT DENSITY TM7	g/cc	0.53	0.50	---
EFFECTIVE SIZE TM47/ASTMD2862	mm	1.3	1.3	1.5
UNIFORMITY COEFFICIENT TM47	Unit	1.2	---	1.4
US SIEVE SERIES ON 8 MESH	%	0	---	15
US SIEVE SERIES <16 MESH	%	1	---	5

COA Contact: Liz Epling
Phone: 606-739-2307

Technical Questions: Fred Caudill
Phone: 606-739-2318

Material: 21301030 / FILTRASORB 816 - 1000LB-SS/C/NL

Batch S13120CK / Quantity 10,000.000 LB / Manufacture Date 01/20/2013

Specification	Unit	Value	Lower Limit	Upper Limit
IODINE NUMBER TM4/ASTM D4607	mg/g	932	900	---
MOISTURE TM1 / ASTM D2867	%	2	---	2
ABRASION NUMBER TM9	Unit	89	75	---
APPARENT DENSITY TM7	g/cc	0.54	0.50	---
EFFECTIVE SIZE TM47/ASTMD2862	mm	1.3	1.3	1.5
UNIFORMITY COEFFICIENT TM47	Unit	1.2	---	1.4
US SIEVE SERIES ON 8 MESH	%	1	---	15
US SIEVE SERIES <16 MESH	%	1	---	5

Batch S13122EG / Quantity 2,000.000 LB / Manufacture Date 01/22/2013

Specification	Unit	Value	Lower Limit	Upper Limit
IODINE NUMBER TM4/ASTM D4607	mg/g	914	900	---
MOISTURE TM1 / ASTM D2867	%	2	---	2
ABRASION NUMBER TM9	Unit	88	75	---
APPARENT DENSITY TM7	g/cc	0.56	0.50	---
EFFECTIVE SIZE TM47/ASTMD2862	mm	1.3	1.3	1.5
UNIFORMITY COEFFICIENT TM47	Unit	1.2	---	1.4
US SIEVE SERIES ON 8 MESH	%	0	---	15
US SIEVE SERIES <16 MESH	%	1	---	5

COA Contact: Liz Epling **Phone:** 606-739-2307	**Technical Questions:** Fred Caudill **Phone:** 606-739-2318

PRODUCT SPECIFICATION OF FILTRALITE®

Filter media

FILTRALITE ® NC 1,5-2,5

Commercial name	FILTRALITE ® NC 1,5-2,5 mm
Density	Bulk density: 235 kg/m³ particle density: 720 kg/m³
Type of material	Expanded clay
Appearance	Crushed particles, porous surface structure
Manufactured by	maxit Leca Rælingen, Norway

Size and weight	Value	Deviation	Comments
Effective size	1,7 mm	± 0,3 mm	d_{10}
Particle size range	1,5-2,5 mm	< 1,4 mm max. 5 % +Δ < 0,125 mm > 2,5 mm max. 5 %	
Coefficient of uniformity	< 1,5		d_{60} / d_{10}
Bulk density, dry	235 kg/m³	± 75 kg/m³	EN 1097-3
Particle density, dry (PDD)	720 kg/m³	± 150 kg/m³	Exclay Norm
Particle density, wet After 1 day in water After 300 days in water	 1038 kg/m³ 1115 kg/m³	 ± 150 kg/m³ ± 150 kg/m³	

Other properties	Value	Comments
Particle porosity	73 %	Porosity internal particle: (1-PDD/2700 kg/m³)*100
Voids	67 %	EN 1097-3
Acid solubility	< 5 %	EN 12902

Chemical composition, average values:

SiO_2	Al_2O_3	FeO_3	K_2O	MgO	CaO	Na_2O	C_{tot}
62%	18%	7%	4%	3%	3%	2%	0,02%

As the particle density in dry conditions is lower than the density of water, parts of the material will float until it is saturated with water.

maxit as P.O. Box 216 Alnabru 0614 Oslo, Norway	Further information: www.filtralite.com E-mail: info@filtralite.com	Telephone: +47 22 88 77 00 Telefax: +47 22 64 54 54

filtralite

maxit
maxit Group

Bioscience, Inc.
Environmental Products and Services ISO 9001:2008 Certified

BIOFILL™ Plastic Media
for Wastewater Plants

Type

The **BIOFILL Plastic Media** is a high-efficiency plastic media used as a support for bacterial growth in wastewater treatment plants. **BIOFILL media** is made by molding thermoplastic of high mechanical strength and resistance to chemical, physical and biological agents.

Applications of BIOFILL® Media

Domestic/Industrial Effluent Treatment

Septic Tanks
Trickling Filters
Moving Bed Systems
Capacity Enhancement
Nitrification Enhancement

Other Applications

Fume, gas, dust and odor elimination, Chemical, petrochemical, pharmaceutical facilities, Gas extraction and cleaning, Absorption and distillation columns.

Features of Biofill Media

	Type A	Type B	Type C
Surface Area/Volume	> 160 m2/m3	125 m2/m3	525 m2/m3
Void Space	96 %	85 %	---
Material Weight	37 Kg/m3	51 Kg/m3	133 Kg/m3
Packing	random	random	random
Material	PP black	PP black	PP charge m.
Resistance to Compression	250 Kg/1m	500 Kg/1m	---
Weight Biofill/ unit	7.5 grams	118.6 grams	1.2 grams
Diameter, Max. Outside	7 cm	17 cm	3 cm
Height	7 cm	9 cm	2 cm
Softening Temperature	72 ºC	75ºC	82 ºC
Maximum Use Temperature	65 ºC	65 ºC	68 ºC
Hydrocarbon Resistance	Good/Medium	Good/Medium	Good/Medium
Acid Resistance	Excellent/Good	Excellent/Good	Excellent/Good
Alkali Resistance	Excellent	Excellent	Excellent

Ask your Bioscience, Inc. Technical Representative for a quotation.

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E-mail: bioscience@bioscienceinc.com • Website: www.bioscienceinc.com