

Filter Performance Optimization for Protozoan Pathogen and Particulate Contaminant Removal During
Drinking Water Treatment

by

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This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

This thesis consists of an introductory chapter, followed by five manuscript chapters which were written for publication in peer-reviewed scientific journals, and concludes with a final chapter. Kalani S. De Silva is the sole author of Chapters 1 and 7, which were written under the supervision of Dr. Monica B. Emelko and were not prepared for publication. Exceptions to sole authorship and contributions in accordance with the CRediT (Contributor Roles Taxonomy) system are as follows:

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Abstract

Physico-chemical filtration (chemically assisted filtration; CAF) remains a critical barrier for the removal of particulate contaminants, including *Cryptosporidium* oocysts and emerging contaminants such as microplastics, during drinking water treatment. Ensuring consistent CAF performance becomes particularly challenging for systems reliant on high-quality source waters—those with low turbidity and low dissolved organic carbon concentrations—where traditional performance indicators such as turbidity may provide limited insight into the adequacy of coagulation, as source waters often already meet treated-water turbidity criteria prior to coagulation. Under these conditions, coagulant inadequacy or under-dosing may not be readily apparent, potentially resulting in insufficient particle destabilization and overestimation of *Cryptosporidium* oocyst removal by CAF and associated regulatory treatment credits.

The goal of this research was to demonstrate the importance of particle destabilization for achieving reliable removal of protozoan pathogens and other particulate contaminants (including microplastics) by CAF for systems reliant on high-quality source waters. While the importance of coagulation in destabilizing particles for effective CAF is well known, its regulatory and operational relevance—particularly for HQSW—needs to be revisited given the public health importance of drinking water treatment. Pilot-scale performance demonstrations were conducted to: (1) demonstrate the inadequacy of filter effluent turbidity as an indicator of coagulant demand required to achieve ≥ 3 -log protozoan removal by CAF; (2) evaluate zeta potential as an operational tool to indicate the sufficiency of particle destabilization needed to maximize protozoan removal by CAF; (3) investigate direct in-line CAF's ability to achieve ≥ 3 -log protozoan removal; (4) determine whether removal of microplastics exhibit behavior consistent with other colloidal particles during CAF; and (5) evaluate key methodological factors that contribute to variability and uncertainty in performance demonstrations to enhance confidence in interpreting measured CAF performance.

Collectively, the findings reinforce that adequate coagulation and particle destabilization are fundamental drivers of CAF performance across particle types, treatment configurations, and methodological approaches. This work demonstrated that turbidity alone cannot indicate adequacy of coagulant application for high-quality source waters, whereas zeta potential offers a tool to guide coagulant dosing and confirm the particle destabilization needed to achieve ≥ 3 -log protozoan removal by CAF, recognizing that sufficient destabilization range and associated coagulant doses vary with system and water quality specific conditions. At the same time, it also demonstrated performance demonstration methods commonly used to evaluate protozoan removal remain reliable and yield consistent results when particle destabilization is optimized.

This work highlights opportunities to strengthen treatment guidance for the removal of protozoan pathogens by CAF for systems reliant on low-turbidity, low-DOC source waters, provides pilot-scale evidence supporting reconsideration of treatment credits assigned to direct in-line CAF, and offers foundational process understanding needed to inform regulatory policy on microplastics.

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List of Abbreviations

AGI	Acute gastrointestinal illness
Al	Aluminum
Alum	Aluminum sulfate
BB	Bright blue
CAF	Chemically-assisted filtration
Cm	Centimeters
DOC	Dissolved organic carbon
EPA	Environmental protection agency
EU	European union
FTIR	Fourier transform infrared
GC/MS	Gas Chromatography/Mass Spectrometry
h	Hour
HBTL(s)	Health-based turbidity limit(s)
HLR	Hydraulic loading rate
HV	High volume
ID	Internal diameter
IJC	International joint commission
IFA	Immunofluorescence assay
L	Liter
LC OCD	Liquid chromatography with organic carbon detection
LT2ESWTR	Long-term 2 enhanced surface water treatment rule
m	Meters
mg	Milligram
mm	Millimeters
MP(s)	Microplastic(s)
mV	Millivolt
NaCl	Sodium chloride
ND(s)	Non-detect(s)
NOAA	National oceanic and atmospheric administration
NOM	Natural organic matter

NTU	Nephelometric turbidity unit
OELR	Overall effective log removal
PACl	Polyaluminum chloride
PBS	Phosphate buffered saline
PBST	Phosphate buffered saline with tween
PP	Polypropylene
SS	Seed suspension
SCADA	Supervisory control and data acquisition
SUVA	Specific ultraviolet absorbance
SWTRs	Surface water treatment rules
T	Time
TMC	Threshold microplastics concentration
TOC	Total organic carbon
TT	Treatment technique
U.S.	United states
UV	Ultraviolet
UV ₂₅₄	Ultraviolet absorbance at 254 nm
WTP	Water treatment plant
WHO	World health organization
YG	Yellow green

List of Symbols

°C	Degree celsius
N	Number of individual experiments/filter runs
N	Number of individual filter effluent samples analyzed
T ₅₀	Mean residence time
μS	micro-Siemens

Chapter 1. General Introduction

1.1 Problem statement

The purpose of drinking water treatment is to protect public health through the distribution of safe drinking water that is sufficiently free of chemical and microbial contaminants (i.e., pathogenic microorganisms). Despite notable advancements in treatment, waterborne disease outbreaks continue to occur globally (Bourli et al., 2023; Kunz et al., 2024), underscoring the persistent vulnerability of drinking water systems and the importance of multi-barrier approach to safe water (EPA, 1974; CDW and CCME, 2002; CCME, 2004). Although threats from chemical contaminants (e.g., perfluorinated substances) continue to emerge (Kleywegt et al., 2020; EPA, 2024; Health Canada, 2025), microbial contaminants remain one of the most prevalent and consequential threats, and their control must remain uncompromised within any treatment strategy (WHO, 2017). As regulatory frameworks evolve and include increasingly stringent threshold- and performance-based criteria, and as expectations for quantifiable removal of protozoan pathogens (which can be considered bioparticles or particulate contaminants from transport and treatment perspectives) and other, emerging particulate contaminants (e.g., microplastics) increase, the need for more effective removal of particulate contaminants through physico-chemical removal and/or inactivation by drinking water processes also increases.

Among regulated microbial contaminants, *Cryptosporidium* continues to pose one of the greatest challenges to drinking water treatment. The most commonly found *Cryptosporidium* species to cause gastroenteritis in humans are *C. parvum* and *C. hominis* (Current and Garcia, 1991; Bujila et al., 2024). There are two forms of *Cryptosporidium* oocysts; oocysts with thin cell walls that remain in the intestine and autoinfect the host, and oocysts with thick cell walls that are environmentally resilient and allow the transmission of infection from host to host (Rose, 1988; Current and Garcia, 1991; Smith and Rose, 1998). As a result, *Cryptosporidium* oocysts are highly resistant to conventional disinfectants, including free chlorine and chloramines, and exhibit only limited susceptibility to ozone at doses typically applied in drinking water treatment (Korich et al., 1990). UV irradiation can inactivate *Cryptosporidium* oocysts; however, its effectiveness depends on adequate filtration to reduce particle loads and prevent shielding effects (Templeton et al., 2005; Mamane and Linden, 2006). As such, filtration remains a critical barrier for ensuring that protozoan pathogens (i.e., *Cryptosporidium* and *Giardia*) are removed during drinking water treatment and central to achieving regulatory compliance and safeguarding public health.

Physico-chemical filtration, also referred to as chemically-assisted filtration (CAF), is not a size-exclusion process. Rather, particle removal occurs because electrostatic repulsion between particles and filter media

surfaces is overcome by coagulant addition, which destabilizes particles (including bioparticles such as *Cryptosporidium*) and promotes their deposition onto filter media. Particle removal by CAF occurs through a two-step process: (1) transport of particles to the filter media and (2) attachment of sufficiently destabilized particles to media surfaces (O'Melia and Stumm, 1967; O'Melia, 1985; Amirtharajah, 1988; Ballantyne et al., 2024). Chemical pre-treatment of particles by coagulant is therefore critical. The importance of coagulants in destabilizing particles, including bioparticles, for effective removal by CAF is well recognized (Amirtharajah and Mills, 1982; Tobiason and O'Melia, 1988; Edzwald and Kelley, 1998; Huck et al., 2001; Emelko, 2003; Emelko et al., 2005). Consequently, filtration performance depends on multiple physico-chemical interactions: particle surface charge, coagulant demand, collision efficiency, and hydraulic conditions.

Waterborne protozoan pathogen concentrations are generally not monitored in treated drinking water because of the impracticalities associated with analyzing the extremely large water volumes needed to detect these organisms in well-treated water (Regli et al., 1991; Haas et al., 1996) and because existing analytical methods are expensive and labor intensive (Signor and Ashbolt, 2006). As a result, implementing maximum acceptable concentrations (MACs) or maximum contaminant levels (MCLs), the standards traditionally used to protect public health from waterborne contaminants, has not been feasible for protozoan pathogens. To manage and regulate microbial risks under these constraints, a treatment technique (TT) based approach was adopted. Under this framework, treatment performance “indicators,” such as filter effluent turbidity, are used to reflect the adequacy of CAF performance (EPA, 2006a; Health Canada, 2012).

According to the U.S. EPA's Surface Water Treatment Rules (SWTRs), conventional treatment systems using CAF are considered “well-operated,” and thus eligible for 3-log *Cryptosporidium* oocyst removal credit, when combined filter effluent turbidity is ≤ 0.3 NTU (nephelometric turbidity units) in at least 95% of monthly measurements and never exceeds 1 NTU. The Long Term 1 Enhanced SWTR (LT1ESWTR) and Long Term 2 Enhanced SWTR (LT2ESWTR) further specify *Giardia* and *Cryptosporidium* oocyst removal credits for a range of filtration technologies (i.e., conventional CAF, direct CAF, slow sand CAF) (EPA, 2006a). Similar to U.S. EPA guidelines, Health Canada assigns treatment credits based on achieving established turbidity criteria. Drinking water treatment plants that meet the turbidity limits specified in the Guideline Technical Document on Turbidity may automatically apply the same treatment credits granted to “well-operated” systems under U.S. EPA guidelines, or they may establish credits through demonstrated performance (Health Canada, 2012). In addition, the Guidelines for Canadian Drinking Water Quality and

the U.S. Partnership for Safe Water program encourage water systems to achieve individual filter effluent turbidity levels of ≤ 0.1 NTU at least 95% of the time (EPA, 2012a; Health Canada, 2012).

Over the decades, considerable research at pilot- and full-scales has established expectations for *Cryptosporidium* and *Giardia* removal by “well-operated” CAF (LeChevallier et al., 1991; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Huck et al., 2001, 2002; Emelko et al., 2005). Across these studies, *Cryptosporidium* oocyst removal ranged from <2 - to >5 -log even when treated water turbidity met regulatory limits (LeChevallier et al., 1991; LeChevallier and Norton, 1992; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; States et al., 1997; Bandin and Laine, 1998; Edzwald and Kelley, 1998; Swertfeger et al., 1999; Edzwald et al., 2000; Nieminski et al., 2000; Dugan et al., 2001; Hashimoto et al., 2001; Huck et al., 2001, 2002; Harrington et al., 2003; Emelko, 2003; Emelko et al., 2005; Hendricks et al., 2005; Mazoua and Chauveheid, 2005; Lee, 2018; Ballantyne et al., 2024).

Notably, much of the existing literature reporting on oocyst removal performance during water treatment has focused on systems treating source water with relatively lower quality; that is, water with higher source water turbidity and/or dissolved organic carbon (DOC) concentrations (Bandin and Laine, 1998; Patania et al., 1995; Emelko et al., 2005; Hijnen and Medema, 2010; Dugan et al., 2001; Harrington et al., 2003; Nieminski and Ongerth, 1995; Swertfeger et al., 1999), because contamination by protozoan pathogens has been considered more likely in such systems (LeChevallier and Norton, 1992; Srisuphanunt et al., 2010). In contrast, higher quality source waters (i.e., with turbidity <2 NTU and DOC <2 mg/L), such as those originating in the Great Lakes and snowmelt-dominated watersheds have been studied less. However, low source water turbidity does not necessarily indicate the absence of waterborne protozoan pathogens (Aboytes et al., 2004; IJC, 2021).

When source waters are more turbid, treatment processes are optimized to remove visible turbidity and abundant particles by sedimentation, and clarified turbidity and filter effluent turbidity can generally correlate well with protozoan pathogen removal (Fox, 1998; Edzwald et al., 2000; Dugan et al., 2001; Hsu and Yeh, 2003). For these source waters, jar testing is reasonably predictive of required coagulant dosing needs for efficient sedimentation (Dennett et al., 1996) and can also be generally indicative of coagulant demand required to achieve effective particle and pathogen removal by CAF. In contrast, high-quality source waters may already meet treated-water turbidity targets before coagulation, such that filter effluent turbidity does not necessarily correlate with pathogen removal and substantial pathogen loads may still be present. Under such conditions, traditional jar tests assessments of the coagulant dose needed to meet clarified-water

turbidity targets may not fully reflect the coagulant demand required for CAF performance for pathogen removal. These observations underscore the need to reassess whether filter effluent turbidity targets used to indicate well-operated CAF performance are sufficiently protective of protozoan removal for high-quality source waters (Knowledge Gap #1).

Notably, low-turbidity source waters can present a treatment paradox: despite their low particle load, they may require a higher coagulant dose than might be expected to achieve maximal particle removal by CAF. In these waters, the limited particle concentration reduces opportunities for collisions and interactions needed to achieve sufficient destabilization (Amirtharajah and O'Melia, 1990; Letterman et al., 1999) making the formation of coagulant-derived micro-precipitates essential for providing additional contact opportunities. Even though regulatory frameworks typically rely on turbidity as a CAF performance indicator (EPA, 2006a; Ministry of Health–Manatū Hauora, 2005; NHMRC and NRMCC, 2011; Health Canada, 2012), turbidity measures only the intensity of light scattered by particles in suspension (Letterman, 1999; Crittenden et al., 2012; Health Canada, 2012) and provides no information about particle destabilization by coagulant addition, which is a key governing factor in the removal by CAF (O'Melia, 1985; Tobiason and O'Melia, 1988; Amirtharajah and O'Melia, 1990; Edzwald and Kelley, 1998; Huck et al., 2001; Emelko, 2003; Lee, 2018; Ballantyne et al., 2024). Therefore, when turbidity is low it may provide a misleading incentive to minimize coagulant addition leading to coagulant under-dosing and inadequate treatment. Consequently, systems reliant on high-quality source waters may suffer from lack of guidance on how to identify adequate coagulant addition to ensure CAF performance. Operational tools to indicate sufficiency of particle destabilization are therefore necessary for maximizing (≥ 3 -log removal) protozoan pathogen removal by CAF (Knowledge Gap #2).

In high-quality waters, where turbidity may provide limited insight into destabilization and low particles limits contact opportunities, treatment configurations that enhance opportunities for particle-coagulant interactions can be particularly valuable for ensuring consistent removal of *Cryptosporidium* oocysts and other particulate contaminants. Direct in-line CAF, where coagulated water is applied directly to filters, omitting flocculation and sedimentation basins (Amirtharajah and O'Melia, 1990; Letterman et al., 1999; Crittenden et al., 2012), is inherently designed for such waters. These systems are designed to manage and retain micro-precipitates formed (Culp, 1977; Treweek, 1979; Valade et al., 2009; Crittenden et al., 2012), providing contact opportunities needed for particles at the surface of the filter media. However, direct in-line CAF only receives 2.5-log treatment credit for protozoan removal because it omits the sedimentation basin. Under current regulatory frameworks, sedimentation is considered to provide 0.5-log of additional

protozoan removal, which is included in the 3.0-log credit assigned to conventional CAF (EPA, 2006a; Health Canada, 2012). For systems treating high-quality source water, where solids concentrations are low and conventional sedimentation provides limited benefit, appropriateness of this credit should be reconsidered and evaluated (Knowledge Gap #3).

Climate change amplifies the urgency of addressing these knowledge gaps. Intensified storm events, prolonged droughts, wildfires, and other landscape disturbances introduce greater variability into raw-water quality, both in the short term and over seasonal scales (Emelko et al., 2011; IPCC, 2021; Emelko et al., 2024). This variability challenges current treatment processes and can lead to conditions that potentially compromise particle removal by CAF (Emelko et al., 2011). Thus, ensuring resilience under these shifting conditions requires operational tools and strategies that help achieve sufficient particle destabilization by adequate coagulant addition for reliable CAF performance.

Simultaneously, utilities face growing pressure to address emerging particulate contaminants, specifically microplastics (MPs). MPs introduce additional complexity due to their diverse physicochemical properties, environmental persistence, and potential toxicity (Pivokonsky et al., 2018; Wang et al., 2021; Li et al., 2023). Their irregular morphology, polymer-dependent surface chemistry, and hydrophobicity raise important scientific and regulatory questions about the extent to which existing treatment infrastructure such as CAF designed to remove fine particulate contaminants, can be leveraged to address MPs without the development of new treatment technologies. While multiple studies have evaluated MPs either as surrogates for protozoa (Dai and Hozalski, 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Brown and Emelko, 2009; Amburgey et al., 2012; Liu et al., 2019) or as emerging contaminants with a focus on aggregation efficiencies (Pivokonsky et al., 2018; Ma et al., 2019; Lapointe et al., 2020; Skaf et al., 2020; Na et al., 2021; Peydayesh et al., 2021; Zhou et al., 2021; Azizi et al., 2023; Khan et al., 2023; Yu et al., 2024), they do not demonstrate whether MPs behave in accordance with established principles of particle destabilization as indicated by zeta potential analysis and subsequent attachment, that underlie the removal of other colloidal particles by CAF. Confirming that established coagulation–CAF process understanding is applicable to MPs to show that they are removed like other colloidal particles, is therefore of high relevance for both operational decision making and regulatory planning (Knowledge Gap #4).

Across all filtration systems and contaminants, performance demonstrations, including bench-scale, pilot-scale, and full-scale evaluations, serve as a cornerstone for validating treatment efficacy. Since natural protozoan pathogen concentrations are far too low for direct measurement of log-removal (Aboytes et al., 2004; Srisuphanunt et al., 2010; Health Canada, 2019), performance demonstrations introduce (oo)cyst

concentrations many orders of magnitude higher than those typically observed in source waters and at defined points within the treatment train (Nieminski and Ongerth, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2001; Harrington et al., 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Emelko et al., 2005; Assavasilavasukul et al., 2008; Scott, 2008; Lee, 2018; Ballantyne et al., 2024). Despite decades of study, however, consensus regarding the reliability and consistency of the methods used in these demonstrations remains elusive. Longstanding questions persist about the variability, uncertainty, and interpretability of the resulting data, including key questions related to the effects of pathogen seeding location, pathogen concentration (Hendricks et al., 2005; Assavasilavasukul et al., 2008), analytical approaches that rely on variable volume water samples (EPA, 2012b; Health Canada, 2019) that can drive measurement variability and uncertainty in reported performance. While these types of data have been generated and utilized for decades, they have not been systematically evaluated with consideration of the factors, such as the handling of non-detects or the influence of coagulation chemistry on removal, that can confound interpretation of performance. Recent advances in understanding of uncertainties and opportunities related to laboratory analyses and piloting protocols (Emelko et al., 2008; Chik et al., 2018; Ballantyne et al., 2024) coupled with increased threats from climate shocks (IPCC, 2021) underscore the need to revisit risk management approaches and provide guidance that reflects contemporary scientific understanding (Knowledge Gap #5).

1.2 Research objectives

Given the research gaps discussed above, the overall goal of this thesis is to demonstrate the importance of sufficient particle destabilization for particulate contaminant removal by physico-chemical CAF for systems reliant on high-quality source waters. This thesis is written in a paper-based format, where Chapters 2–6 consist of individual manuscripts, each addressing one objective of the study. These specific objectives are listed below:

Chapter 2: Demonstrate the inadequacy of clarified or filtered water turbidity for indicating the adequacy of coagulant demand required to achieve ≥ 3 -log protozoan pathogen removal by CAF for systems reliant on high-quality source water;

Chapter 3: Evaluate zeta potential as an operational tool to indicate the adequacy of coagulant addition for particle destabilization for ensuring protozoan pathogen removal by CAF of high-quality source water;

Chapter 4: Investigate direct in-line CAF's ability to achieve 3-log or greater *Cryptosporidium* oocyst removal;

Chapter 5: Demonstrate that microplastics generally behave like other particulate contaminants (e.g., *Cryptosporidium* oocysts) during CAF and associated performance demonstration approaches for assessing their removal can also be used for microplastics; and

Chapter 6: Evaluate key methodological factors that contribute to variability and uncertainty in performance demonstrations to enhance confidence in interpreting measured CAF performance.

1.3 Research approach and thesis structure

This thesis is composed of seven chapters that describe the pilot-scale and laboratory investigations conducted to evaluate protozoan pathogen and microplastics removal by CAF for high-quality source waters, with Chapters 2–6 presented as individual manuscripts prepared in a paper-based thesis format.

In Chapters 2 and 3, pilot-scale performance demonstrations were conducted using a range of destabilization conditions (optimal, sub-optimal, and no destabilization), temperatures, and hydraulic conditions (stable operation, ripening, and hydraulic surge) across seven filter configurations representative of systems reliant on Great Lakes. These experiments were designed to demonstrate that filter effluent turbidity was insufficient as a performance indicator of pathogen removal by CAF for high-quality source waters and to also investigate the use of zeta potential analysis as a tool to determine the level of coagulant addition needed to achieve at least 3-log (99.9%) *Cryptosporidium* oocyst removal by CAF.

In Chapter 4, additional pilot-scale performance demonstrations were conducted to investigate the potential of direct in-line CAF in achieving ≥ 3 -log *Cryptosporidium* oocyst removal for high-quality source waters. Using data collected from the previous chapter, comparison of *Cryptosporidium* oocyst removal performance of direct in-line CAF and conventional CAF was conducted. Here, zeta potential was used as a tool to inform sufficiency of particle destabilization (optimal and sub-optimal) building on from Chapter 3.

In Chapter 5, microplastic (MP) removal was evaluated to determine whether they exhibit removal behavior consistent with other colloidal particles during CAF using pilot-scale performance demonstrations. Experiments were conducted using pristine MPs, weathered MPs, and *Cryptosporidium* oocysts across both optimal and sub-optimal destabilization conditions informed by zeta potential analysis. Performance demonstration approaches used for protozoan pathogen removal by CAF for Chapter 4 was used here to offer insight into analytical approaches that can be used for evaluating MP removal by CAF and clarify the extent to which existing drinking water treatment infrastructure can manage MPs.

In Chapter 6, multiple performance demonstrations were conducted at pilot-scale using different seeding points, concentrations, and analytical methods to address longstanding questions related to methodological variability and uncertainty related to protozoan pathogen removal by CAF. Multiple experiments using different approaches for both conventional and direct in-line CAF configurations were conducted under optimal, sub-optimal and no destabilization conditions informed by zeta potential analysis. Finally, in Chapter 7, a summary of the main findings and implications from this thesis is presented along with recommendations for future investigations.

Chapter 2. Sole reliance on turbidity is insufficient for ensuring removal of protozoan pathogens by filtration

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Summary

Minimizing health risks from waterborne pathogens is the central goal of drinking water treatment. *Cryptosporidium* remains difficult to manage because of resistance to chlorine-based disinfectants and complex, time-consuming detection methods. Thus, filtration remains critical to achieving regulatory compliance. Although turbidity is not a direct indicator of particle or pathogen concentrations, it provides real-time insight into source water quality and treatment performance. Accordingly, turbidity-based criteria are used to prescribe regulatory credits for *Cryptosporidium* removal by filtration, typically 3-log (i.e., 99.9%). However, this work shows that in systems treating low turbidity (<2 NTU) and low dissolved organic carbon (DOC; <2 mg/L) source waters, reliance on turbidity alone is insufficient to indicate treatment adequacy because it does not assure sufficient particle destabilization by coagulant addition prior to filtration. Additional tools are therefore needed in these systems to ensure U.S. Surface Water Treatment Rules and international counterpart treatment credits are justified.

2.1 Introduction

The minimization of acute health risks—predominantly those attributable to waterborne pathogens—remains the paramount objective of drinking water treatment (Hrudey and Hrudey 2004; WHO 2017). Historically, advancements in safe water technologies, particularly physico-chemical filtration and chlorination, were instrumental in reducing mortality. Between 1900 and 1936, these interventions contributed to nearly half of the total mortality reduction in major U.S. cities, with even greater reductions observed in infant and child mortality rates (Cutler and Grant, 2005). While public health threats from protozoa had not yet been identified, the combination of these technologies was nonetheless critical in managing them because *Giardia* cysts and particularly *Cryptosporidium* oocysts exhibit resistance to traditional oxidant-based disinfectants like chlorine (Korich et al., 1990; EPA, 1991; Finch et al., 1994; 1997). Although ultraviolet (UV) irradiation emerged as an effective method for inactivating *Cryptosporidium* oocysts, effective filtration before UV treatment is critical for ensuring removal of

suspended particles that can shield pathogens and reduce UV inactivation efficacy (Templeton et al., 2005; Mamane and Linden, 2006). While the implementation of filtration and disinfection processes has significantly reduced the prevalence and severity of waterborne disease outbreaks (Rochelle & Clancy, 2006), they continue to pose significant public health concerns globally (Aboytes et al., 2004; Hrudey & Hrudey, 2004; Schuster et al., 2005; Mason et al., 2010; Chalmers, 2012; Widerström et al., 2014; Benedict et al., 2017; Pignata et al., 2019; Robertson et al., 2021; Martinez et al., 2024; Toriro et al., 2024; Bourli et al., 2023; Kunz et al., 2024).

Reliance on such Maximum Contaminant Level or Maximum Acceptable Concentrations in treated water is not feasible for regulating treatment of *Cryptosporidium* oocysts because of their infrequent and low-level (e.g., <5 oocysts/100L) occurrence, low infectious dose, and slow, unreliable detection methods (Regli et al., 1991; DuPont et al., 1995; Haas et al., 1996). Instead, a “treatment technique” approach is used. The U.S. suite of Surface Water Treatment Rules (SWTRs) and their Canadian analogs establish treatment, monitoring, and operational requirements (i.e., primarily filtration [or equivalent technology], disinfection, turbidity performance, and microbe log-removal standards) to protect public health by ensuring “well-operated” drinking water treatment is maintained (EPA, 1989; EPA, 1996; EPA, 1998; EPA, 2002; MECP, 2003; EPA, 2006a; Health Canada, 2019).

The SWTRs rules culminate in the Long-Term 2 Enhanced SWTR (LT2ESWTR; EPA, 2006a), which targets *Cryptosporidium* and focuses on ensuring well-operated filtration as a proxy for pathogen removal. It is a risk-based rule that uses a fixed 2-years of source water monitoring to determine treatment requirements and requires minimum levels of oocyst treatment through filtration, disinfection, or a combination of the two. Conventional treatment (i.e., coagulation, flocculation, clarification, and filtration), slow sand, and diatomaceous earth filtration plants receive a prescribed 3.0-log *Cryptosporidium* treatment credit for the combined performance of all processes prior to and including filtration, with the understanding that the majority of treatment occurs during filtration. This is reflected in the LT2ESWTR, which grants a 2.5-log *Cryptosporidium* treatment credit to direct filtration plants that use coagulation, flocculation, and filtration processes like conventional plants, but lack sedimentation or an equivalent clarification process, and assigns 0.5-log less credit than for conventional treatment on the basis that clarification processes can achieve at least 0.5-log *Cryptosporidium* removal (EPA, 2006a). Whether systems treating low turbidity, low DOC source water achieve at least 0.5-log *Cryptosporidium* removal during sedimentation (especially when source water turbidity is near compliance levels for treated water) has not been explicitly discussed, however. Regardless, the LT2ESWTR awards treatment credits when systems achieve a turbidity

performance standard of ≤ 0.3 NTU in at least 95% of monthly combined filter effluent (CFE) measurements while never exceeding 1.0 NTU during operation. Canadian guidelines and regulations use the same criteria for regulatory performance credits (MECP, 2003; Health Canada, 2019). Systems identified as higher risk based on source water oocyst concentration require additional treatment under the LT2ESWTR; for example, an additional 0.5-log *Cryptosporidium* removal credit is prescribed for maintaining ≤ 0.15 NTU in at least 95% of monthly CFE measurements (EPA, 2006a).

Although turbidity is used as a general indicator of effective filtration performance, it is neither a precise nor universally reliable surrogate for *Cryptosporidium* oocyst removal by filtration (Patania et al., 1995; Emelko et al., 2005; Ballantyne et al., 2024). Turbidity measures the amount of light scattered by particles in suspension; however, it is not linearly proportional to particle concentration because light scattering depends on particle size, shape, color, and refractive index, meaning similar NTU values can correspond to widely different particle loads (Davies-Colley & Smith, 2001; Crittenden et al., 2012; HACH, n.d). Larger, aggregated particles scatter light more efficiently; smaller particles scatter less (Lawler, 1997; Crittenden et al., 2012; HACH, n.d). The utility of turbidity in water quality evaluation lies in its affordability, ease of real-time monitoring, and reproducibility (Greenley & Adams, 1990; LeChevallier & Norton, 1992; EPA, 2006a; Payment & Locas, 2011; WHO 2017). It is routinely monitored at key points throughout the treatment process to inform performance. Raw/untreated water turbidity (together with dissolved organic carbon (DOC) concentration and character) is a primary factor governing coagulant dosing requirements (Edzwald, 1993; Edzwald & Tobiason, 1999; Tobiason and O'Melia, 1988; Letterman et al., 1999; EPA, 1999; Crittenden et al., 2012; Health Canada, 2023; Ballantyne et al., 2024). Following clarification, turbidity primarily reflects colloidal particles that must be removed by filtration, while after filtration it indicates residual particles that will be present during disinfection before distribution.

Coagulant under-dosing, and consequently undetected inadequate treatment is not only plausible, but also likely in systems treating low turbidity (< 2 NTU), low DOC (< 2 mg/L) source/untreated water. This is because turbidity often may be so low that it meets treated water targets (e.g., 0.3 NTU, 0.15 NTU, or lower), providing a potentially misleading incentive to minimize chemical coagulant addition. As described in Chapter 3, particle destabilization reduces electrostatic repulsion and promotes attachment between particles and filter media, enabling efficient particle removal by more than mere physical straining—this is why filtration is sometimes referred to as “chemically-assisted filtration”. When source water turbidity and DOC are low, turbidity measurements provide limited to no diagnostic value for determining the coagulant doses that lead to the particle (and oocyst) destabilization required to ensure effective treatment by filtration.

A recent International Joint Commission report (IJC, 2021) of acute gastrointestinal illnesses (AGIs) in communities largely reliant on low turbidity, low DOC Great Lakes source water punctuates these concerns because it reports increased relative risk of protozoan AGIs. In such systems, guidance beyond turbidity change after clarification and regulatory requirements beyond filter effluent turbidity may be needed to determine the coagulant dose required to achieve sufficient particle destabilization for well-operated filtration that achieves minimum (e.g., 3-log) *Cryptosporidium* removal expectations.

Given the critical role of drinking water treatment in protecting public health, it is essential to periodically re-evaluate the scientific understanding underpinning regulatory frameworks, including the suite of SWTRs and their international counterparts. Although *Cryptosporidium* removal by filtration has been extensively studied, it has not been systematically examined with a focus on low turbidity, low DOC source water systems where inadequate treatment resulting from coagulant under-dosing is plausible and prescribed regulatory treatment credits may overestimate actual treatment performance. Here, the available data that highlight the potential for systematic risk for protozoan pathogen passage through drinking water systems compliant with current regulatory requirements were summarized and the removal of parasitic protozoa, specifically *Cryptosporidium*, by pilot-scale conventional filtration was investigated to explore the adequacy of relying on filtered water turbidity alone to conclude that ≥ 3 -log (or ≥ 2.5 -log) *Cryptosporidium* removal by filtration is achieved in systems reliant on low turbidity, low DOC source water.

2.2 Results and discussion

Although numerous studies have examined *Cryptosporidium* removal by filtration, most have been conducted in systems treating more impaired source waters characterized by higher turbidity and/or DOC concentrations (Appendix D), which are generally expected to present greater protozoan contamination and associated public health risk (Mann et al., 2007; LeChevallier & Norton, 1992; Srisuphanunt et al., 2010). Notably, these studies have collectively shown that while filter effluent turbidities of ≤ 0.3 or even ≤ 0.1 NTU are generally associated with ≥ 3 -log *Cryptosporidium* removal by filtration (Patania et al., 1995; Harrington et al., 2003; Emelko et al., 2003; 2004; Campbell et al., 2014), they do not guarantee the absence of oocysts in treated water (Gammie et al., 1998; Aboytes et al., 2004; Emelko & Huck, 2004). For example, several studies have reported individual events (e.g., hydraulic surges) or short-term sub-optimal operational conditions (e.g., filter ripening, the period of filter performance improvement following a filter backwash cycle during which filter effluent turbidity is elevated and more variable as filter media [Crittenden et al., 2012]) at which 2.5-, 3-log, or greater *Cryptosporidium* removals were not attained

(LeChevallier & Norton, 1992; Kelley et al., 1995; Nieminski & Ongerth, 1995; States et al., 1997; Baudin & Laîné, 1998; Harrington et al., 2003, Xagorarakis et al., 2004); however, filter operation is not considered “stable” or “typical” at these times. Of greater concern, as shown in Figure 2.1, *Cryptosporidium* removals below the 3- and 2.5-log treatment credits have been reported in several studies in which filter operation was considered stable and “well-operated” because of compliance with regulatory turbidity limits (i.e., filter effluent turbidity ≤ 0.3 NTU).

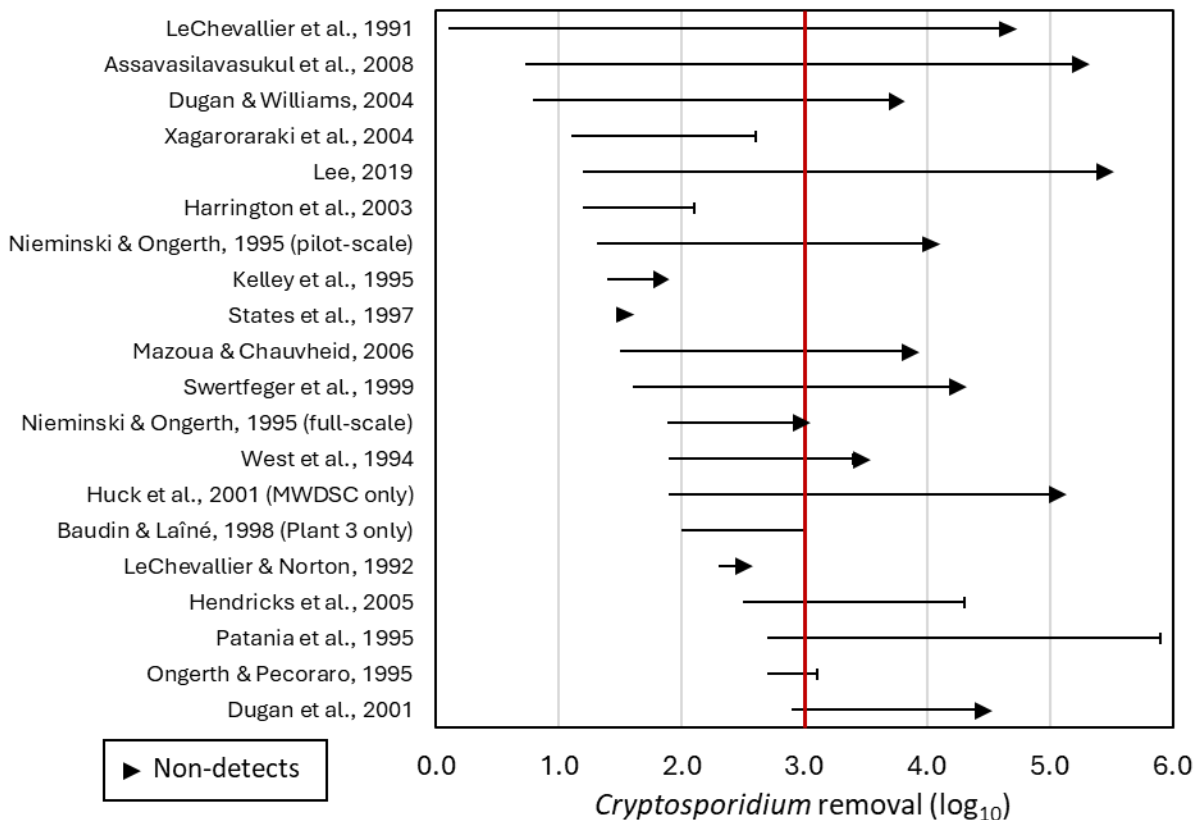


Figure 2.1. *Cryptosporidium* removal by stable, “well-operated” (i.e., filter effluent turbidity ≤ 0.3 NTU) filtration during which ≥ 3 -log oocyst removal was not consistently achieved. Studies presented here met the following criteria: (i) filter challenge studies using *Cryptosporidium* oocysts, (ii) less than 3-log removal was achieved in some cases, and (iii) filters were considered to be “well-operated” as indicated by filter effluent turbidity (i.e., ≤ 0.3 NTU). Data for multiple treatment trains were individually detailed in some cases. In others, only single removal values were reported for multiple treatment plants/trains/conditions, and this is reflected in the range. Triangles indicate observation of non-detects in at least some filter effluent

samples. The substitution of one for all effluent non-detects (in place of the counted zero) was used to allow calculation of oocyst removal.

Analytical limitations that lead to the prevalence of non-detects in filter effluents may contribute to some of the *Cryptosporidium* removals by filtration that fall below the 3- and 2.5-log treatment expectations in Figure 2.1 because effluent concentrations are often assigned a value of 1 organism per sample volume processed; this artificially inflates the effluent concentration used calculating treatment performance, biases removal estimates downward, and increases removal uncertainty (Emelko et al., 2010; Chik et al., 2018). However, non-detects are not relevant to all the studies in which *Cryptosporidium* removal expectations have not been met during stable filter operation (Figure 2.1). While non-detects and transient events such as hydraulic surges and filter ripening are readily recognized contributors to observations of reduced *Cryptosporidium* removal by filtration, they cannot explain all the observed instances in which it fails to meet the treatment credits prescribed by the suite of SWTRs. Coagulant under-dosing prior to filtration may help to explain some of these observations because it can be undetected in systems treating low turbidity, low DOC source water and lead to periodic or even chronic insufficiency in particle (and *Cryptosporidium* oocyst) destabilization and removal by filtration when untreated water is close to or meets regulatory turbidity criteria for treated water.

A total of 119 pilot-scale filter runs generating 600 effluent samples were conducted to evaluate *Cryptosporidium* oocyst removal by conventional filtration of Lake Ontario source water (turbidity rarely exceeds 1 NTU and is often less than 0.3 NTU) at varying particle-destabilization conditions achieved by coagulant addition. Untreated water turbidity rarely exceeds 1 NTU and is commonly less than 0.3 NTU. Pre-chlorinated raw and filter effluent turbidity for each filter run is provided in Appendix E. Overall effective oocyst removal during these experiments is presented relative to the corresponding filter effluent turbidity in Figure 2.2, which shows that filter effluent turbidity was below 0.1 NTU in all but 25 of the 119 experiments. These 25 experiments involved either sub-optimal particle destabilization by coagulation or no coagulant addition, and none achieved the 3.0-log *Cryptosporidium* oocyst removal expected of stable, well-operated conventional filtration. Of these, only five exhibited effluent turbidities exceeding 0.3 NTU, all occurring in absence of coagulant addition. The red-shaded zone in Figure 2.2 highlights conditions in which 2.5- and 3-log oocyst removals were not achieved despite meeting treated water turbidity targets. Although 114 of the 119 individual filter experiments met the filter effluent turbidity required by the suite of SWTRs, the data in Figure 2.2 incontrovertibly demonstrate that compliance with SWTR turbidity requirements alone does not necessarily ensure 3-log *Cryptosporidium* removal in all systems.

Throughout a typical filter run, filter effluent turbidity remained consistently low (frequently below 0.3 NTU) and remained largely unchanged, including during the seeding and sample collection period when oocysts were introduced to the influent and grab samples were collected (Figure 2.2). This behaviour was consistent across all stable operation (steady-state filtration with consistent effluent water quality) experiments, except for those intentionally operated during ripening or under hydraulic disturbance (conditions following filter backwash or during abrupt flow changes). Filter effluent turbidity values for individual experiments can be found in Appendix E. The influent *Cryptosporidium* oocyst concentration data shown in Figure 2.2 further illustrate that oocyst concentrations entering each column were generally similar within any given experiment and did not influence the observed filter effluent turbidity.

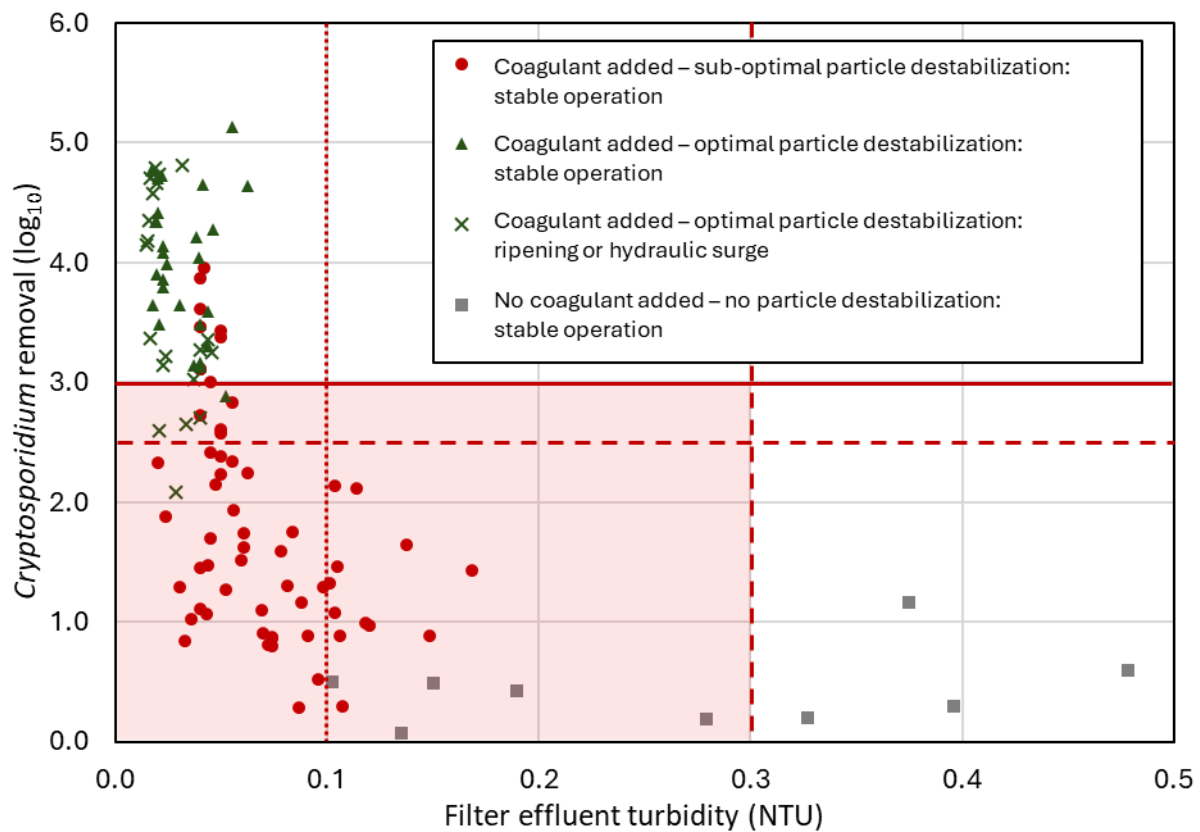


Figure 2.2. Overall effective log reduction of *Cryptosporidium* oocysts by pilot-scale filtration and filter effluent turbidity during experiments conducted with different levels of particle destabilization (optimal, sub-optimal, and no coagulant addition) during stable operation, filter ripening, and hydraulic surges.

Dotted lines are included at 0.3 and 0.1 NTU to represent the turbidity thresholds outlined in the AWWA Partnership for Safe Water guideline and Guidelines for Canadian Drinking Water Quality, respectively (EPA, 2012a; Health Canada, 2012). The solid red line and dotted lines denote the 3-log and 2.5-log oocyst removal benchmarks, respectively, corresponding to the performance expected from well-operated conventional and direct filtration systems. The red box highlights experiments in which 3-log *Cryptosporidium* oocyst removal was not achieved, despite filter effluent turbidities meeting the ≤ 0.3 NTU criterion currently used to indicate well-operated treatment and justify a 3-log removal credit.

The data in Figure 2.2 were labelled to distinguish between: (1) filtration with and without coagulant addition, (2) optimal and sub-optimal particle destabilization, and (3) performance evaluated during stable filter operation and periods of hydraulic change within the filter beds (i.e., filter ripening or hydraulic surge). In all but one of the no coagulant experiments, the filters achieved less than 1-log oocyst removal; filter effluent turbidity was less than 0.3 NTU in just over half of these experiments (Figure 2.2) and thus would lead to 3-log *Cryptosporidium* treatment credits although they are clearly unwarranted. Coagulant doses during the sub-optimal coagulation experiments (e.g., <15 mg/L alum; Appendix E) reflected typical practices at plants treating low turbidity, low DOC source water (Son & Wang, 2019). Here, 52 of the 60 filter runs conducted with sub-optimal particle destabilization failed to achieve the 3-log oocyst removal expectation of the SWTRs, despite filter effluent turbidities being well below 0.3 NTU in all cases and below 0.15 NTU in all but one run. These experiments further demonstrated that 3-log or higher *Cryptosporidium* oocyst removal can sometimes be achieved by filters (in eight of the 60 filter runs here) when particle destabilization by coagulant addition is sub-optimal because coagulant adsorption is rarely uniform, leading to the formation of localized regions or “patches” of charge that enable particle deposition on filter media surfaces even when the average zeta potential remains relatively far from zero; moreover, not all particle destabilization mechanisms are electrostatic (Gregory, 2006; Chapter 3). When particle destabilization was optimal, filter effluent turbidities were consistently below 0.3 and 0.1 NTU; overall effective log reductions of *Cryptosporidium* oocysts were 3-log or higher in all cases except one in which it was 2.9-log. This lower value was attributed to higher uncertainty attributable to lower processed sample volume that led to low oocyst counts and non-detects (Emelko et al., 2008; Chik et al., 2018). Notably, for the low turbidity, low DOC source waters, especially those with $\text{pH} > 7.5$, hydrolyzed alum species dominate and sufficient particle destabilization for maximizing filtration performance requires that the coagulation regime shifts (or at least starts to shift) from adsorption and charge neutralization to micro-precipitate formation and sweep flocculation (Stumm & O’Melia, 1968; Amirtharajah and Mills, 1982;

Amirtharajah and O'Melia, 1990; Crittenden et al., 2012; Chapter 3). At these conditions, higher coagulant doses are required to generate sufficient hydrolysis products to promote particle–coagulant interactions and achieve the destabilization needed for ≥ 3 -log removal by filtration (O'Melia, 1985; Tobiasson & O'Melia, 1988; Edzwald & Kelley, 1998).

The particle destabilization experiments align with previous investigations that have discussed the importance of coagulation prior to filtration (LeChevallier et al., 1991; Ongerth & Pecoraro, 1995; Patania et al., 1995; Edzwald & Kelley, 1998; Emelko, 2001; Huck et al., 2002; Emelko et al., 2005; Nascimento et al., 2020) and noted that sub-optimal coagulation can compromise *Cryptosporidium* oocyst removal by filtration (Hall et al., 1995; Patania et al., 1995; Huck et al., 2001; 2002; Emelko et al., 2004; 2005; Hendricks et al., 2005). They further emphasize the critical importance of ensuring sufficient coagulant addition in systems treating low turbidity, low DOC water—regardless of filter effluent turbidity—for ensuring particle destabilization so that particles, including oocysts, are effectively removed by physico-chemical filtration, which is sometimes referred to as “chemically-assisted” filtration (Chapter 3). Finally, they demonstrate that sole reliance on turbidity is insufficient for ensuring that 2.5- or 3-log removal of oocysts is achieved by filtration in systems treating low turbidity, low DOC source water because turbidity does not inform sufficiency of particle destabilization by coagulant addition in these systems. While zeta potential analysis can likely be useful for this purpose, confirmation of that capacity was beyond the scope of the present work and discussed elsewhere (Chapter 3).

It is important to note that when coagulant addition for particle destabilization was optimal, but the experiments were conducted during hydraulically unstable periods (i.e., filter ripening when flow pathways through the media are dynamic and adjusting toward pseudo-steady-state conditions and hydraulic surges reflecting transient, abrupt changes in the flow rate through the filters), filter effluent turbidities of less than 0.1 NTU were maintained, but *Cryptosporidium* oocyst removals by filtration were highly variable, ranging from 2- to 5-log (Figure 2.2). These observations are consistent with previous reports (Patania et al., 1995; Emelko, 2001; Huck et al., 2001; Amburgey et al., 2003; Emelko & Huck, 2004; Amburgey et al., 2005; Amburgey & Amirtharajah, 2005) and underscore that particle, including oocyst, removal by filtration is not guaranteed solely by sufficiency of particle destabilization; shifts in filter hydraulics can reduce particle removal efficiency.

The *Cryptosporidium* oocyst removals achieved by filtration at each of the different operating conditions investigated are summarized in Figure 2.3. The coagulant doses required to achieve optimal particle destabilization conditions reflect the adage that “cleaner” (i.e., low turbidity, low DOC) source water is

more difficult to treat, meaning that it requires a high coagulant dose relative to more turbid water to achieve sufficient particle destabilization for effective coagulation and filtration (O'Melia & Stumm, 1968). Collectively, the results in Figure 2.3 demonstrate that monitoring filter effluent turbidity alone is insufficient for ensuring that the 3-log *Cryptosporidium* oocyst removal expectations of the suite of SWTRs are achieved by filtration in systems treating low turbidity, low DOC source water. Additional guidance or tools are needed to ensure sufficient particle destabilization by coagulant addition so that maximal *Cryptosporidium* oocyst removal by filtration is reliably achieved. Zeta potential analysis is a useful tool for this purpose, but confirmation of its utility was beyond the scope of this investigation; it was reported in Chapter 3. Notably, this work also provides an extensive dataset that re-confirms the previously established regulatory expectation of 3-log *Cryptosporidium* oocyst removal from well-operated filtration processes during typical operating conditions when performance is stable (EPA, 2006a; Health Canada, 2012).

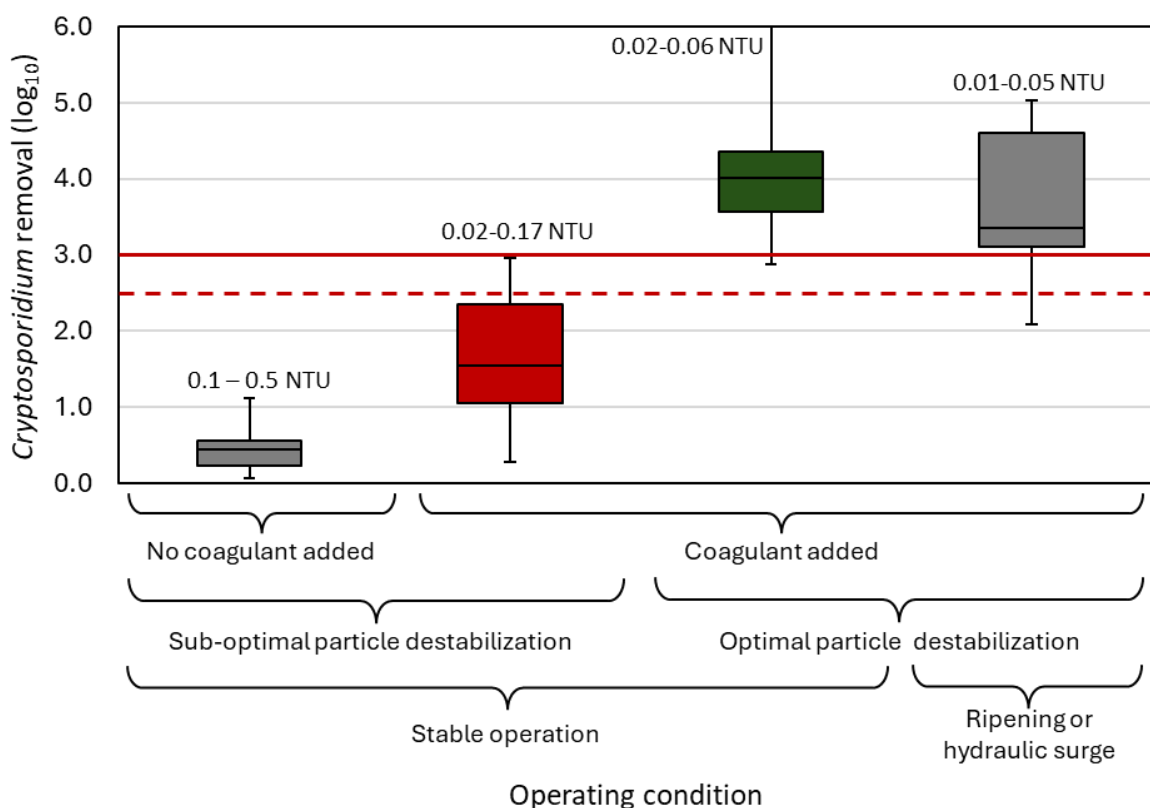


Figure 2.3. Overall effective log reduction of *Cryptosporidium* oocysts by pilot-scale filtration at different operational conditions. Each boxplot summarizes *Cryptosporidium* oocyst removals by filtration that were observed at each operational condition investigated, including coagulant addition and particle

destabilization for stable and ripening or hydraulic surge conditions. The whiskers in the box plots indicate maximum and minimum oocyst removals by CAF, while the boxes indicate the 75th and 25th percentile oocyst removals and the dashes indicate median (50th percentile) oocyst removal. The solid red line and dotted lines denote the 3-log and 2.5-log oocyst removal benchmarks, respectively, corresponding to the performance expected from well-operated conventional and direct filtration systems. The corresponding range of filter effluent turbidity for each operational condition is presented alongside the boxplots.

Despite their expected absence due to generally low environmental occurrence and expectations of removal by coagulation, flocculation, and sedimentation processes, naturally-occurring, environmental oocysts (as opposed to the oocysts that were introduced to the filter influent streams) were occasionally detected in negative control samples: filter influents and effluents collected prior to initiating any experimental pilot filter runs (Figure 2.4). On two occasions, forensic genotyping (Li et al., 2015) was conducted and confirmed that successfully genotyped oocysts were either *Cryptosporidium andersoni* or *Cryptosporidium* spp. Goose Genotype II in origin; as these are not human infective (LeChevallier & Norton, 1992; Ryan et al., 2021; Helmy & Hafez, 2022), they were not the inactivated *Cryptosporidium parvum* oocysts used during the pilot-scale experiments. It should be noted that samples that did not yield any genotype results do not necessarily indicate a lack of infective oocyst presence and these instances of environmental oocyst presence did not affect the overall study results because the few associated experiments were excluded from subsequent analyses.

Figures 4(a) and 4(b) are photomicrographs of the same field of view at 400x magnification, with changes made to the focal point of the image to demonstrate the depth of the clump of oocysts being observed. The same approach was used with Figures 4(c) and 4(d), which were captured at 200x magnification. The clumps of oocysts visible in these figures are approximately 250 μm in longest diameter and estimated to contain well over 500 oocysts. Figures 4(e) and 4(f) show oocysts as they appeared on the membrane surface during enumeration at 200x magnification. Figure 4(e) also shows other particulate material among the visible oocysts in filter effluent samples. Figure 4(f) show the presence of interior cellular structures typical of *Cryptosporidium* spp. oocysts (though not always visible under microscopy).

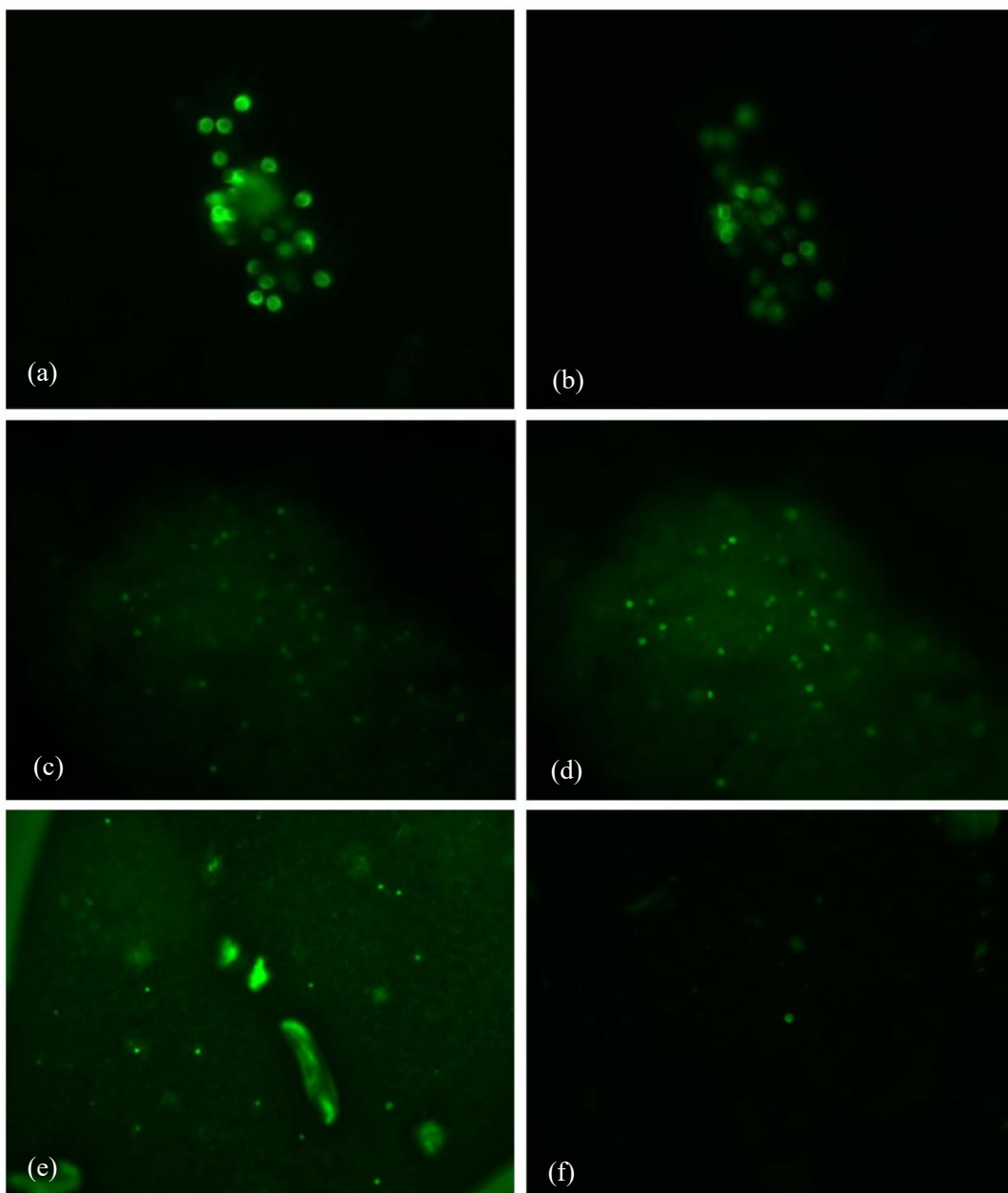


Figure 2.4. *Cryptosporidium* oocysts detected in negative control samples collected from filter influent and effluent streams. Images (a) through (d) are examples of oocysts detected in pilot-scale filter influent samples prior to any oocyst addition to filter influent streams. Images (a) and (b) show the same cluster of oocysts from different focal points to demonstrate the depth of oocyst clusters seen on some sample slides, as do images (c) and (d). Images (e) and (f) show examples of oocysts detected in filter effluent samples. Slides were enumerated using 200x magnification for initial scanning of the slide surface to ensure

sufficient oocyst staining had occurred, and at 400x magnification to detect potential interior structures in oocysts found.

The detection of confirmed *Cryptosporidium* oocysts in negative controls provides critical insights into chemical pretreatment (coagulation, flocculation, and sedimentation). The presence of oocysts in very small volume (i.e., 1 L) influent samples (e.g., as depicted in Figure 4(a) and (b)) is notable. While detection of oocysts in a negative control could be a result of sample contamination with seeded oocysts (i.e., oocysts intentionally added to filters during the pilot-scale experiments), this is unlikely due to pilot-plant cleaning (i.e., filter backwash using air scour before and after each individual experiment) between experiments. Instead, it may indicate the clarification process prior to filtration is not effectively removing them, likely due to insufficient particle destabilization and coagulation. Oocysts that enter filters without sufficient particle destabilization are unlikely to be removed by the filtration process. The clumps of oocysts in Figure 2.4 appear as if they may be trapped in fecal matter, which could contribute to poor oocyst removal by filtration and challenges with enumeration of oocysts (Ginn et al., 1992; Kuczyńska et al., 2005).

More critically, the occasional detection of *Cryptosporidium* oocysts in filter effluent streams (Figure 2.5e and 2.5f) was particularly concerning because it indicated unexpected oocyst passage through filtration processes during periods classified as stable operation. In these instances, filter effluent turbidity was 0.02 NTU, well below the 0.3 and 0.15 NTU thresholds used to define ‘well-operated’ conditions and to respectively justify 3-log and 3.5-log treatment credits under the LT2ESWTR (EPA, 2006a). Although oocyst reduction could not be quantified at those times because *Cryptosporidium* cannot be monitored in real time, the relatively high numbers detected in only 1 L of effluent were highly unexpected. Industry-wide experience and global consensus indicate that detection of even a few oocysts in much larger effluent volumes (e.g., 1000 L) is unlikely during well-operated treatment (LeChevallier and Norton, 1995; Gammie et al., 1998; Aboytes et al., 2004). Thus, the relatively elevated counts observed in at least three negative-control effluent samples during this investigation suggest that treatment at those times was not actually well-operated because of inadequate particle destabilization (associated with undetected under-dosing of coagulant) and associated *Cryptosporidium* passage through filtration processes as suggested in Figures 2.2 and 2.3 and discussed in detail in Chapter 3. This further supports the notion that turbidity is insufficient as an indicator of safe effluent water quality and further indicates that additional filter effluent sampling may be warranted.

Collectively, the data presented herein and the IJC (2021) report suggest that low-turbidity, low-DOC source waters pose unique challenges to ensuring filter performance in removing protozoan pathogens such

as *Cryptosporidium* because raw water turbidity may often be so low that it meets treated water targets (i.e., 0.3 NTU or lower). During such conditions, turbidity measurement cannot meaningfully inform coagulant dose selection; as a result, coagulant under-dosing, and consequently undetected inadequate filtration are likely and can lead to protozoan pathogen passage through treatment processes believed to be well-operated and in full compliance with the suite of SWTRs and their international counterparts.

The suite of SWTRs and their Canadian analogs were developed mostly using relatively deteriorated source waters (Appendix D), due to the assumption that waters with higher turbidity and DOC were more likely to contain protozoan contamination (Rose et al., 1988; LeChevallier & Norton, 1992; Chauret et al., 1995). Despite this development approach, these regulations are applied to drinking water treatment regardless of source water in question, resulting in reliance on turbidity to remain compliant despite minimal turbidity to interpret. Turbidity-based guidance works better under circumstances where turbidity is present.

2.3 Conclusions

1. Monitoring filter effluent turbidity alone is insufficient for universally ensuring removal of protozoan pathogens by filtration.
2. High-quality (i.e., low-turbidity, low-DOC) source waters pose unique challenges to ensuring *Cryptosporidium* oocyst removal by filtration. When aluminum-based coagulants are used to treat source waters with pH above ~7.5, particle destabilization by micro-precipitate formation that enables sweep flocculation is likely required for effective coagulation and filtration. As a result, relatively high coagulant doses are required to achieve minimum 3-log *Cryptosporidium* oocyst removal expectations,
3. Previously established regulatory expectations of 2.5- and 3-log *Cryptosporidium* oocyst removal by well-operated filtration during typical operating conditions when performance is stable remain reasonable and can be achieved in systems treating low turbidity, low DOC when particle destabilization by coagulant addition is sufficient, and
4. Guidance is needed to determine the coagulant doses required for achieving sufficient particle destabilization for well-operated filtration that achieves minimum 2.5- and 3-log *Cryptosporidium* removal expectations of the suite of SWTRs and their international counterparts in systems treating low turbidity, low DOC raw water.

2.4 Methods

2.4.1 General research approach

To highlight the risk of protozoan pathogen passage through drinking water systems that are compliant with current regulatory turbidity requirement, a review of published literature was first conducted. Studies were only included if they met the following criteria: i) filter challenge studies using *Cryptosporidium* oocysts, ii) less than 3-log removal was achieved, and iii) filters were “well-operated” as indicated by filter effluent turbidity (i.e., <0.3 NTU).

Following the literature review, the reliability of filter effluent turbidity as an indicator of *Cryptosporidium* oocyst removal by filtration systems treating high-quality source water was evaluated at pilot-scale. Filter configurations and loading rates were representative of full-scale systems treating low turbidity, low DOC source waters. Performance demonstrations were conducted by introducing oocyst seed suspensions directly into the filter influent streams, a common approach for assessing pathogen removal by filtration (e.g., Nieminski and Ongerth, 1995; Huck et al., 2001; Huck et al., 2002; Emelko, 2003; Emelko and Huck, 2004; Assavasilavasukul et al., 2008; Hijnen and Medema, 2010; Nascimento et al., 2020; Lee et al., 2018; Ballantyne 2024).

A total of 119 filter runs were conducted at both warm ($\geq 8^{\circ}\text{C}$) and cold ($< 8^{\circ}\text{C}$) raw water temperatures producing 600 filter effluent samples. High influent oocyst concentrations ($\sim 10^5$ oocysts/L) were used to ensure quantifiable recovery in effluent samples and minimize uncertainty in log removal estimates (Emelko et al., 2008). Raw water received a constant coagulant dose typical of Lake Ontario source water treatment: 4–9 mg/L alum (Train 1) and 0.9–1.0 mg/L PACl (Train 2) as shown in Figure 2.6. Seed suspensions were coagulated prior to introduction to the filter influent to create a range of particle destabilization conditions informed by zeta potential analysis.

In this study, optimal particle destabilization was operationally defined as described in Chapter 3; specifically, it was the post-coagulant addition symmetrical zeta potential range (i.e., either positive or negative) of the seed suspension around 0 mV that consistently led to 3-log or higher oocyst removal by CAF. Thus, this was retroactively identified based on the *Cryptosporidium* oocyst removal; specifically, the most negative zeta potential value at and above which *Cryptosporidium* removal by CAF was always 3-log or greater was identified by visual estimation and the resulting zeta potential range for optimal particle destabilization was plus or minus ($\pm$) that value around 0 mV. Post-coagulant addition seed suspension zeta potentials outside of this range were thus considered sub-optimal particle destabilization.

2.4.2 Pilot plant overview and operational conditions

Pilot-scale filtration experiments were conducted between 2017 and 2022 at the R.C. Harris Water Treatment Plant (WTP) in Toronto, Ontario, Canada, with a smaller subset of experiments performed at the Horgan WTP also located in Toronto. Both facilities operated pilot-scale systems receiving raw water from Lake Ontario. Experiments conducted at Horgan WTP followed the same methodology and operational approach as those at Harris WTP but were conducted in a smaller pilot plant. As the majority of testing was performed at the Harris WTP, the detailed system description provided below focuses on the Harris pilot facility; comprehensive details of the Horgan pilot configuration are available in Appendix A.

The full-scale Harris WTP draws raw water through two intake pipelines that extend 1.3 km into Lake Ontario at a depth of 15 m. The intake water is pre-chlorinated to maintain a chlorine residual throughout the treatment process and to inhibit the growth of invasive species. A portion of this pre-chlorinated water is diverted to supply the pilot-scale system. During the investigation, raw water had a free chlorine residual of ~ 0.29 mg/L and a total chlorine residual of ~ 0.45 mg/L.

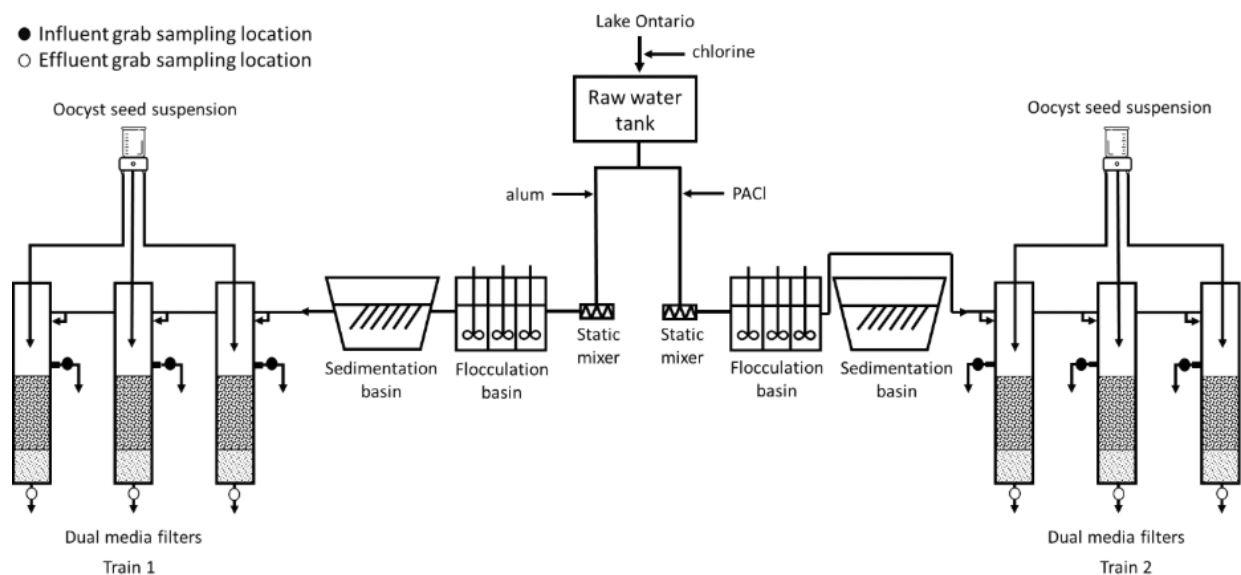


Figure 2.5. Schematic flow diagram of pilot-scale filtration plant at R.C. Harris WTP, Toronto (not to scale). Train 1 was representative of conventional filtration (i.e., flocculation, sedimentation, and filtration) whereas Train 2 was representative of direct filtration (i.e., flocculation and filtration). For performance demonstration studies, a *Cryptosporidium* oocyst seed suspension was continuously introduced into the filter influents, and influent and effluent grab samples were collected to estimate overall oocyst removal achieved by the process.

Average raw water turbidity and pH in the pilot plant were 0.37 ± 0.29 NTU and 8.1 ± 0.32 , respectively, compared to 0.33 ± 0.23 NTU and 8.0 ± 0.15 in the full-scale plant. Although total organic carbon (TOC) was not routinely monitored at the pilot, full-scale values averaged 1.8 ± 0.01 mg/L. These raw water quality parameters remained consistent across all studies and further details can be found in Appendix E and L.

Cryptosporidium oocyst removal by conventional filtration and direct filtration was investigated at pilot-scale in a constant head, constant flow operational mode using conventional filter media designs and hydraulic loading rates (HLR) consistent with those used by systems reliant on high-quality Great Lakes supplies. The coagulated or settled water in each treatment train was then directed to a rack of three granular media filter columns, each with an internal diameter of 15 cm and a height of 5 m. Configurations 2B and 4B are those that were investigated at the Horgan WTP (Appendix A).

Table 2.1. Pilot-scale configurations and operational conditions

Filter #		1	2		3	4		
			A	B		A	B	C
Coagulant		alum	alum	alum/PACl	alum	PACl	alum/PACl	PACl
HLR (m/h)		2 or 4.6	2 or 4.6	9.8 – 24.4	2 or 4.6	4.6	9.8 – 24.4	4.6
Media depth (mm)	Anthracite	250	450	450	1000	900	450	1500 (GAC)
	Sand	250	300	300	300	300	300	300

2.4.3 *Cryptosporidium* oocyst suspension preparation, addition, and sample collection

Stock solutions of *Cryptosporidium parvum* oocysts (P102C, 5% formalin-inactivated, without Tween®20, ~50 mL in 1× phosphate buffer solution (PBS); Waterborne, Inc., New Orleans, LA, USA) were stored at 4 °C in the dark until use. For each experiment, oocysts from the stock solution were vortexed and then added to 2 L of raw water to achieve a target influent concentration of $\sim 10^5$ oocysts/L ($\sim 10^7$ total oocysts), selected to yield 30–100 oocysts per slide (Emelko et al., 2008). For Horgan WTP experiments, a 2.5 L seed suspension was prepared with a filter influent target concentration of 10^4 – 10^5 oocysts/L (Scott, 2008).

The seed suspension was placed on a jar test apparatus (PB-700, Phipps and Bird, Richmond, VA, USA) and mixed with coagulant (alum ($\text{Al}_2(\text{SO}_4)_3 \cdot 14(\text{H}_2\text{O})$) and PACl; ChemTrade Logistics, Toronto, Canada) to destabilize oocysts prior to introduction at the filter influents. Zeta potential analysis (see Section 2.4.5) was used: (i) before oocyst addition to raw water, (ii) after oocyst addition and 1 min of mixing at 80 RPM, and (iii) after 1 min of mixing following alum or PACl addition, to evaluate particle destabilization in the seed suspension. After coagulant addition the seed suspension was continuously stirred to maintain uniform

oocyst distribution and was introduced into filter influent streams (Figure 2.6) via a peristaltic pump (Masterflex, Avantor, ON, Canada) at 5 mL/min for 90 min at Harris WTP and for 60 minutes at Horgan WTP (Scott, 2008).

Influent and effluent grab samples were collected in sterilized glass vials (40 mL) and bottles (1 L), respectively. Sampling began at time zero (T0), coinciding with the start of oocyst seeding; these initial samples served as negative controls for each experiment. Effluent samples were then collected every 15 minutes for 90 minutes, with an additional sample at 105 minutes, 15 min after seeding ceased, to confirm the expected decline in oocyst concentrations. Seeding and sampling occurred following a filter backwashing (typically 24 hours prior) at stable operating conditions with consistent effluent turbidity. Effluent samples were collected for 5 minutes from a continuously running effluent line for each filter, while influent samples were collected over 30 s from a port above the filter media (Figure 2.6) after the line had been flushed for at least 15 s. The timing of sample collection relative to turbidity and seeding is illustrated in Figure 2.7. Pilot-scale experiments at the Horgan WTP followed the same procedures, with influent and effluent samples collected at 10-minute intervals (Scott, 2008).

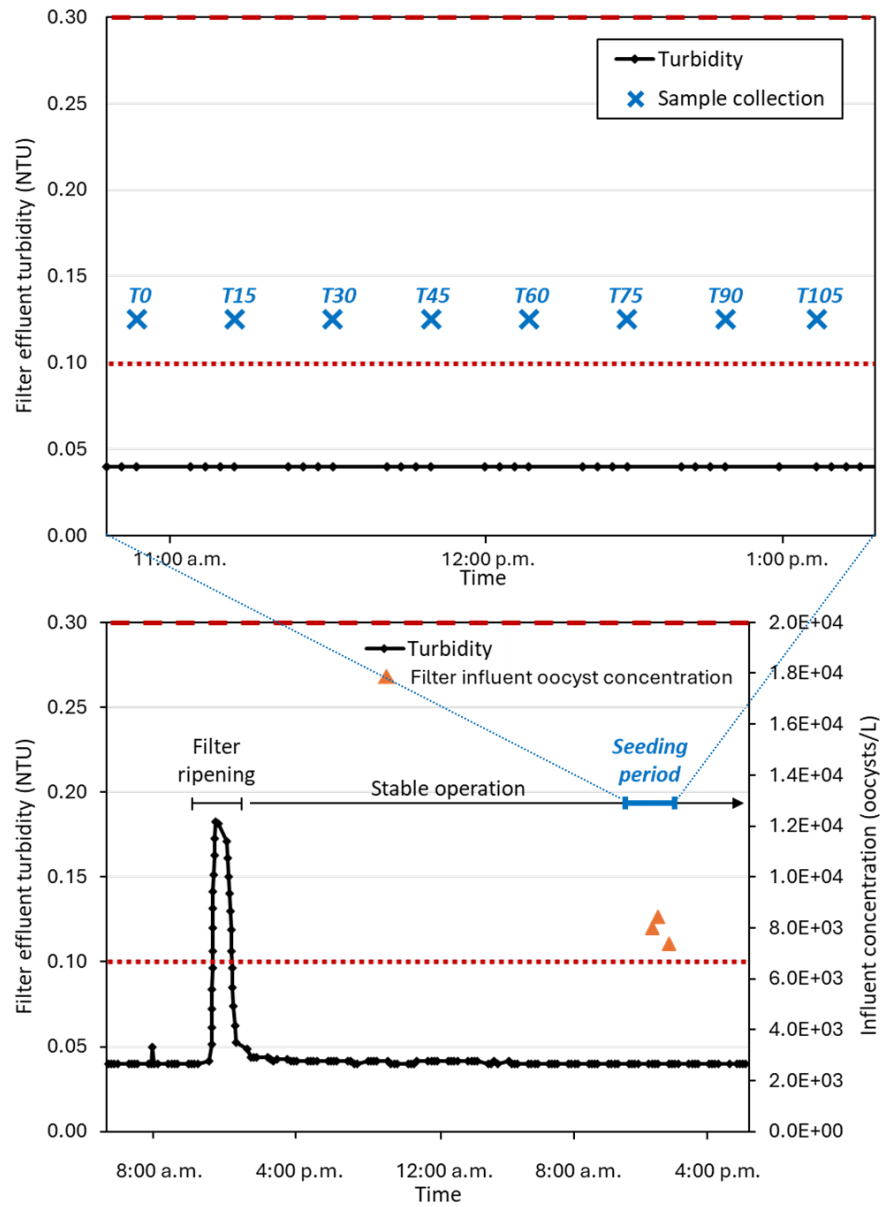


Figure 2.6. Sample collection timing relative to turbidity during a typical filter run (as shown and described by Figure 2.2). Turbidity changes are shown throughout the run, highlighting *Cryptosporidium* oocyst seeding and sampling stable operation. The inset provides higher-resolution timing of paired influent and effluent sample collection within the seeding period. Dotted lines at 0.3 NTU and 0.1 NTU indicate turbidity thresholds from the EPA, AWWA Partnership for Safe Water, and the Canadian Drinking Water Quality Guidelines.

2.4.4 *Cryptosporidium* concentration, identification, and enumeration

Cryptosporidium oocysts in filter influent and effluent samples were concentrated, identified, and enumerated using membrane filtration and immunofluorescence assay (IFA), followed by fluorescence microscopy at 400x magnification. All glassware was rinsed with detergent (1× PBS with Tween 80 [PBST]) and then with PBS prior to use. For effluent samples, 700 mL–1 L were processed, with volumes measured using glass graduated cylinders. For influent samples, only 1–5 mL of the collected 40 mL grab sample was analyzed due to the high oocyst concentrations at the influent. For the membrane filtration step, samples were vacuum-filtered through polycarbonate membranes (0.4 µm nominal porosity; Whatman Nuclepore®, GE Healthcare, Mississauga, ON, Canada)—25 mm filters for effluent and 12 mm filters for influent samples—at –21 in Hg (–533 mm Hg). IFA stain (Crypt-a-Glo, Waterborne Inc., New Orleans, LA, USA) was then applied directly and evenly to the filter membrane surface, which were incubated in a humidified chamber in the dark at 35 °C for ≥30 min and subsequently mounted on glass slides for enumeration using fluorescence microscope (Axioskop 2 Plus, Zeiss, Göttingen, Germany).

For each filter run, average filter influent and effluent oocyst concentrations were used to calculate percent oocyst reduction and the logarithm of this value was used to determine the effective log reduction of *Cryptosporidium* oocysts for each run (Teunis et al., 2009; Schmidt et al., 2020).

Conventional statistical analyses such as the determination of confidence intervals for *Cryptosporidium* oocyst removal data were not conducted as such analyses are limited by the non-normality and non-uniform variance of oocyst removal data (Emelko et al., 2008, 2010). *Cryptosporidium* oocyst count data are discrete in nature and therefore associated with uncertainty that is asymmetric with very low counts and depended on concentration (i.e., heteroscedastic), making traditional confidence interval approaches inappropriate. To incorporate analytical uncertainties associated with the methods used to collect the data and to produce intervals that better represent uncertainty in removal performance, approaches using Bayesian methods and credible intervals have been proposed (Emelko et al., 2010). However, there is currently no single agreed-upon method for calculating such intervals for *Cryptosporidium* oocyst removal. Consequently, *Cryptosporidium* oocyst removal data are often reported without statistical intervals (LeChevallier et al., 1991; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2001, 2002; Emelko et al., 2005; Hashimoto et al., 2001; Mazoua and Chauveheid, 2005; Ballantyne et al., 2024). For these reasons, and consistent with regulatory practice (EPA, 2006a; Health Canada, 2012) which relies on average levels of removal rather than average values with associated statistical bounds, log removal values in this study are reported as point estimates.

2.4.5 Water quality analysis

2.4.5.1 Turbidity

Online turbidity monitoring of raw and effluent water at the pilot-plant was conducted utilizing the HACH 1720E continuous reading nephelometric turbidimeter (HACH, London, ON, Canada) and Filter Trak 600 Laser Nephelometer (HACH, London, ON, Canada), respectively. The SCADA (Supervisory Control and Data Acquisition) data logging program records turbidity readings at 15-minute intervals except when a turbidity shift of 0.01 NTU or more occurs. In such cases, the recording time is changed to an interval of one minute. The turbidity trend is refreshed every 0.5 seconds on SCADA, with historical updates occurring every 30 seconds. It is important to highlight that the turbidity monitoring approach implemented at the pilot scale mirrors the methodology employed at the full-scale treatment plant.

2.4.5.2 Zeta potential

Zeta potential was evaluated using a ZetaSizer Nano Z analyzer (Malvern Panalytical, Mississauga, ON, Canada). A 10 mL aliquot was taken from the main sample and passed through the measurement cuvette for rinsing; however, only 0.75 mL was retained in the cuvette for the measurement. For each sample, the ZetaSizer was configured to perform three runs (triplicates), with each run consisting of an average of up to 50 individual zeta potential readings (though the maximum number of readings was not always required). Reported zeta potential values were calculated as the average of the three obtained values for each sample. Between each run, the syringe used for sample collection and the measurement cartridge were thoroughly rinsed with ultrapure Milli-Q™ Type I water (resistivity >18 MΩ·cm; conductivity <0.056 µS/cm; <50 ppb total organic carbon [TOC]).

While quantitative analysis of zeta potential data is desirable, it is not possible because the raw data are not available. Although some instruments like the one used herein reports a “zeta deviation,” it cannot be readily used because the underlying distribution is unknown. This is especially relevant following coagulant addition because some particles may be preferentially destabilized thereby altering the underlying distribution of particle (including *Cryptosporidium* oocyst) zeta potentials. Variability between repeated runs was evaluated and found inconsequential (i.e., typically within 1-2 mV). Accordingly, zeta potential is reported herein as average values only.

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Chapter 3. Determining sufficient coagulant addition to ensure protozoan pathogen removal by filtration when reliance on turbidity is inadequate

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Summary

Physico-chemical filtration—also known as “chemically-assisted” filtration (CAF)—is critical for ensuring removal of the parasitic protozoan *Cryptosporidium* during drinking water treatment. The suite of U.S. Surface Water Treatment Rules (SWTRs) and their Canadian analogs prescribe treatment credits for *Cryptosporidium* and *Giardia* removal based on filtered water turbidity targets believed to reflect well-operated treatment, particularly CAF performance. However, recent work has revealed that sole reliance on filtered water turbidity is inadequate for ensuring the assumed 3-log or greater oocyst removal in systems reliant on high-quality (i.e., low turbidity, low dissolved organic carbon concentration) source water. In these systems, raw water turbidity often meets or exceeds filtered water targets, making it difficult to verify adequate coagulant dosing for effective CAF performance. While the role of coagulant in destabilizing particles (including oocysts) for effective removal by CAF is generally recognized, its crucial importance for their removal from high-quality source waters and the high potential for underdosing in these systems have not been discussed. Here, a series of pilot-scale investigations of *Cryptosporidium* oocyst removal by CAF were conducted in a system reliant on relatively high-quality source water. Results from 600 individual analyses showed that oocyst removal was especially dependent upon sufficiency of oocyst destabilization, which could be assessed using post-coagulation zeta potential analysis. While zeta potential itself is not a direct indicator of CAF performance, it reliably signaled sufficiency of oocyst destabilization by coagulant addition, which is needed to maximize oocyst removal by CAF. Post-coagulation zeta potential within ± 5 mV of zero (0 mV) was needed to consistently achieve 3-log or greater oocyst removal by CAF. The coagulant doses that were required to achieve this level of destabilization were higher than those typically expected for systems treating high-quality source waters, emphasizing that sole reliance on filter effluent turbidity as an indicator of sufficient chemical pre-treatment (i.e., coagulation) prior to CAF results in a high potential for underdosing in systems reliant on high-quality source water. Thus, this work emphasizes that “treatment technique” based drinking water regulations that aim to protect public health

from waterborne protozoa would benefit from additional guidance to ensure that performance expectations are achieved—zeta potential analysis could advance such guidance for systems reliant on high-quality source water.

3.1 Introduction

Both outbreaks and endemic waterborne disease remain significant threats to public health; they are among the most common and widespread health risks associated with drinking water (Ramírez-Castillo et al., 2015; Lee et al., 2023; Kunz et al., 2024). As such, control of microbial contamination during drinking water treatment is of utmost importance and must never be compromised (World Health Organization, 2017). Human-infectious protozoa, including *Cryptosporidium* spp. and *Giardia duodenalis* (*Giardia lamblia*), are of particular concern. While *Giardia* is the most reported waterborne protozoan globally, *Cryptosporidium* is often a focus due to its resistance to traditional oxidant-based disinfection processes such as chlorination. UV irradiation can inactivate *Cryptosporidium* oocysts; however, its effectiveness depends on adequate filtration to reduce particle loads and prevent shielding effects (Templeton et al., 2005; Mamane and Linden, 2006). Thus, physico-chemical filtration—often referred to as “chemically assisted filtration” (CAF)—remains a critical and required treatment barrier for ensuring *Cryptosporidium* oocyst removal during drinking water treatment.

Treated water protozoa concentrations are not monitored because of impracticalities associated with analyzing the extremely large water volumes that would be required to detect them (Regli et al., 1991; Haas et al., 1996). As well, the methods for their analysis are expensive, time consuming, and sometimes unreliable (Signor and Ashbolt, 2006). Instead, a “treatment technique” (i.e., treatment-based) approach was developed in which “indicators” such as filter effluent turbidity are relied upon to reflect treatment sufficiency. Under U.S. EPA’s suite of Surface Water Treatment Rules (SWTRs) and their Canadian analogs, conventional water treatment (i.e., CAF) plants are considered “well-operated” and in compliance—and granted a 3-log *Cryptosporidium* oocyst removal credit—when combined filter effluent turbidity is less than or equal to 0.3 NTU (nephelometric turbidity unit) in at least 95 percent of measurements taken each month (EPA, 2006a; Health Canada, 2019). The U.S. Long-term 2 Enhanced SWTR (LT2ESWTR) provides an additional 0.5-log *Cryptosporidium* oocyst removal credit when individual filter effluent turbidity is less than or equal to 0.15 NTU in at least 95 percent of samples collected from individual filters during each month and is never greater than 0.3 NTU in two consecutive measurements from any filter (EPA, 2006a). The Guidelines for Canadian Drinking Water Quality (Health

Canada, 2012) and the U.S. Partnership for Safe Water program (EPA, 2012) further encourage water systems to strive for an individual filter effluent turbidity level of ≤ 0.1 NTU 95% of the time, excluding the 15-minute period following filter backwash. This goal is seen as a benchmark for optimizing treatment processes and improving water quality.

Cryptosporidium oocyst removals ranging from less than 1-log to greater than 5-log have been reported for CAF processes considered “well-operated” (Nieminski and Ongerth, 1995; Patania et al., 1995; Emelko, 2003; Emelko et al., 2005; Assavasilavasukul et al., 2008; Chapter 2). There are many cases in which less than 3-log removal of oocysts has been reported even though filter effluent turbidity values are below 0.3 NTU and even 0.1 NTU (Chapter 2). In some cases, low *Cryptosporidium* oocyst removals by CAF may be attributed to low counts (Emelko et al., 2008), non-detects (Chik et al., 2018), and variable analytical recovery (Emelko et al., 2010), which can contribute orders-of-magnitude to uncertainty in particle/oocyst count and removal estimates. Nonetheless, these factors do not fully explain all cases where *Cryptosporidium* oocyst removal by CAF is less than 3-log. A recent investigation demonstrated that insufficient coagulant addition prior to CAF may explain several such observations of less than 3-log oocyst removal in systems reliant on high-quality source water (Ballantyne et al., 2024; Chapter 2). In this context, “high-quality” refers specifically to low particle and organic carbon content in the water (turbidity < 2 NTU, dissolved organic carbon [DOC] < 2 mg/L), not to broader ecosystem health.

Adequate coagulant addition prior to CAF is essential for ensuring removal of particles, including oocysts, because CAF is not a size exclusion process; rather, it depends on particle destabilization and subsequent attachment (AWWA, 1999; Crittenden et al., 2012; Edzwald, 2013; Ballantyne et al., 2024). Most particles and microorganisms (e.g., *Cryptosporidium* oocysts, microplastics, filter media grains) suspended in or in contact with natural water carry a negative surface charge, largely due to the presence of natural organic matter (NOM). This net charge affects how they interact with other particles and surfaces (also predominantly negatively charged in natural waters) because it results in repulsive interaction forces that stabilize the particles, preventing their aggregation and deposition on surfaces such as filtration media (O’Melia and Stumm, 1967; Edzwald, 2013), therefore coagulant addition is essential prior to CAF. Physico-chemical filtration is more than mere physical straining: particle destabilization by coagulant addition reduces electrostatic repulsion and promotes attachment between particles (including oocysts) and filter media, thereby enabling their efficient removal (AWWA, 1999; Crittenden et al., 2012; Tobiason and O’Melia, 1988)—this is why filtration is sometimes referred to as “chemically-assisted filtration”.

Importantly, low untreated/source water turbidity does not necessarily indicate the absence of waterborne pathogens (Aboytes et al., 2004). In systems where source and clarified water turbidity may already be so low that they meet treated water turbidity targets, sole reliance on turbidity is insufficient for determining coagulant addition needed to ensure particle and oocyst destabilization for effective removal by CAF (Ballantyne et al., 2024; Chapter 2). Low particle concentrations limit the collisions and interactions needed for effective destabilization and may require higher than expected coagulant doses to promote micro-precipitate formation and increase contact opportunities. In such cases, zeta potential analysis, which indicates net charge at the boundary layer of particles suspended in water, should be useful for informing coagulant dosing needs. Particle destabilization is maximized when zeta potential is close to 0 mV and repulsion forces are minimized. While the use of zeta potential analysis to guide coagulant dosing in water treatment is not novel, its widespread adoption in the drinking water industry has been limited due to lack of optimization guidance. Most reported investigations of zeta potential analysis in drinking water treatment have focused on process optimization to minimize clarified (settled) water turbidity or maximize DOC removal (Bean et al., 1964; Gupta et al., 1975; Jefferson et al., 2004; Morfesis et al., 2009; Waller et al., 2012; Zimoch and Mroczko, 2020), not to ensure CAF performance.

Here, use of zeta potential analysis was investigated at pilot scale to determine the level of coagulant addition needed to achieve at least 3-log *Cryptosporidium* oocyst removal by CAF and to develop system-specific guidance on zeta potential targets. Thus, the importance of coagulation and sufficient particle destabilization for effective oocyst removal by CAF in systems reliant on high-quality source waters was also assessed.

3.2 Methods

3.2.1 Research approach

Cryptosporidium oocyst removal by conventional CAF was investigated from September 2022 to April 2026 at pilot scale using filter media designs and loading rates consistent with those used by systems reliant on high-quality source waters. These pilot-scale filter performance demonstrations (i.e., challenge tests) involved addition of oocysts to filter influent streams—a method that has been widely reported (Nieminski and Ongerth, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Emelko, 2001; Huck et al., 2001; Emelko, 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Emelko et al., 2005; Assavasilavasukul et al., 2008; Scott, 2008; Brown and Emelko, 2009; Hijnen and Medema, 2010; Lee, 2018; Ballantyne et al., 2024) and is commonly used to or quantifying pathogen removal and setting performance targets. A high-

concentration oocyst seed suspension was prepared and introduced at the filter influent to provide reliable treatment performance data. The use of high oocyst concentrations ensured that oocyst counts in the filter effluent were high enough (i.e., >10 oocysts per sample) to improve precision by avoiding random sampling error contributing more than an order of magnitude uncertainty in log removal estimates (Emelko et al., 2008).

A total of 119 individual experiments (filter runs), culminating in 600 individual effluent samples, were conducted to evaluate *Cryptosporidium* oocyst removal by conventional CAF at pilot scale. The filter runs were conducted using a range of zeta-potential-informed coagulant doses in the oocyst seed suspension to represent different destabilization conditions and filter media configurations, operated at both warm (≥ 8 °C) and cold (< 8 °C) raw water temperatures. Coagulant was added both to the pilot plant's raw water—consistent with typical practice for systems treating high-quality source water, including the one supplying the pilot—and to the oocyst seed suspension that was introduced at the filter influent. Oocyst addition alters raw water quality, sometime so much that it can be measured as a change in turbidity. Regardless, it affects coagulant demand relative to raw water alone (Appendix C). Since the focus of this study was *Cryptosporidium* oocyst removal by CAF, emphasis was placed on the destabilization of oocysts within the seed suspension. Accordingly, coagulant doses applied to the seed suspension were varied to produce a range of particle destabilization conditions (informed by zeta potential) and to observe corresponding removal performance.

Zeta potential values near 0 mV indicate minimized electrostatic repulsion and are therefore commonly associated with effective CAF (AWWA, 1999; Crittenden et al., 2012; Tobiason and O'Melia, 1988). However, filtration performance is not governed solely by electrostatic conditions, and the degree of particle destabilization required to achieve ≥ 3 -log *Cryptosporidium* oocyst removal varies among systems. Removal may occasionally occur even when zeta potential values indicate incomplete destabilization, because coagulant adsorption is heterogeneous and can produce localized zones or “patches” of charge that can promote attachment on filter media, and because destabilization mechanisms beyond electrostatic interactions—such as those involving enmeshment and precipitation—also contribute to particle capture and removal (Tobiason and O'Melia, 1988; Duan & Gregory, 2003; Gregory, 2006). In low-turbidity, low-DOC source waters, particularly with pH >7.5 where alum coagulation is practiced, particle destabilization will be driven by electrostatic mechanisms (i.e., adsorption and charge neutralization) directly informed by zeta potential analysis and the formation and transport of aluminum hydroxide micro-precipitates that increase contact opportunities; the primary particle destabilization regime will depend on applied coagulant

dose (Stumm and O'Melia, 1968; Amirtharajah and Mills, 1982; Amirtharajah and O'Melia, 1990; Crittenden et al., 2012). In this study, optimal particle destabilization was operationally defined as the post-coagulant addition symmetrical zeta potential range (i.e., either positive or negative) of the seed suspension around 0 mV that consistently led to 3-log or higher oocyst removal by CAF. Thus, this was retroactively identified based on the *Cryptosporidium* oocyst removal; specifically, the most negative zeta potential value at and above which *Cryptosporidium* oocyst removal by CAF was always 3-log or greater was identified by visual estimation and the resulting zeta potential range for optimal particle destabilization was plus or minus ($\pm$) that value around 0 mV. Post-coagulant addition seed suspension zeta potentials outside of this range were thus considered sub-optimal particle destabilization. While it is recognized that zeta potential analysis does not reflect all particle destabilization mechanisms, it is particularly useful for identifying the transition between (i) adsorption and charge neutralization and (ii) sweep flocculation coagulation regimes where particle destabilization is most likely to be optimal in systems treating natural low turbidity and low DOC source waters (Stumm & O'Melia; 1968).

For all filter runs, the coagulant doses applied to the pilot plant raw water were maintained at levels typical of common practice for high-quality source water; specifically, 4 to 9 mg/L of aluminium sulfate (alum) and 0.3 to 1 mg/L of polyaluminum chloride (PACl). These doses corresponded to sub-optimal particle destabilization (as indicated by zeta potential) across all pilot filter runs. In the no-coagulant addition filter runs, no coagulant was added to either the pilot plant raw water or the oocyst seed suspension.

3.2.2 Pilot-scale treatment plant

Experiments were almost exclusively conducted at the R.C. Harris Water Treatment Plant (WTP) in Toronto, Ontario, Canada, with a small subset (36 of 119 individual filter runs) performed at the Horgan WTP in Toronto (all at sub-optimal or no particle destabilization conditions and only four conducted with zeta potential analysis). Both facilities employed pilot-scale systems receiving raw water from Lake Ontario. Experiments performed at Horgan WTP followed the same methodology and operational approach as those at Harris WTP but were conducted in a smaller pilot plant. Since experiments were predominantly conducted at the Harris WTP, the detailed description below focuses on its pilot plant, while full details of the Horgan pilot plant can be found in Appendix A.

The Harris WTP intake is located 1.3 km from the plant at a depth of 15 m. Raw water quality during the experiments was generally consistent, with key parameters as follows (mean $\pm$ standard deviation): turbidity 0.33 ± 0.23 NTU, pH 8.0 ± 0.15 , and total organic carbon (TOC) 1.8 ± 0.01 mg/L. The pilot system includes

a comprehensive treatment sequence of coagulation, flocculation, sedimentation, and dual media filtration, handling 2–10 m/h hydraulic loading rates (HLR). This setup closely mirrors the operational conditions of the full-scale plant on a smaller scale housed within a two-story structure at the Harris WTP. It allows simultaneous testing of up to six filter column configurations across two separate trains, with three columns in each train (Figure 3.1). Raw water was pre-chlorinated initially and pumped to a constant head reservoir and then directed through an in-line static mixer, followed by a flocculation basin and a sedimentation basin in Train 1. By bypassing the sedimentation basin, Train 2 is configured to simulate direct CAF. The coagulated or settled water in each treatment train was then directed to a rack of three granular media filter columns, each with an internal diameter of 15 cm and a height of 5 m. Coagulant (either alum or PACl) was added prior to the static mixer.

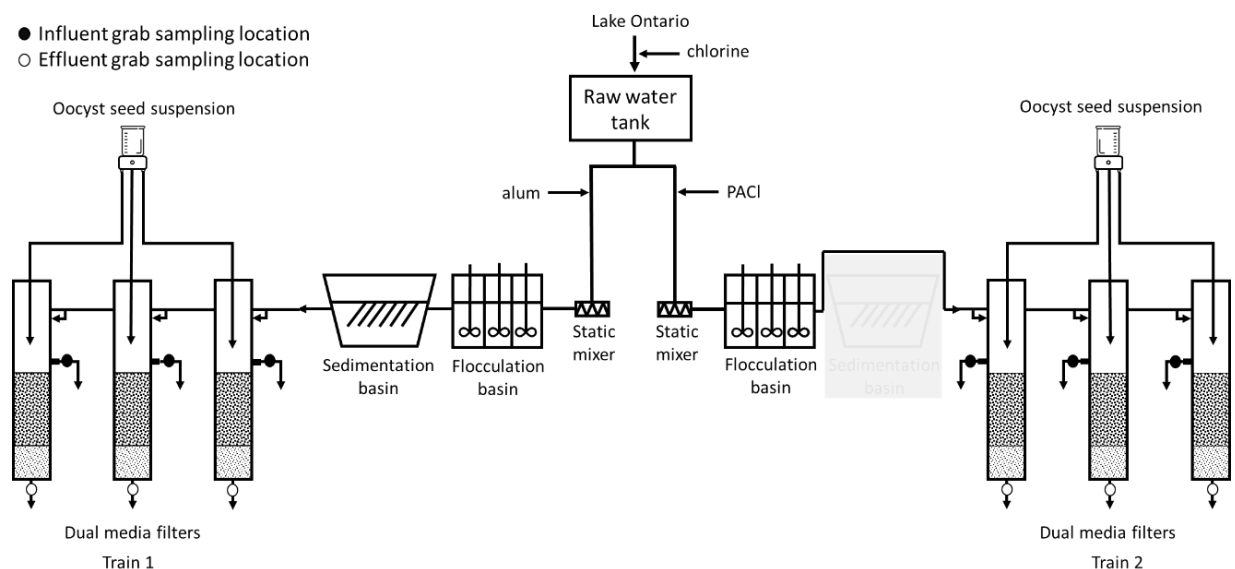


Figure 3.1. Schematic flow diagram of pilot-scale filtration plant at R.C. Harris WTP, Toronto. The study examined *Cryptosporidium* oocyst removal by CAF with conventional filter media designs and loading rates comparable to those used by systems dependent on high-quality Great Lakes water (detailed in Table 3.1). During the experiments, a continuous input of *Cryptosporidium* oocyst seed suspension was introduced to the filters. Influent and effluent grab samples were collected to estimate *Cryptosporidium* oocyst removal by the filters.

Seven conventional filter media configurations and loading rates consistent with those used by systems reliant on high-quality Great Lakes supplies were investigated, as shown in Table 3.1. Configurations 2B and 4B are those that were investigated at the Horgan WTP (Appendix A). It is important to note that the

filter runs conducted using these filter designs were not intended to directly compare operational conditions but were instead grouped to highlight trends based on three comparisons: (1) coagulant added vs. no coagulant, (2) optimized vs. unoptimized particle destabilization, and (3) stable filter operation vs. periods of ripening or hydraulic surge.

Table 3.1. Pilot-scale filter configurations and operational conditions investigated.

Filter #		1	2		3	4		
			A	B		A	B	C
Coagulant		alum	alum	alum/PACl	alum	PACl	alum/PACl	PACl
HLR (m/h)		2 or 4.6	2 or 4.6	9.8 – 24.4	2 or 4.6	4.6	9.8 – 24.4	4.6
Media depth (mm)	Anthracite	250	450	450	1000	900	450	1500 (GAC)
	Sand	250	300	450	300	300	300	300

3.2.3 *Cryptosporidium* handling and analysis

3.2.3.1 *Cryptosporidium* seed suspension preparation and addition to filters

Cryptosporidium parvum oocysts (P102C) inactivated with 5% formalin (final concentration) in approximately 50 mL of 1x phosphate buffered saline (PBS) were obtained from Waterborne, Inc. (New Orleans, LA, USA) without Tween® 20. The *Cryptosporidium* stock suspensions were refrigerated at 4 °C in the dark until use. In this study, oocysts from the stock suspension were vortexed and then added to 2 L of pre-chlorinated raw water to prepare a seed suspension with a target concentration of approximately 10^7 oocysts/L, resulting in an expected concentration of $\sim 10^5$ oocysts/L in the filter influent and at least 10 oocysts in each filter effluent sample. For Horgan WTP experiments, a 2.5 L seed suspension was prepared with a filter influent target concentration of 10^4 – 10^5 oocysts/L (Scott, 2008). The seed suspension was then mixed (PB-700, Phipps and Bird, Richmond, VA, USA) with coagulant to destabilize the oocysts prior to introducing them to filter influent streams. Zeta potential analysis (detailed in section 3.2.4) was used to evaluate particle and oocyst destabilization by alum or PACl coagulant addition. The seed suspension was continuously fed into the three filter influent streams (Figure 3.1) with a peristaltic pump (Masterflex, Avantor, Inc., ON, Canada) at 5 mL/min for 90 minutes at Harris WTP and 60 minutes at Horgan WTP (Scott, 2008). To ensure uniform distribution of oocysts during filter runs, the seed suspension was continuously mixed with a magnetic stirrer.

3.2.3.2 Sample collection

Grab samples were collected from both filter influents and effluents (Figure 3.1) in sterilized clear glass vials and bottles, respectively. Sample collection commenced at time zero (T0) when seeding was initiated. These T0 samples served as negative controls for each filter run. Samples were subsequently collected from the filter effluent every 15 minutes for 90 minutes following the start of the seeding process. Tracer studies conducted at the Harris pilot plant indicated that the water residence time between the seed suspension addition point and the influent sample collection location was approximately 15-20 minutes (Appendix B). Hence, the first sample after T0 was collected at T15. An additional sample at 105 minutes was collected to confirm a steady reduction in oocyst concentrations after seeding was stopped. In total, 14 samples (including influent and effluent samples) were collected from each filter during each filter run. Effluent samples were collected in 1 L bottles over a 5-minute period from a continuously running effluent line. Influent samples were collected in 40 mL vials for 30 seconds from a port directly above the filter media as shown in Figure 3.1. The filter influent stream flowed for at least 15 seconds before sample collection to ensure a representative sample. Pilot-scale experiments at the Horgan WTP followed the same procedures, with influent and effluent samples collected at 10-minute intervals (Scott, 2008).

3.2.3.3 *Cryptosporidium* enumeration and removal estimation

Cryptosporidium oocysts were concentrated using membrane filtration, identified using immunofluorescence assay (IFA) (Crypt-a-Glo, Waterborne Inc., New Orleans, Louisiana, USA), and enumerated using fluorescence microscopy at 400x magnification (Axioskop 2 plus, Zeiss, Göttingen, Germany), similar to the method of Emelko et al. (2003). In brief, all glassware was rinsed with detergent solution (1x PBS with Tween® 80 [PBST]) and then PBS prior to use. The 1 L effluent sample was used to evaluate *Cryptosporidium* oocyst concentration, with volumes measured using glass graduated cylinders. In contrast, only 1–5 mL of influent samples was required for enumeration due to the high oocyst concentrations in the influent. These smaller volumes were measured using 15 mL syringes. All samples were vacuum-filtered through polycarbonate filter membranes with a nominal porosity of 0.4 µm (Whatman Nuclepore®, Whatman Inc., GE Healthcare Life Sciences, Mississauga, ON, CA). Effluent samples were filtered using 25 mm diameter membranes, and influent samples were filtered using 12 mm diameter membranes. The filtration process was carried out on a manifold at -21 inHg (-533 mmHg). The subsequent application of IFA stain involved pipetting the stain evenly across the filter membrane surfaces, followed by an incubation in a humidified chamber in the dark at 35 °C for at least 30 minutes. Thereafter, the membranes were mounted on glass slides to facilitate oocyst enumeration through microscopy.

Average influent and effluent oocyst concentrations were used to calculate the effective log reduction of *Cryptosporidium* oocysts during each filter run (Teunis et al., 2009; Schmidt et al., 2020). Calculations of confidence intervals for *Cryptosporidium* oocyst removal were not conducted in this study because oocyst removal data do not satisfy the underlying assumptions required for such analyses. Oocyst counts are discrete, resulting in non-normal distributions, asymmetric uncertainty at low counts, and heteroscedastic variance (Emelko et al., 2008, 2010), which limit the applicability of conventional confidence interval approaches. Bayesian frameworks using credible intervals have been proposed for evaluating *Cryptosporidium* oocyst removal performance (Emelko et al., 2010), however, no single, standardized, or widely accepted approach currently exists for implementing these methods in practice. As a result, *Cryptosporidium* oocyst removal results are frequently reported without associated statistical intervals in the literature (LeChevallier et al., 1991; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2001, 2002; Emelko et al., 2005; Hashimoto et al., 2001; Mazoua and Chauveheid, 2005; Ballantyne et al., 2024). Accordingly, and consistent with regulatory practice—which evaluates treatment performance based on average log-removal credits rather than estimates with accompanying statistical bounds (EPA, 2006a; Health Canada, 2012)—log removal values in this study are presented as point estimates.

3.2.4 Zeta potential analysis

For each measurement, a 10 mL subsample was withdrawn from the bulk sample and used to rinse the measurement cuvette, after which approximately 0.75 mL was retained for analysis. Each sample was analyzed in triplicate, with the instrument configured to perform three independent runs. Each run represented the mean of up to 50 individual zeta potential measurements, although fewer readings were sometimes sufficient depending on signal stability. Final reported zeta potential values correspond to the average of the three replicate runs. Between measurements, both the sampling syringe and the measurement cell were thoroughly rinsed using ultrapure Milli-Q™ Type I water (resistivity >18 MΩ·cm; conductivity <0.056 µS/cm; TOC <50 ppb) to minimize cross-contamination. Seed suspension zeta potential was analyzed both before and after the addition of oocysts to the pre-chlorinated raw water.

Quantitative analysis of zeta potential data was not feasible because the raw data were not available. While the instrument provides a reported “zeta deviation,” this metric cannot be readily interpreted in the absence of information on the underlying distribution of measured values. This limitation is particularly relevant following coagulant addition, where some particles may be preferentially destabilized thereby altering the underlying distribution of particle (including *Cryptosporidium* oocyst) zeta potentials. Variability among

replicate runs was assessed and found to be insignificant, typically within 1–2 mV. As such, zeta potential values reported herein are as average values only.

3.3 Results and Discussion

3.3.1 *Cryptosporidium* oocyst removal by pilot-scale conventional CAF

Cryptosporidium oocyst removal by pilot-scale CAF with seven media configurations (Table 3.1) operated at warm (>8 °C) and cold (<8 °C) pre-chlorinated raw water temperatures is summarized in Figure 3.2. As evident in this figure, the seven different filter configurations examined during this study exhibited notably similar *Cryptosporidium* oocyst removal performance. In general, these data reflect what has been reported in the literature as well as broader industry experience: coagulation is critical for achieving *Cryptosporidium* oocyst removal by CAF, but other operational factors also affect it (LeChevallier et al., 1991; Ongerth and Pecoraro, 1995; Edzwald and Kelley, 1998; Huck et al., 2002; Nascimento et al., 2020). For example, it has been reported that *Cryptosporidium* oocyst removal by CAF during periods of rapid changes in filter hydraulics (e.g., hydraulic surges/filter ripening) is often 0.5- to 1-log lower than during periods of stable CAF operation preceded by sufficient particle destabilization from coagulant addition (Patania et al., 1995; Huck et al., 2001; Amburgey et al., 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Amburgey and Amirtharajah, 2005). This difference in performance during different periods of filter operation was also observed here, as summarized in Figure 3.2.

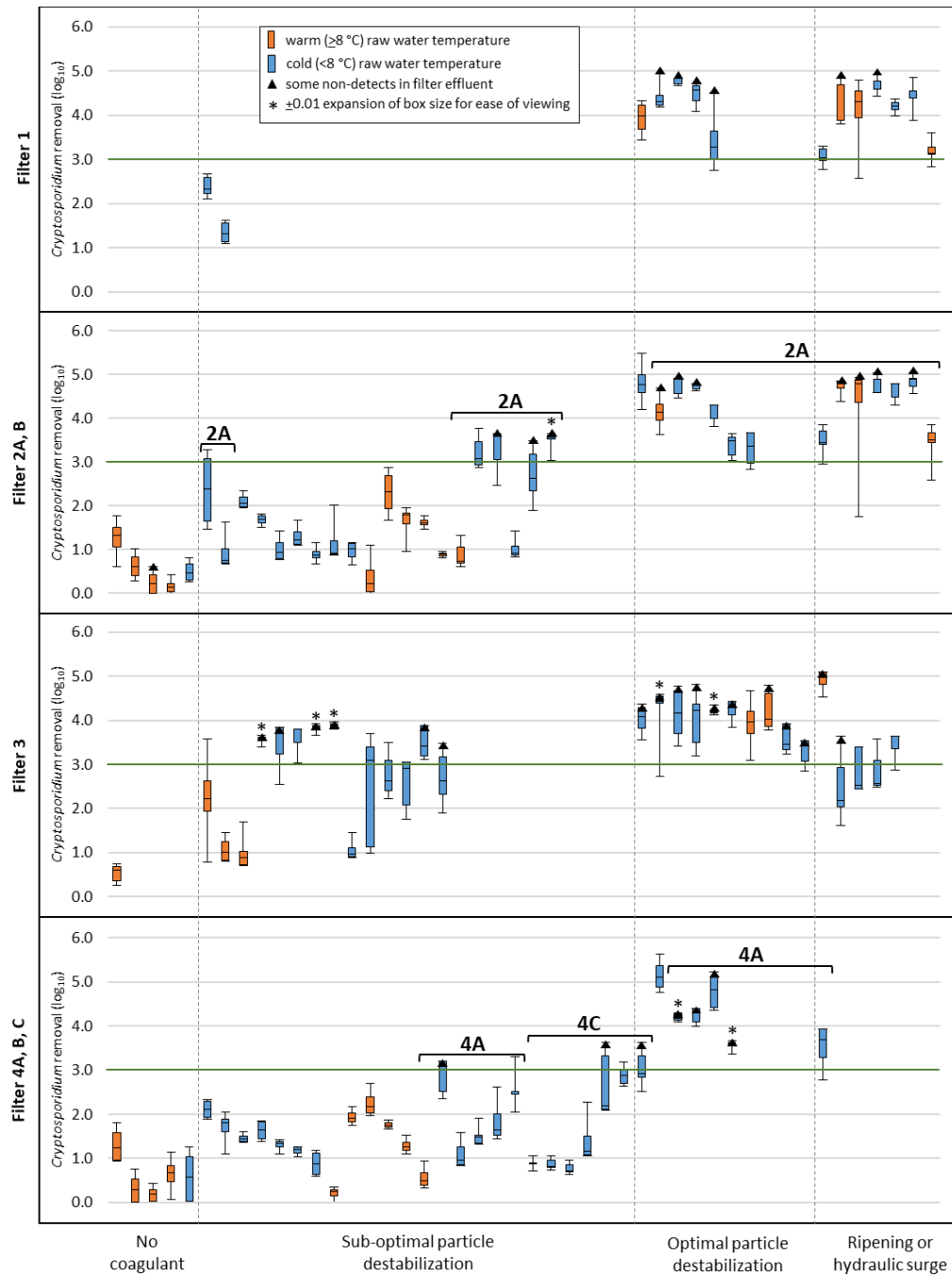


Figure 3.2. *Cryptosporidium* oocyst removal by pilot-scale conventional CAF configurations described in Table 3.1. Each box and whisker combination represents one individual filter run/experiment. Dashed vertical lines separate different operational conditions. The whiskers indicate maximum and minimum oocyst removals by CAF, while the boxes indicate the 75th and 25th percentile removals and the dashes

indicate median (50th percentile) removals. Triangles indicate filter runs with non-detects (i.e., zero oocyst counts) in the filter effluent samples. In some filter runs, highly similar oocyst removals were observed at all time points, resulting in narrow boxes. To enhance visual clarity, box plots summarizing these runs were expanded slightly; they are marked with an asterisk (*). The green horizontal lines indicate the 3.0-log oocyst removal performance expected from "well-operated" CAF. Pre-chlorinated raw water quality and operational conditions relevant to all experiments, along with individual oocyst removal data, are provided in Appendix F.

The individual filter evaluations shown in Figure 3.2 were used to identify and differentiate “optimal” from “sub-optimal” particle destabilization by coagulant addition, as described in Section 3.2.1. Oocyst seed suspension zeta potentials (after coagulant addition) that reliably enabled ≥ 3 -log removal of oocysts by CAF were classified as “optimal,” whereas those resulting in < 3 -log removal were classified as “sub-optimal. As expected, *Cryptosporidium* oocyst removal by CAF ranged from 0- to 2-log in the absence of coagulant addition for destabilization of particles and oocysts, with most values falling near 0-log. At sub-optimal destabilization conditions, they ranged from 0.2- to 3-log. These observations underscore that particle removal by CAF is not linear with respect to coagulant dose because coagulation is governed by complex, non-linear physical and chemical interactions between particles, coagulant species, and the surrounding water matrix (e.g., presence of DOC, pH). CAF performance in removing oocysts at these conditions was inconsistent and insufficient for reliably meeting pathogen removal targets.

In contrast, under optimal particle destabilization conditions, *Cryptosporidium* oocyst removals by CAF ranged from 3.2- to 4.8-log, with most of the observations falling between 3.8- and 4.3-log, regardless of filter configuration or water temperature. Although a factorial or side-by-side designed set of experiments comparing filter design and operational impacts was not conducted because it was not the objective of the present work and such investigations have been reported previously (Emelko 2001; Huck et al., 2001; 2002), an obvious performance advantage between operational conditions was not observed when particle destabilization was optimized. This tighter grouping of the data demonstrates the greater CAF performance consistency that can be expected when particle destabilization is maximized by chemical pretreatment with sufficient coagulant addition. These findings are consistent with existing literature and industry consensus, which recognize coagulation as a crucial factor in achieving ≥ 3 -log *Cryptosporidium* oocyst removal by CAF (LeChevallier et al., 1991; Ongerth and Pecoraro, 1995; Patania et al., 1995; Emelko, 2001; Edzwald and Kelley, 1998; Huck et al., 2002; Emelko et al., 2005; Nascimento et al., 2020).

3.3.2 Zeta potential as a control for ensuring adequate coagulant addition for CAF

Cryptosporidium oocyst removal by pilot-scale conventional CAF is shown as a function of oocyst seed suspension zeta potential in Figure 3.3. This figure demonstrates that the zeta potential values that corresponded to consistent 3-log or higher *Cryptosporidium* oocyst removals by CAF were within ± 5 mV of 0, regardless of water temperature or filter configuration. Accordingly, -5 mV was identified as the minimum zeta potential value associated with optimal particle destabilization. This value also corresponded to the minimum coagulant dose required to achieve effective oocyst removal by CAF. While adding further coagulant so that zeta potential approaches 0 mV improves and ultimately maximizes destabilization (e.g., as seen here when zeta potential was within ± 5 mV of 0), exceeding it and shifting the zeta potential substantially into the positive range likely offers little or no additional CAF performance benefit and leads to unnecessary coagulant use and sludge production, making it an inefficient operational target.

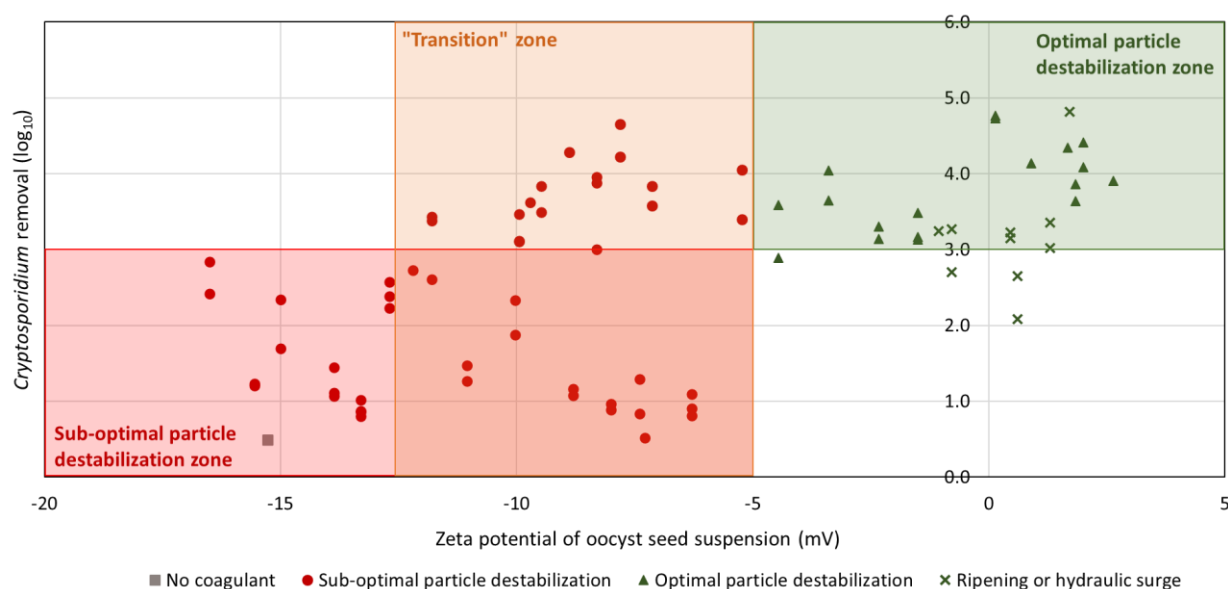


Figure 3.3. *Cryptosporidium* oocyst removal by pilot-scale conventional CAF as a function of zeta potential after coagulant addition. Each point is the effective log reduction calculated from 4-5 samples collected during a filter run. Data are overlaid with color-shaded regions: the optimal particle destabilization zone (green) corresponds to zeta potentials within ± 5 mV of 0 and is associated with consistent, reliable achievement of ≥ 3 -log oocyst removal; the sub-optimal particle destabilization zone (red) represents zeta potentials more negative than -5 mV and operational conditions during which ≥ 3 -log oocyst removal is not reliably achieved; and a small transition zone (orange) within the sub-optimal particle destabilization zone

indicates that particle destabilization is improving with increased coagulant addition but is insufficient for reliably achieving ≥ 3 -log oocyst removal by CAF. Pre-chlorinated raw water quality and operational conditions relevant to all experiments, along with individual oocyst removal data, are provided in Appendix F.

Figure 3.3 highlights that, in Toronto, a zeta potential within ± 5 mV of 0—shown in green as the “optimal particle destabilization zone”—was required to consistently achieve 3-log or greater removal of *Cryptosporidium* oocysts by CAF. This performance level aligns with expectations for “well-operated” CAF systems under most U.S. and Canadian drinking water regulations and guidance. Although previous studies on Great Lakes source waters have suggested that a broader zeta potential range of within ± 7 mV of 0 is “optimal” (Waller et al., 2012), those conclusions were based on bench-scale jar tests focused on settling and optimizing organic matter removal rather than particle or pathogen destabilization and CAF performance. In contrast, the present investigation directly evaluated the relationship between oocyst destabilization and removal by CAF, showing that consistently achieving 3-log or higher oocyst removal by CAF requires chemical pretreatment to achieve a near neutral filter influent zeta potential that is within ± 5 mV of 0, as shown in Figure 3.3.

There was one slight exception to this trend, a pilot test in which the oocyst seed suspension zeta potential was -4.5 mV (i.e., within the optimal particle destabilization zone), but the resulting *Cryptosporidium* oocyst removal by CAF was only 2.9-log (instead of 3-log or higher). It should be noted that uncertainty in this estimate is particularly high because of low number of oocysts including some non-detects observed as a result from a low processed sample volume (i.e. 800 mL). Ideally, sample volumes should be sufficient to detect a minimum of 10 and preferably 30 or more oocysts per sample to ensure statistically robust removal estimates (Emelko et al., 2008); however, this was not feasible with this experiment due to insufficient volume.

In filter runs where zeta potential values were more negative than -5 mV—defined as the “sub-optimal particle destabilization zone” shown in red in Figure 3.3—*Cryptosporidium* oocyst removals by CAF varied widely, with many performance results falling below the 3-log target. While zeta potential values more negative than -5 mV do not definitively indicate insufficient destabilization, greater deviations from 0 mV generally corresponded to less favorable conditions for oocyst attachment and subsequent removal by CAF. The sub-optimal particle destabilization zone contains a smaller “transition zone” in which oocyst removals both above and below 3-log are found, as shown in Figure 3.3. This zone emphasizes the lack of direct correlation between zeta potential and particle destabilization, reflecting the non-linear system responses to

variations in operational and water quality parameters—such as coagulant dose, pH, alkalinity, DOC concentration and character—when colloidal particle suspensions are destabilized by coagulant addition (James et al., 1977; Duan and Gregory, 2003). In practice, *Cryptosporidium* reductions of at least 3-log are not reliably achieved by CAF when chemical pretreatment is operated within this zone. Finally, as expected, *Cryptosporidium* oocyst removals by CAF consistently fell below 3-log outside the transition zone where minimal or no particle destabilization occurred due to insufficient or absent coagulant addition, as shown in Figure 3.3.

Collectively, these findings highlight the inherent challenge of achieving sufficient particle destabilization of high-quality source waters in which low turbidity and low DOC concentrations can create a misleading sense of lesser treatment needs. High-quality source waters have long been recognized as among the most difficult to coagulate and treat (O’Melia and Stumm, 1967; Edzwald, 1993; Letterman et al., 1999). In such waters, coagulant doses required to achieve effective CAF performance are often higher than anticipated because of low particle concentrations and reduced collision frequencies that necessitate the addition of particles (e.g. clay). Inadequate dosing—whether due to underestimation or operational conservatism—can compromise both performance and public health protection. At present, drinking water providers predominantly rely on CAF process effluent turbidity as an indicator of process performance, including expected protozoan pathogen removal (EPA, 2006a; Health Canada, 2019). Sole reliance on turbidity to guide coagulant dosing is inadequate for ensuring optimal particle destabilization and effective protozoan pathogen removal by CAF (Chapter 2), underscoring a concerning limitation of turbidity based regulatory benchmarks as sole indicators of well-operated treatment systems capable of protecting public health, particularly against cryptosporidiosis and giardiasis. This concern is reinforced by findings from the International Joint Commission (IJC, 2021), which examined the relationship between Great Lakes source water quality measured at drinking water intakes and precipitation patterns in relation to the risk of acute gastrointestinal illnesses (AGIs). The study reported that the water systems reliant on Lake Ontario had the highest combined incidence of giardiasis and cryptosporidiosis, with 9.94 cases per 10,000 residents—higher than all other Canadian and U.S. cities included in the analysis despite operation of conventional CAF treatment considered to be well-managed by any standard and in compliance with all current regulations (MECP, 2003; 2021; Health Canada, 2019).

Particle and pathogen removal by CAF, more widely known as physico-chemical filtration, is governed by a two-step process requiring effective particle destabilization via coagulant addition to facilitate attachment, followed by transport to filter media surfaces where deposition can occur (AWWA, 1999; Crittenden et al.,

2012). It is for this reason that physico-chemical filtration is often referred to as CAF. While effective particle destabilization via coagulation is essential for *Cryptosporidium* oocyst removal by CAF, it does not guarantee effective filtration; hydraulic conditions within the filter also play a critical role. Operational factors such as filter design and transient hydrodynamic conditions can influence both particle transport to filter media surfaces and the stability of their attachment. Previous studies have reported that *Cryptosporidium* oocyst removal by CAF declines during periods of hydraulic instability (e.g., surges caused by sudden changes in flow) or change (e.g., filter ripening when flow pathways through the media are transient and continue to adjust before reaching pseudo-steady) (Patania et al., 1995; Emelko, 2001; Huck et al., 2001; Amburgey et al., 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Amburgey and Amirtharajah, 2005; Emelko et al., 2005); this was similarly observed in the present investigation. As shown in Figure 3.2 and Figure 3.3, even optimally destabilized oocysts are removed to a lesser extent during “Ripening and hydraulic surge” conditions, possibly due to hindered deposition or increased detachment of previously deposited oocysts. Although transient conditions were not a focus, these experiments confirmed that achieving a zeta potential of within ± 5 mV of 0—indicative of optimal particle destabilization—is not, on its own, predictive of 3-log or greater *Cryptosporidium* oocyst removal by CAF. Rather, zeta potential serves as an operational indicator of coagulant addition sufficiency, where the probability of particle (including oocyst) retention within filters is maximized.

While zeta potential values near 0 mV are broadly indicative of optimal particle destabilization needed for maximizing their removal by CAF, the specific zeta potential target corresponding to the minimum coagulant dose required to reliably achieve ≥ 3 -log *Cryptosporidium* oocyst removal by CAF is system specific (e.g., -5 mV in Toronto). Identifying this target, however, is not straightforward. Zeta potential ranges alone do not capture the complexity of particle destabilization dynamics; both the location of sample collection and the timing of zeta potential evaluation are important. This is because the physico-chemical reactions that govern zeta potential continue to evolve after coagulant addition. As shown in Figure 3.4, with higher coagulant doses, zeta potential declines over time, emphasizing the dynamic nature of particle destabilization processes (e.g., continued hydrolysis of metal salt coagulants, precipitate formation and aging) and the importance of interpreting zeta potential data within an appropriate operational context.

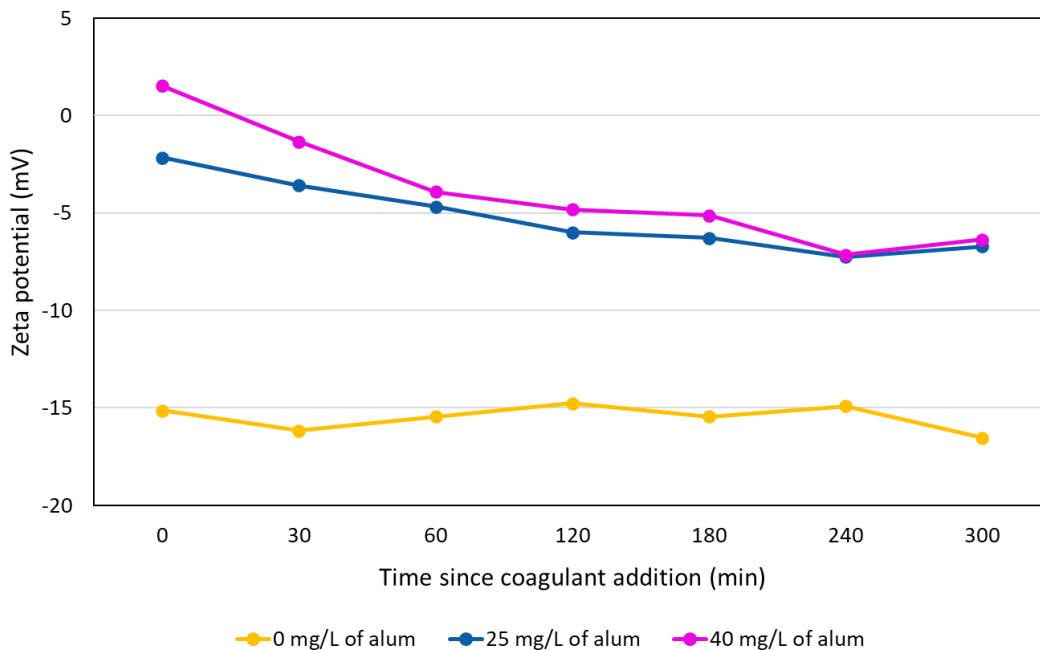


Figure 3.4. Zeta potential of coagulated pilot plant pre-chlorinated raw water as a function of time (further details can be found in Appendix G).

What is reported by the zeta potential analyzer is an average that masks the inherent variability within the distribution of particles present in a water sample. Zeta potential is determined by assessing the electrophoretic mobility of individual particles subjected to an electric field; however, particles do not exhibit uniform electrokinetic behavior because they differ in size, composition, surface chemistry, and interactions with dissolved constituents. The reported value reflects a statistical abstraction, not a fixed physico-chemical property of a homogeneous system. Although the analytical method is designed to yield a reproducible and interpretable number, it inherently compresses a potentially broad and complex distribution of particle behaviors into a single value. This convergence does not eliminate the underlying heterogeneity, nor does it provide insight into the shape or spread of the distribution—information that may be critically relevant to particle destabilization and CAF performance. As such, reliance on a single zeta potential value without consideration of its underlying distribution may lead to misinterpretation, particularly when using zeta potential to guide coagulant dosing or inform the sufficiency of particle destabilization. Thus, zeta potential targets are inherently system specific, not “one-size-fits-all”.

Accurate interpretation of zeta potential data depends on where and when it is evaluated within the treatment process. In conventional drinking water treatment, zeta potential optimization has traditionally focused on

achieving minimum clarified water turbidity or maximum DOC removal, aligning zeta potential with performance indicators in the sedimentation step. However, in most conventional CAF systems, coagulated water may take several hours to travel from the sedimentation basin before reaching the filter media, during which time both water quality and coagulant speciation can evolve significantly. Although primary hydrolysis of metal coagulants occurs within seconds (Duan and Gregory, 2003; Gregory, 2009), extended residence times enable further hydrolysis and complexation reactions to proceed (Amirtharajah and Mills, 1982), potentially altering the surface chemistry of particles and their zeta potential. Consequently, zeta potential values optimized for sedimentation performance may not accurately reflect the conditions experienced at the filter, where particle destabilization is critical for removal. This has important implications: optimization based solely on clarified water turbidity may not result in effective filtration, particularly for protozoan pathogens. Plant-specific factors such as the point of coagulant addition, hydraulic residence time, and water quality variability must therefore be considered when identifying zeta potential targets.

Chapter 2 previously identified a critical limitation in relying solely on turbidity to determine coagulant dose sufficiency for protozoan pathogen removal, particularly in systems treating high-quality source waters. This study addresses that limitation by demonstrating how zeta potential analysis can effectively be used to assess particle destabilization and guide coagulant application for systems reliant on high-quality source waters. It also highlights that exact zeta potential targets are system specific in terms of acceptable range from 0 mV and coagulant demand varies depending on source water characteristics (i.e., different turbidity levels, DOC, or organic matter character), process configurations, and operational conditions.

While a threshold of -5 mV was identified in this study as the minimum value associated with reliable ≥ 3 -log *Cryptosporidium* oocyst removal in Toronto, similar approaches can and should be applied elsewhere to develop system-specific operational targets. The alum doses required to achieve this level of destabilization were higher than those frequently applied in low turbidity, low DOC Great Lakes systems, reinforcing the potential for under-dosing when relying solely on turbidity for informing CAF performance. Although it may be desirable to define a quantitative threshold for adequate coagulant dosing, this is not feasible in practice, as optimal destabilization is inherently system-specific and dependent on temporally and spatially variable raw water characteristics, including particle concentration and dissolved organic carbon concentration and character. As a result, no single coagulant dose or zeta potential target can be universally applied across systems. While these findings support the use of zeta potential as a tool to inform

dosing, such elevated alum concentrations may be costly and may require retrofitting coagulation and sludge handling infrastructure.

Given that zeta potential ranges or thresholds are highly dependent on site-specific conditions and process configurations, a process understanding of how zeta potential evolves throughout the treatment train—and how it is influenced by site-specific conditions, seasonal variability, and operational dynamics—is essential to ensuring resilient treatment performance. As climate change accelerates shifts in source water quality—including potential increases in pathogen concentrations (Chhetri et al., 2019) and changes in dissolved organic matter content or character (Emelko et al., 2011, 2024; IPCC, 2021)—proactive and adaptive management of coagulation will become increasingly critical. It's increasingly critical so that treatment systems to be more responsive to both seasonal and event-driven fluctuations in source water quality. Ensuring appropriate coagulant dosing under such conditions is fundamentally a public health issue, as inadequate particle destabilization directly compromises pathogen removal and broader drinking water treatability. Seasonal adjustments to water quality change and associated system-specific zeta potential targets are necessary to maintain optimal CAF and broader treatment performance in systems reliant on low turbidity and low DOC concentrations are necessary to safeguard public health and meet regulatory expectations for protozoan pathogen risk management.

3.4 Conclusions

This study provides a mechanistic evaluation of *Cryptosporidium* oocyst removal by conventional chemically-assisted filtration (CAF), with a particular focus on the role of particle destabilization informed by zeta potential analysis. Key findings and their implications are summarized below:

1. Zeta potential analysis is a valuable operational tool for assessing coagulant dose sufficiency and supporting effective by CAF in systems reliant on high-quality (low turbidity, low dissolved organic carbon concentration) source water.

While the importance of coagulation in enhancing CAF performance is well established, this work demonstrates that consistent achievement of ≥ 3 -log *Cryptosporidium* oocyst removal depends on sufficient coagulant addition to ensure optimal particle and pathogen destabilization. Importantly, this requirement is often overlooked for high-quality source waters—where turbidity alone is a poor indicator of coagulation adequacy—resulting in sub-optimal performance despite meeting or exceeding seemingly well-operated treatment conditions as defined by regulatory turbidity thresholds (e.g., U.S. EPA SWTRs and Canadian analogs).

Zeta potential analysis provides a direct indication of coagulant dose adequacy for optimization of particle destabilization. However, it must not be misinterpreted as a surrogate or predictor of particle or pathogen removal by CAF, as it does not account for critical factors such as filter design or operational hydraulics that can significantly reduce particle removal efficiency. Instead, zeta potential analysis serves as a tool for identifying when coagulant addition is sufficient and compliments—but does not replace—turbidity analysis in performance evaluation for supporting effective CAF.

2. A system-specific zeta potential target can be established to guide coagulant dosing for reliable CAF performance.

In Toronto's Lake Ontario source water, a post-coagulation filter influent zeta potential within ± 5 mV of 0 was associated with sufficient particle destabilization to achieve ≥ 3 -log *Cryptosporidium* oocyst removal by CAF. This study demonstrates the feasibility of establishing site-specific zeta potential targets to guide coagulant dosing, optimize pretreatment, and maximize removal performance. While such targets will vary based on source water quality, coagulant application points, residence time, and measurement methodology, the general approach is transferable and can be adapted to other treatment systems to support improved microbial risk reduction. This is particularly critical in systems treating high-quality source water, where traditional performance indicators like clarified or filtered water turbidity do not reliably reflect the extent of particle destabilization.

3. Temperature and filter media depth were not primary drivers of oocyst removal by CAF; rather, performance was governed by the sufficiency of particle destabilization.

Water temperature did not appear to significantly affect *Cryptosporidium* oocyst removal by conventional CAF. While a controlled, side-by-side comparison was not performed—as this was not the focus of the investigation—no clear performance difference was observed between various filter configurations or coagulant types. Instead, the extent of particle destabilization—quantified through zeta potential—was the dominant factor influencing *Cryptosporidium* oocyst removal by CAF. While optimal destabilization improved removal potential, it did not guarantee performance at all conditions. Transient hydraulic events, such as filter ripening and hydraulic surges, were observed to impair performance by promoting particle detachment or limiting deposition on filter media surfaces. These findings underscore that while filter design and operating conditions influence particle removal performance, their effects can be secondary to the fundamental requirement for adequate destabilization.

4. Zeta potential analysis offers a critical tool for climate-resilient treatment optimization.

As climate change increases the variability and extremity of source water conditions—even in systems traditionally considered stable, like the Great Lakes—flexible, process-informed control strategies are essential. Seasonal shifts in water quality and potential increases in waterborne pathogen concentrations or organic matter loading may demand higher coagulant doses to maintain consistent CAF performance; however, such elevated alum doses may not be feasible for all systems. In such cases zeta potential analysis enables treatment operators to respond to these challenges proactively, adjusting coagulant dosing in real time based on system specific performance needs. As such, zeta potential should be considered a valuable element of future-ready treatment optimization and climate adaptation strategies in drinking water treatment.

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Chapter 4. Revisiting direct filtration: Enhanced control, enhanced pathogen removal

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Summary

Effective removal of protozoan pathogens such as *Cryptosporidium* spp. is a critical challenge in drinking water treatment, particularly for high-quality source waters with low turbidity and organic content. Direct in-line chemically assisted filtration (CAF) is specifically designed to treat high-quality source water, where conventional coagulation–flocculation–sedimentation provides limited removal. Despite this design intent, current regulatory frameworks assign lower log-removal credits to direct in-line CAF because it bypasses sedimentation. This study evaluates the performance of pilot-scale direct in-line CAF using Lake Ontario water and seeded *Cryptosporidium* oocysts. Coagulated water was fed directly to filters, bypassing the flocculation and sedimentation basins, minimizing hydraulic residence time (between point of coagulant addition and filter influent) and increasing contact opportunities between particles and coagulant species for effective pathogen removal by CAF. Zeta potential analysis was used to inform adequate coagulant addition and particle destabilization conditions. Direct in-line CAF consistently achieved ≥ 3 -log oocyst removal and, on average, 1.5-log higher removal than conventional CAF under same operational conditions. The study also provides experimental evidence to support reconsideration of the 2.5-log removal credit currently assigned to direct in-line CAF systems when treating high-quality source waters.

4.1 Introduction

The control of waterborne pathogens has historically relied on sequential treatment processes: coagulation, flocculation, clarification, filtration, and disinfection (EPA, 2006a; WHO, 2017; Health Canada, 2019). While this level of treatment has substantially reduced disease incidence (CCME, 2004; Health Canada, 2012; Ramsay et al., 2014), its effectiveness against chlorine-resistant organisms such as *Cryptosporidium* spp. (Korich et al., 1990) depends on the performance of physico-chemical filtration. Failures in coagulation and filtration are frequently implicated in *Cryptosporidium* related outbreaks (MacKenzie et al., 1994; WHO, 2009; Bourli et al., 2023). Advanced disinfection technologies such as ozonation and ultraviolet (UV) irradiation can effectively inactivate oocysts; however, their implementation is limited by high operational cost, maintenance complexity, and vulnerability of upstream processes to source-water

variability (Bukhari et al., 2000; Clancy et al., 2004; Mamane and Linden, 2006). Consequently, physico-chemical filtration—also referred to as chemically assisted filtration (CAF)—remains a critical barrier for *Cryptosporidium* control in drinking water treatment.

In conventional CAF, coagulant addition is followed by flocculation and clarification (typically sedimentation) prior to filtration. These processes facilitate particle aggregation and the removal of settleable solids. However, in system treating high-quality source water—characterized by low turbidity (<2 NTU) and low dissolved organic carbon concentrations (DOC <2 mg/L)—these upstream sedimentation stages contribute minimally to overall particle removal because the formation of settleable floc is limited (O'Melia, 1985; Amirtharajah and O'Melia, 1990; Letterman et al., 1999). Importantly, for systems where source water turbidity already meets treated-water targets, both clarified and filter effluent turbidity may provide a false sense of adequate coagulant addition for protozoan removal by CAF, simply because effluent turbidity meets regulatory targets (Chapter 3).

Despite the low particle concentrations, these high-quality waters present a treatment paradox: they are often more difficult to treat (Amirtharajah and O'Melia, 1990; Stumm and Morgan, 1996; Letterman et al., 1999) and may require higher than expected coagulant doses to achieve sufficient particle removal by CAF (Ballantyne et al., 2024; Chapter 2; Chapter 3). Low concentrations of particles and organic matter in these waters provide fewer contact opportunities reducing the effectiveness of particle destabilization. Therefore, achieving adequate destabilization often requires higher than expected coagulant doses to generate micro-precipitates that increase contact opportunities to maximize particle destabilization and removal by CAF (Amirtharajah and Mills, 1982; O'Melia and Stumm, 1967; Duan and Gregory, 2003; Chapter 3).

Under such conditions, achieving appropriate coagulant dosing for particles (including protozoan pathogens) removal by CAF is particularly challenging for conventional treatment. In low-turbidity, low-DOC waters, where settleable floc does not readily form, the micro-precipitates generated during coagulation pass through sedimentation without effective settling (O'Melia, 1985; Edzwald, 1993; Dennett et al., 1996; Letterman et al., 1999). Because conventional CAF relies on upstream removal in the flocculation and sedimentation basins, they are not designed to manage these micro-precipitates. Direct in-line CAF can address these limitations since they are designed to treat high-quality source waters, where solids concentrations are low and conventional clarification provides limited benefit (Letterman et al., 1999; Crittenden et al., 2012). This configuration eliminates flocculation and sedimentation, feeding coagulated water directly to filters (Ngo et al., 1995; Crittenden et al., 2012). The filters are designed to manage and retain these micro-precipitates generated during rapid mixing (Culp, 1977; Treweek, 1979; Valade et al.,

2009; Crittenden et al., 2012), providing contact opportunities that promote particle–coagulant interactions to sufficiently destabilize and attach to filter media surfaces (Culp 1977; O’Melia; 1985; Amirtharajah and O’Melia, 1990; Letterman et al., 1999; Crittenden et al., 2012). This approach also reduces process footprint, lowers infrastructure and energy demand, and simplifies operation (Letterman, 1999; Crittenden et al., 2012).

Under current U.S. and Canadian regulatory frameworks, direct in-line CAF is assigned a lower *Cryptosporidium* oocyst removal credit (2.5-log) compared to conventional treatment (3-log), solely because it omits sedimentation (EPA, 2006a; Health Canada, 2019). Regulatory frameworks, such as the U.S. EPA suite of Surface Water Treatment Rules (SWTRs) and their Canadian counterparts, consider treatment plants to be “well operated” when combined filter effluent turbidity remains ≤ 0.3 NTU in at least 95% of monthly measurements (EPA, 2006a; Health Canada, 2019). While this standard provides a useful operational target, oocyst removals of less than 3-log are frequently observed even when turbidity criteria are met, particularly for high-quality source waters (Chapter 2). As a result, it remains unclear whether the 2.5-log credit currently assigned to direct in-line CAF accurately reflects the removal potential of well-operated direct in-line CAF systems, and whether—when particle destabilization is optimized—they can achieve the 3-log credit assigned to conventional CAF for high-quality source waters.

This study investigated direct in-line CAF’s ability to achieve 3-log or greater *Cryptosporidium* oocyst removal for high-quality source waters when particle destabilization is optimized. Pilot-scale experiments compared oocyst removal performance by direct in-line and conventional CAF configurations. Zeta potential was used as a tool to inform sufficiency of particle destabilization, building on previous findings that have established its value as a tool assess particle destabilization and guide coagulant application for high-quality source waters (Chapter 3). In addition, the study examines whether well-operated direct in-line CAF can achieve greater *Cryptosporidium* oocyst removal than currently credited, providing insight into its potential for broader regulatory recognition.

4.2 Materials and methods

4.2.1 Experimental approach

Pilot-scale CAF experiments were conducted at the R.C. Harris Water Treatment Plant (WTP) in Toronto, Ontario, Canada. Inactivated *Cryptosporidium parvum* oocysts were seeded into the filter influent to assess oocyst removal during CAF. Seeding at this location minimizes upstream oocyst losses, allowing more accurate evaluation of filter performance which is a widely used approach in pilot-scale challenge studies

(Nieminski and Ongerth, 1995; Huck et al., 2001; Emelko and Huck, 2004; Emelko et al., 2005; Lee, 2018; Liu et al., 2019; Wang et al., 2020).

A total of 23 individual filter runs (experiments) were conducted for direct in-line CAF, yielding 110 effluent samples to evaluate *Cryptosporidium* oocyst removal at pilot scale. For comparison with conventional CAF, data from Chapter 3 were used. Specifically, 33 filter runs (162 effluent samples) from Train 01, filters 2A and 3, were selected to match experimental conditions, including zeta potential-informed coagulant dosing, filter media configurations operated at both warm ($\geq 8^{\circ}\text{C}$) and cold ($< 8^{\circ}\text{C}$) pre-chlorinated raw water temperatures. Experiments were conducted under stable filter operation conditions, with varying coagulant doses to investigate both optimal and suboptimal particle destabilization. Based on previous pilot-scale experiments conducted for conventional CAF, ± 5 mV was identified as the range for optimal particle destabilization that consistently enabled ≥ 3 -log removal of *Cryptosporidium* oocysts by CAF (Chapter 3). Based on this, optimal destabilization was defined as zeta potential within ± 5 mV of 0, while suboptimal destabilization corresponded to zeta potentials less than -5 mV after coagulant addition.

Coagulant was added both to the pilot plant's pre-chlorinated raw water and to the *Cryptosporidium* oocyst seed suspension, which was introduced at the filter influent for 23 individual filter runs (110 individual effluent samples). For experiments focused on oocyst removal via direct in-line CAF, emphasis was placed on oocyst destabilization within the seed suspension, following a similar approach described in Chapter 3, to enable direct comparison with conventional CAF performance data reported in that study. To investigate the impact of particle destabilization on removal efficiency, coagulant doses applied to the seed suspension were varied to generate a range of destabilization conditions, characterized using zeta potential measurements. During these experiments, the pilot plant's pre-chlorinated raw water was consistently coagulated with 4 to 9 mg aluminum sulfate (alum)/L, reflecting typical dosing practices for high-quality source waters. These doses resulted in sub-optimal destabilization across all filter runs.

In a separate set of experiments designed to explore the broader influence of coagulation and particle destabilization on CAF performance, coagulant doses were systematically varied for both the pre-chlorinated raw water and the seed suspension to achieve optimal and sub-optimal particle destabilization. A total of 39 individual filter runs (190 individual effluent samples) at different destabilization conditions at both the pilot and seed suspension were looked at to evaluate how different approaches of coagulation and particle destabilization can affect the overall CAF effectiveness. All other aspects of the experimental design were kept the same, as described in the following sections.

4.2.2 Pilot plant

The pilot plant located at R.C. Harris WTP, draws water directly from Lake Ontario and encompasses a treatment sequence involving pre-chlorination, alum (aluminum sulfate [$\text{Al}_2(\text{SO}_4)_3 \cdot 14(\text{H}_2\text{O})$]; ChemTrade Logistics, Toronto, Canada) coagulation, flocculation, sedimentation, and dual media filtration. The water quality during the experiments was generally constant, as follows: turbidity: 0.33 ± 0.23 NTU, pH: 8.0 ± 0.15 , and total organic carbon (TOC): 1.8 ± 0.01 mg/L. This location serves as a representation of high-quality Great Lakes supply, characterized by its low turbidity and TOC concentrations, with a relatively low coagulant dosage employed for particle removal.

For this study, modifications were made to one of the two trains located in the pilot. Train 1 was modified to replicate direct in-line CAF by bypassing the flocculation and sedimentation basins (Figure 4.1). The pilot plant setup diverted a portion of pre-chlorinated raw water from the full-scale plant into a constant head tank, from which water was withdrawn and coagulated with alum. The coagulated water then entered three parallel 15 cm internal diameter (ID), 5 m tall filter columns (2A, 3-1, 3-2). Filter 3 was investigated in duplicate (3-1 and 3-2). Filter media consisted of an anthracite layer with a depth of 45 cm for Filter 2A and 100 cm for Filters 3-1 and 3-2 (effective size of 0.95 mm). All 3 filters contained 30 cm of sand (effective size of 0.48 mm). Based on the total media depths, Filter 2A was classified as a shallow filter whereas Filters 3-1 and 3-2 were classified as deep filters. It should be noted that the experiments were not intended for direct operational comparison but were instead grouped to highlight trends across two comparisons: (1) coagulant addition vs. no coagulant, and (2) optimized versus unoptimized particle destabilization.

The three filter columns were representative of two filter media and operations configurations that are representative of those used by systems reliant on high-quality Great Lakes supplies. All filters were operated in constant head and constant flow mode using hydraulic loading rates of 4.6 m/h. During filtration, influent and effluent turbidity, pH, and flow rates were monitored at 1-minute intervals by SCADA (Supervisory Control and Data Acquisition) data-logging program.

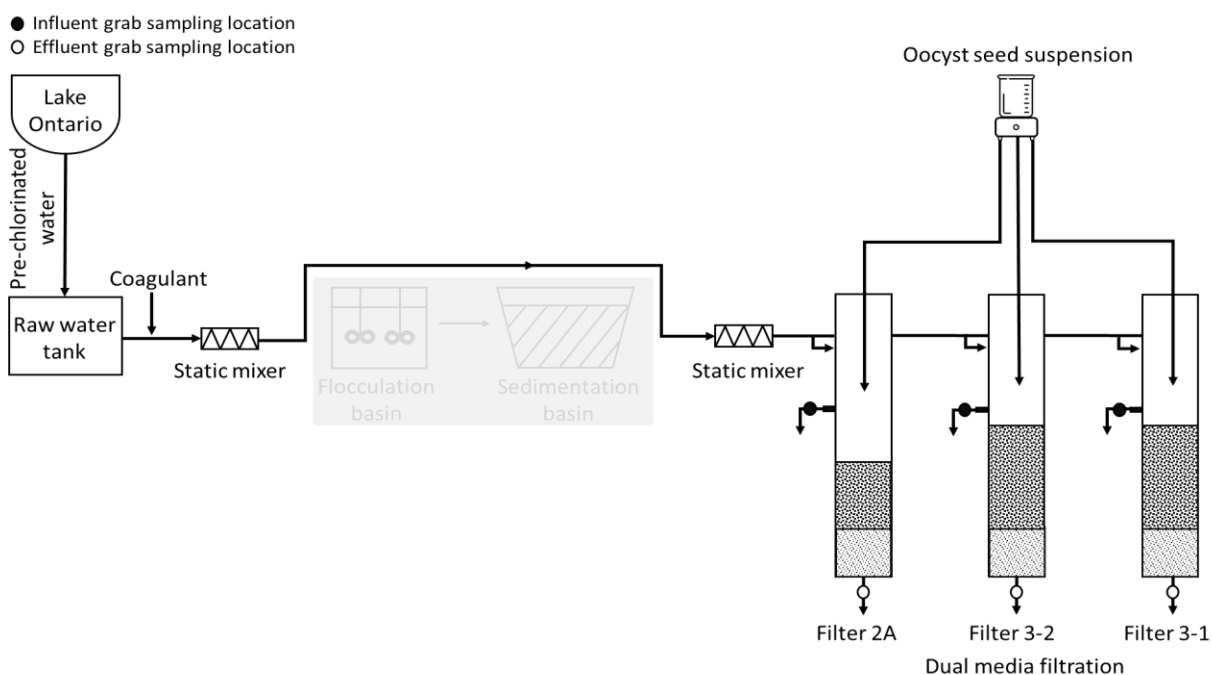


Figure 4.1. Schematic flow diagram of the modified pilot plant. During the experiments, a continuous input of *Cryptosporidium* oocyst seed suspension was introduced into the filters. Influent and effluent grab samples were collected at the identified points to estimate *Cryptosporidium* oocyst removal by the filters.

4.2.3 *Cryptosporidium* seeding and sampling protocols

All pilot-scale seeding experiments employed continuous seeding of oocysts at the filter influent during stable operation. The seed suspension of formalin-inactivated *Cryptosporidium parvum* oocysts (Waterborne, Inc., New Orleans, LA, USA) was diluted with pre-chlorinated raw water to achieve a target number of $\sim 10^7$ oocysts, a concentration of $\sim 10^5$ oocysts/L in the filter influent. The suspension was then jar-coagulated to destabilize oocysts/particles and zeta potential analysis (detailed in section 4.2.5) was used to indicate particle and oocyst destabilization (i.e., optimal and sub-optimal). After the addition of alum, the coagulated seed suspension was introduced in the filter influent streams of the three filters by using a peristaltic pump with three pump heads (Masterflex, Avantor, Inc., ON, Canada) at 5 mL/min for a span of 60 minutes (Figure 4.1). The seed suspension was delivered through flexible tubing (Masterflex, Avantor, Inc., ON, Canada), which provided consistent oocyst flow to each filter. To ensure uniform distribution of oocysts during the experiment, the seed suspension was constantly agitated with a magnetic stirrer (Thermo Scientific, Thermo Fisher Scientific Inc., Massachusetts, USA) over the period of seeding.

During the course of this study, the grab sampling method was employed to quantify pathogens in both the filter influent and effluent. Influent and effluent samples were systematically collected in sterilized plastic (PP) bottles (Fisher Scientific, Thermo Fisher Scientific Inc., Massachusetts, USA). The sampling commenced at time zero (T0) when seeding was initiated. Subsequently, samples were collected from the filter effluent port (Figure 4.1) at regular intervals, specifically every 10 minutes starting from 15 minutes (T15) and continuing up to 75 minutes (T75) following the start of the seeding process. Drawing insights from tracer studies conducted it was established that the residence time between the seed suspension addition point and the influent sample collection location spanned 15-20 minutes (Appendix B). Hence, the first sample post T0 was collected at T15. In total, 16 samples (including influent and effluent samples) were collected for each filter throughout the experimental duration. Each filter effluent sample was collected in a 500 mL bottle over 5-minute period from a continuously running effluent line. The entire filter effluent sample was analyzed for *Cryptosporidium* oocysts. In contrast, influent samples were collected in 125 mL bottles over a brief 0.5-minute period from a port directly above the filter media (Figure 4.1). The filter influent stream flowed for at least 15 seconds before each sample collection to ensure a representative sample.

4.3.4 *Cryptosporidium* enumeration protocol

Cryptosporidium oocyst concentration, identification, and enumeration analyses were conducted following direct membrane filtration, immunofluorescence assay (IFA) staining (EasyStain™, Biotpoint, Narabang Way Belrose, Sydney, Australia), and fluorescence microscopy at 400x magnification (Axioskop 2 plus, Zeiss, Göttingen, Germany), respectively. The filter effluent sample (500 mL) was used to evaluate *Cryptosporidium* oocyst concentration. In contrast, due to the high oocyst concentrations in the influent, only a fraction, specifically 2–5 mL, underwent analysis for the presence of *Cryptosporidium* oocysts. The samples were vacuum filtered through 25 mm diameter 1 µm nominal porosity polycarbonate filter membranes (Whatman Nuclepore®, Whatman Inc., GE Healthcare Life Sciences, Mississauga, ON, CA) on a manifold at -21 inches of Hg (-533 mmHg). All bottles and manifolds were rinsed with a detergent solution (1X phosphate-buffered saline with Tween 80 [PBST]) before and after use (VWR®, Avantor™, Pennsylvania, USA). The subsequent application of IFA stain to the filter membrane surfaces was followed by an incubation period at 35°C, lasting a minimum of 30 minutes. Post-incubation, the membranes were mounted on glass slides to facilitate oocyst enumeration through microscopy. For an initial seed concentration of 10⁵ oocysts/L, an oocyst count of at least 10, preferably ranging from 30 to 100 oocysts per slide, was targeted (Emelko et al., 2008).

4.2.5 *Cryptosporidium* oocyst removal estimation

Oocysts removals were calculated from the individual pairs of measured filter influent and effluent sample *Cryptosporidium* oocyst concentrations. All non-detects were documented as zero, and a value of "1" was utilized to ensure a conservative estimate of the removal achieved if an effluent sample yielded a count of zero (Chik et al., 2018). Filter influent oocyst concentrations from each filter run were averaged and oocyst percent reduction by CAF was calculated for each filter effluent sample collected (except for the sample collected at T0). These percent reductions were then averaged, and the logarithm of the average was used to determine the effective log reduction of *Cryptosporidium* oocysts during each filter run (Teunis et al., 2009; Schmidt et al., 2020).

Conventional confidence interval analyses were not applied to *Cryptosporidium* oocyst removal data because oocyst counts are discrete, non-normally distributed, and exhibit concentration-dependent (heteroscedastic) variance, violating the assumptions of traditional statistical methods (Emelko et al., 2008, 2010). Although Bayesian approaches using credible intervals have been proposed to better represent analytical uncertainty (Emelko et al., 2010), no standardized method currently exists for their application to *Cryptosporidium* oocyst removal. As a result, oocyst removal results are commonly reported without statistical intervals in the literature (LeChevallier et al., 1991; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2001, 2002; Emelko et al., 2005; Hashimoto et al., 2001; Mazoua and Chauveheid, 2005; Ballantyne et al., 2024). Consistent with regulatory practice, which evaluates treatment performance based on average log-removal credits rather than statistical bounds (EPA, 2006a; Health Canada, 2012), log removal values in this study are therefore reported as point estimates.

4.2.6 Zeta potential analysis

Zeta potential was measured using a ZetaSizer Nano Z analyzer (Malvern Panalytical, Mississauga, ON, Canada). For each sample, an aliquot of 10 mL was used to rinse the measurement cuvette, after which approximately 0.75 mL was retained for analysis. Measurements were conducted in triplicate, with each run comprising multiple individual zeta potential readings (i.e., maximum 50) that were averaged by the instrument to give a single zeta potential value per run. Between measurements, sampling and measurement components were rinsed with ultrapure Milli-Q™ Type I water (resistivity >18 MΩ·cm; conductivity <0.056 µS/cm; <50 ppb total organic carbon [TOC]).

Although statistical characterization of zeta potential variability would be desirable, this was not feasible because raw measurement distributions were not available. Instrument-reported “zeta deviation” values but could not be interpreted or used due to the unknown underlying distributions, particularly following coagulant addition when preferential particle destabilization may occur. This can change the underlying distribution of particle (including *Cryptosporidium* oocyst) zeta potentials. The variability between replicate runs was inconsequential (typically within 1–2 mV); therefore, zeta potential results are reported as average values of the triplicate runs only.

4.3 Results and Discussion

4.3.1 Direct in-line CAF performance in the removal of *Cryptosporidium* oocysts

Cryptosporidium oocyst removal by pilot-scale direct in-line CAF with three filter media configurations (i.e., configuration 2A, 3-1, and 3-2) operated at warm ($>8^{\circ}\text{C}$) and cold ($<8^{\circ}\text{C}$) pre-chlorinated raw water temperatures is summarized in Figure 4.2. The figure presents results from 23 experiments in which the pilot’s pre-chlorinated raw water was coagulated at a dose resulting in sub-optimal particle destabilization (5 to 9 mg/L alum), while the oocyst seed suspension received varying coagulant doses to create both optimal and sub-optimal particle destabilization conditions. This experimental design allowed for controlled investigation of oocyst destabilization effects under otherwise consistent pilot operating conditions.

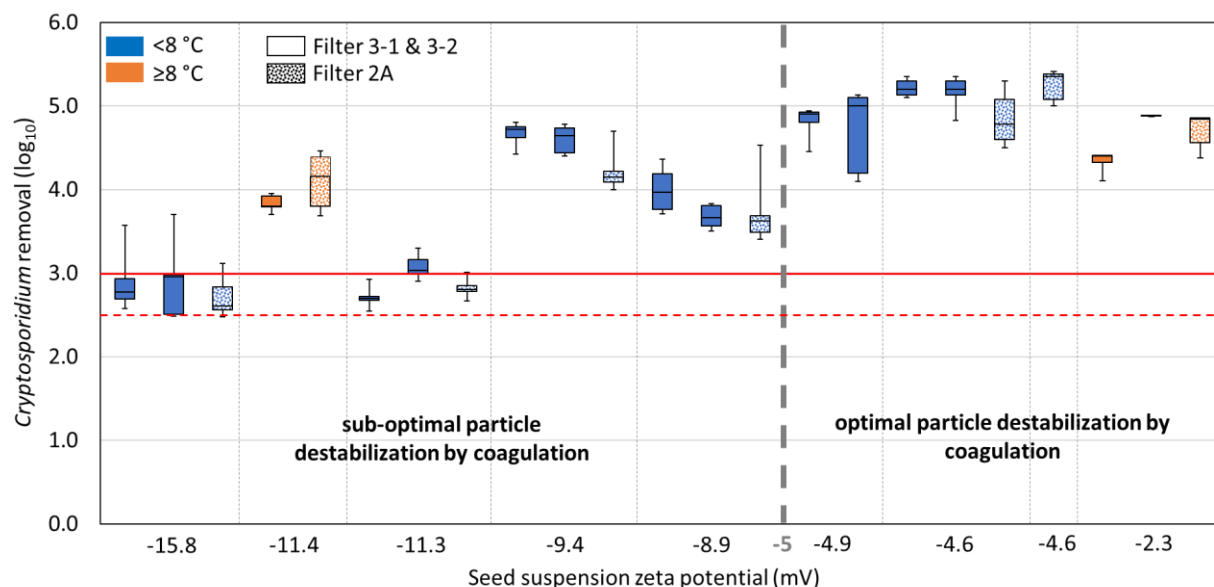


Figure 4.2. Effective removal of *Cryptosporidium* oocysts by pilot-scale direct in-line CAF with destabilized oocysts added to the filter influent. The Y-axis of the graph indicates the *Cryptosporidium*

oocyst log removal, and the X-axis indicates the extent of particle destabilization (i.e., zeta potential) measured for each experiment. The X-axis does not follow a continuous scale; instead, it represents individual zeta potential values observed for sets of experiments separated by dotted lines. The box and whisker plots in the figure represent the minimum, 25th, 50th, and 75th percentiles, and maximum values for removals. Experiments were conducted under different temperature conditions, with warm (>8°C) represented by orange box plots and cold (<8°C) by blue box plots. The pattern-filled box plots indicate Filter 2A and solid-filled boxplots indicate duplicate Filters 3-1 and 3-2. The experiments were categorized into two particle destabilization conditions separated by the thick dashed gray line at -5 mV. Those on the left of the dashed line were conducted with sub-optimal particle destabilization (i.e., zeta potential < -5 mV), while those on the right had optimal particle destabilization (i.e., zeta potential ≥ -5 mV). The dotted red line denotes the 2.5-log oocyst removal benchmark expected for well-operated direct filtration (or direct in-line) CAF, while the solid red line denotes the 3-log oocyst removal benchmark expected for well-operated conventional CAF. Pre-chlorinated raw water quality and operational conditions relevant to all experiments, along with individual oocyst removal data, are provided in Appendix J. The overall effective log reductions (OELR: Schmidt et al., 2020) corresponding specifically to the experiments shown in this figure are presented in Appendix H.

Figure 4.2 shows a clear trend between particle destabilization, measured by zeta potential, and *Cryptosporidium* oocyst removal. As expected, removal increased when zeta potential approached ±5 mV of 0 (moving from left to right in Figure 4.2), indicating more effective particle destabilization. This relationship is particularly important for high-quality source waters, where low particle concentrations make it more challenging to achieve adequate coagulation and sufficient destabilization. Achieving zeta potential closer to 0 mV ensures colloidal particles, including *Cryptosporidium* oocysts, are effectively captured by the filter, thereby reducing the risk of particle breakthrough. This finding is consistent with previous research and industry practice, which emphasizes the central role of adequate coagulation and sufficient destabilization for 3-log *Cryptosporidium* oocysts removal by CAF performance (LeChevallier et al., 1991; Ongerth and Pecoraro, 1995; Edzwald and Kelley, 1998; Emelko, 2003; Nascimento et al., 2020). Comparable results were also reported for pilot-scale studies of conventional CAF (Chapter 3).

When oocyst destabilization was optimal (±5 mV of 0), removals consistently exceeded 3-log and in several cases approached 5-log, surpassing the regulatory benchmark for “well-operated” CAF systems. This performance advantage can be attributed to increased opportunities for particle destabilization, enabled by the shortened residence time between coagulant addition and filter influent. At low turbidity, low DOC

conditions, adequate coagulant addition produces micro-precipitates and short-lived monomeric or oligomeric species that act as effective contactors (Amirtharajah and Mills, 1982; Amirtharajah and O'Melia, 1990; Crittenden et al., 2012), increasing particle–coagulant interaction opportunities and facilitating effective oocyst destabilization. In the absence of flocculation and sedimentation basins, the shorter residence time between coagulant addition and the filter influent may enable rapid delivery of micro-precipitates, limiting further hydrolysis and polymerization (Amirtharajah and Mills, 1982) and minimizing coagulant retention or losses to upstream basin surfaces. Together, these conditions likely enhanced collisions between particles (including oocysts) and micro-precipitates, promoting destabilization and easier control over coagulant hydrolysis endpoints, and attachment to filter media, thereby improving coagulant efficiency and overall particle removal by CAF.

This performance reflects the fundamental design intent of direct in-line CAF: to maximize particle–collector interactions when low source water turbidity and particle concentrations preclude effective clarification (Ngo et al., 1995; Letterman, 1999; Crittenden et al., 2012). Conventional CAF relies on flocculation and sedimentation to remove most solids upstream and is designed to manage lower particle loads using smaller filter media grain sizes (ES ~ 1 mm for anthracite and ~0.5 mm for sand). In contrast, direct in-line CAF relies on larger media grain sizes (ES ~ 1.4 mm for anthracite and ~0.6 mm for sand) to allow for depth filtration, which increases the filter's capacity to store solids, reduce time to breakthrough, and increase time to limiting headloss (Crittenden et al., 2012). The absence of sedimentation is therefore not a limitation, but an intentional design change that allows for increased contact opportunities for particle destabilization and effective depth filtration within the treatment process. Although U.S. and Canadian regulatory frameworks currently assign only a 2.5-log removal credit to direct in-line CAF (EPA, 2006a; Health Canada, 2012), the results of this study demonstrate that, when particle destabilization is optimized, direct in-line CAF can consistently meet or exceed the 3-log removal benchmark credited to well-operated conventional CAF systems. These findings suggest that the removal credit assigned to direct CAF and direct in-line CAF should be based on demonstrated treatment performance rather than derived indirectly through the subtraction of credits associated with the absence of additional treatment processes, such as sedimentation as is presently prescribed in regulatory guidance (EPA, 2006a).

The data also indicates that the zeta potential range associated with achieving ≥ 3 -log oocyst removal in direct in-line CAF may differ from the previously observed range of ± 5 mV of 0. As described in Chapter 3, this range was identified for conventional CAF treating the same source water and was assumed to distinguish optimal from sub-optimal particle destabilization. However, for direct in-line CAF, the lower

end of this range may be different. As shown on Figure 4.2, removals exceeding 3-log were achieved even at ZP values near -10 mV. This further emphasizes that zeta potential should be interpreted as a system-specific indicator rather than a universal range applicable to all systems, recognizing limitations associated with it as described in Chapter 3.

Although the figure displays the temperature conditions for each experiment, with warm ($>8^{\circ}\text{C}$) and cold ($<8^{\circ}\text{C}$) pre-chlorinated raw water temperatures, it's important to note that the study did not primarily focus on the effects of temperature on *Cryptosporidium* oocyst removal. Temperature was routinely recorded as it cannot be controlled, and it is possible to have substantial shifts in large lakes such as Lake Ontario (due to lake currents, mixing dynamics, or “turn over”). Nevertheless, no significant temperature-dependent trends were observed, consistent with prior findings for conventional CAF (Chapter 2).

While filter performance between the media configurations were not analyzed using a factorial design, no discernible performance differences were observed between filter media configurations when particle destabilization was optimized. It is worth emphasizing that variability of approximately an order of magnitude (i.e., 1-log) or more in *Cryptosporidium* oocyst removal has been frequently documented among replicate filters operated under identical conditions (Emelko, 2001; Huck et al., 2001; Xagorarakis and Harrington, 2004; Emelko et al., 2005; Assavasilavasukul et al., 2008; Chapter 2; Chapter 3). Therefore, the findings reported here align with trends previously described in the literature.

4.3.2 Comparison of direct in-line and conventional CAF performance

A performance comparison of *Cryptosporidium* oocyst removal by pilot-scale conventional and direct in-line CAF was conducted to investigate how the removals observed in Figure 4.2 compared to those achieved by conventional CAF. The first comparison examined experiments conducted under optimal particle destabilization conditions, as shown in Figure 4.3.

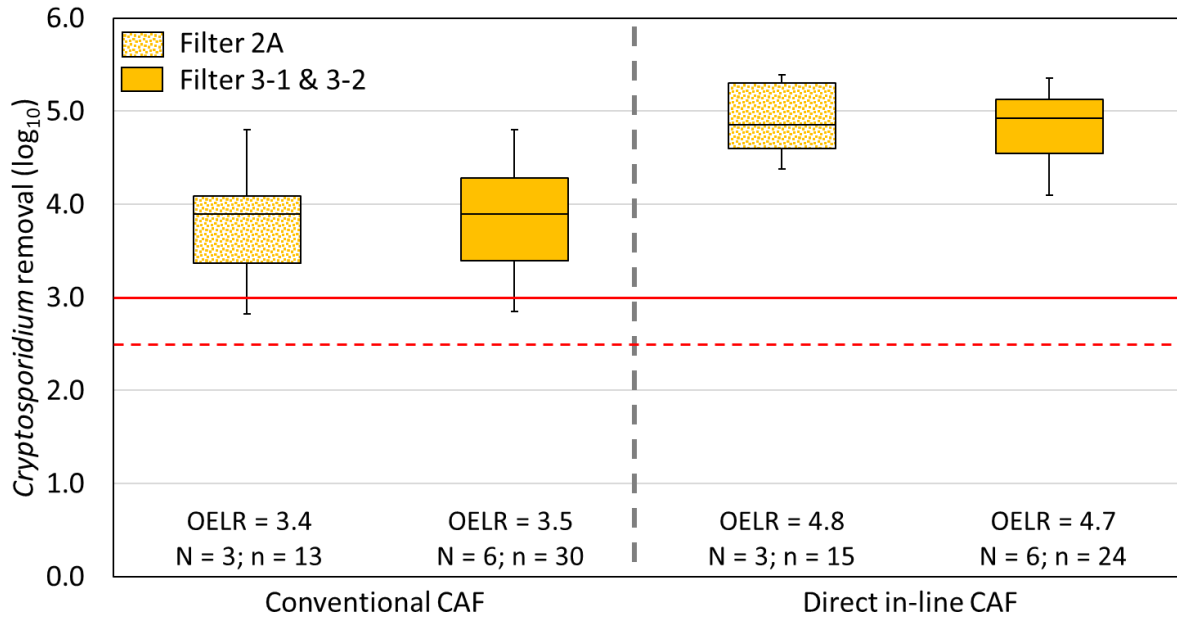


Figure 4.3. Comparison of *Cryptosporidium* oocyst removal by pilot-scale conventional and direct in-line CAF with high concentrations of optimally destabilized oocysts added to filter influent streams. Conventional CAF data are reported in Chapter 3. Each box plot summarizes data from multiple experiments, where N signifies the count of individual filter runs/experiments, and n denotes the number of filter effluent samples considered. The effective log reduction, a logarithmically expressed average of reduction or passage rates, is additionally indicated for each box plot as OELR. The pattern-filled box plots indicate Filter 2A and solid-filled boxplots indicate duplicate Filters 3-1 and 3-2. The dotted red line denotes the 2.5-log oocyst removal benchmark expected for well-operated direct filtration (or direct in-line) CAF, while the solid red line denotes the 3-log oocyst removal benchmark expected for well-operated conventional CAF. Pre-chlorinated raw water quality and operational conditions relevant to all experiments, along with individual oocyst removal data, are provided in Appendix J.

The data set presented in Figure 4.3 includes eight individual filter runs for conventional CAF and six for direct in-line CAF conducted under same operational conditions and filter configurations. Under optimal destabilization conditions, direct in-line CAF demonstrated a discernible upward shift in removal compared to conventional CAF, despite the only distinction being the bypassing of flocculation and sedimentation basins. Across all experiments, the OELR for direct in-line CAF was approximately 1.5-log higher than that of conventional CAF. This enhancement can be attributed to differences in coagulation behavior between the two configurations. As discussed previously, for direct in-line CAF, the shorter residence time

between coagulant addition and filter influent and the minimized coagulant retention to upstream basin surfaces likely increased contact opportunities and delivered destabilized particles more rapidly to the filter bed, enhancing attachment and removal. In contrast, in conventional CAF, coagulant is retained by adsorption onto flocculation and sedimentation basins, reducing its availability for particle destabilization. For these reasons, residual coagulant present in the pilot influent stream (Figure 4.1) for direct in-line CAF may have further contributed to particle destabilization (Emelko, 2021; Huck et al., 2001) than in conventional CAF. In addition, the longer residence times from coagulation to filtration (often several hours) for conventional CAF allows further hydrolysis and complexation of coagulant species (Amirtharajah and Mills, 1982; Duan and Gregory, 2003; Gregory, 2009), which can alter surface chemistry of particles and zeta potential prior to filtration (Chapter 3). As such, the increased removals observed for direct in-line CAF are consistent with established understanding of particle transport and deposition in porous media, which emphasize the importance of particle–collector interactions and the physicochemical environment at the point of filtration (Ives, 1970; Amirtharajah, 1988; Tobiasson and O’Melia, 1988).

A similar comparison was made for experiments conducted under sub-optimal particle destabilization conditions and is illustrated in Figure 4.4. The dataset includes 25 individual filter evaluations for conventional CAF and 14 evaluations for direct in-line CAF. As with the optimal particle destabilization comparison, the primary difference was the absence of flocculation and sedimentation basins in the direct in-line configuration. It should be noted, however, that the extent of oocyst destabilization can vary across experiments due to differences in the degree of sub-optimal destabilization present in each individual run.

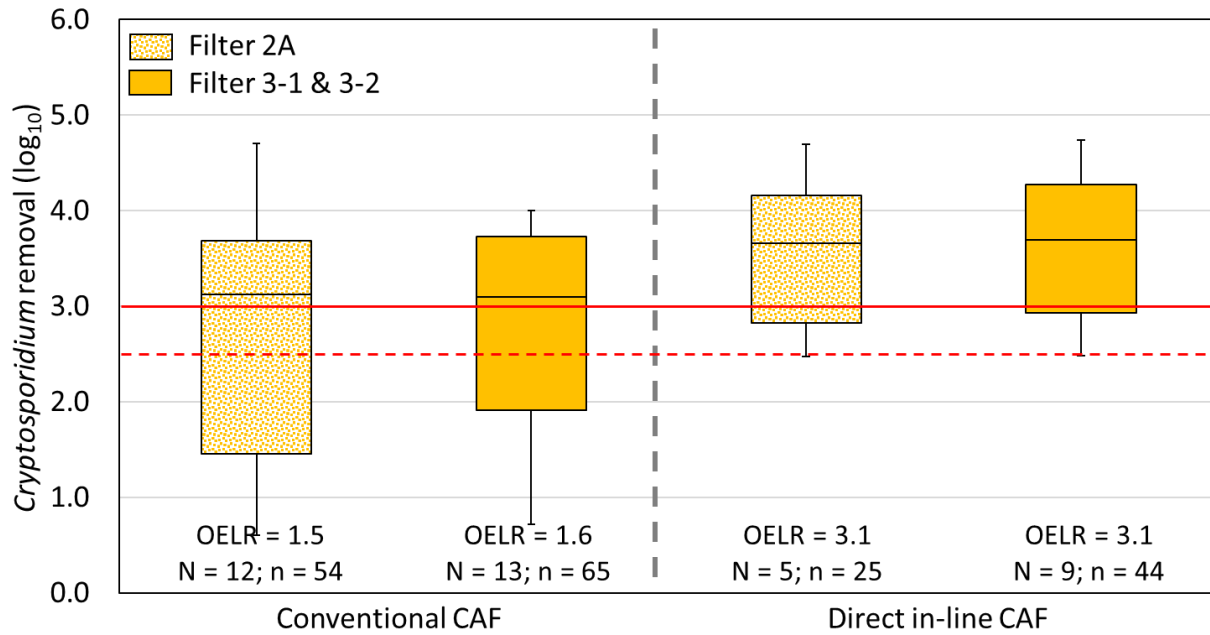


Figure 4.4. Comparison of *Cryptosporidium* oocyst removal by pilot-scale conventional and in-line CAF with high concentrations of sub-optimally destabilized oocysts added to filter influent streams. Each box plot summarizes data from multiple experiments, where N signifies the count of individual runs/experiments, and n denotes the number of filter effluent samples considered. The effective log reduction, a logarithmically expressed average of reduction or passage rates, is additionally indicated for each box plot as OELR. The pattern-filled box plots indicate Filter 2A and solid-filled boxplots indicate Filters 3-1 and 3-2. The dotted red line denotes the 2.5-log oocyst removal benchmark expected for well-operated direct filtration (or direct in-line) CAF, while the solid red line denotes the 3-log oocyst removal benchmark expected for well-operated conventional CAF. Pre-chlorinated raw water quality and operational conditions relevant to all experiments, along with individual oocyst removal data, are provided in Appendix J.

As observed earlier in this study, *Cryptosporidium* oocyst removal by CAF was more variable under sub-optimal particle destabilization, reflecting the sensitivity of CAF performance to particle surface charge when coagulation is insufficient. Although the data showed that direct in-line CAF still outperformed conventional CAF, achieving oocyst removals roughly 1.5-log higher on average, OELRs decreased by about 1-log and the range of removals for both configurations expanded by at least 1-log compared to optimal destabilization conditions. The extended whiskers in Figure 4.4 illustrate this increased variability,

indicating that sub-optimal conditions span a broad continuum of partially destabilized states (i.e., zeta potentials <-5 mV). Under these conditions, differing degrees of incomplete destabilization make it difficult to attribute differences in oocyst removal to specific operational factors. This inherent chemical variability reduces reproducibility from one experiment to the next, and the difficulty is further compounded by natural fluctuations in raw-water particle concentrations and surface charge characteristics. These observations show that achieving high pathogen removal is not solely a matter of plant design; it also depends on well-operated CAF with adequate coagulant addition to achieve sufficient particle destabilization. Without this understanding, even well-designed systems may fall short of expected pathogen removals, because physico-chemical filtration is a two-step process and inadequate particle destabilization limits subsequent attachment and particle removal by CAF (Ives, 1970; O'Melia, 1985; Amirtharajah, 1988; Amirtharajah and O'Melia, 1990; Crittenden et al., 2012).

The figures illustrating the observed performance for Filters 3-1 and 3-2 individually rather than combined as presented in Figures 4.3 and 4.4 are provided in Appendix I.

4.3.3 Broader influence of coagulation and particle destabilization on direct in-line CAF performance

To further investigate the role of particle destabilization in *Cryptosporidium* oocyst removal by direct in-line CAF, 39 additional experiments were conducted. In these trials, coagulant doses were applied to both pre-chlorinated raw water and the oocyst seed suspension, representing various combinations of destabilization conditions.

Figure 4.5. Role of particle destabilization in *Cryptosporidium* oocyst removal by direct in-line CAF with various combinations of particle destabilization of pre-chlorinated raw water and/or oocysts in the seed suspension added to filter influent streams. SS indicates the oocyst seed suspension. Symbols represent different destabilization conditions: grey circles (no destabilization), grey circles with a dashed blue border (sub-optimal particle destabilization), and grey circles with a solid blue border (optimal particle destabilization). N indicates the number of individual filter runs/experiments and n indicates the number of individual filter effluent samples analyzed. The dotted red line denotes the 2.5-log oocyst removal benchmark expected for well-operated direct filtration (or direct in-line) CAF, while the solid red line denotes the 3-log oocyst removal benchmark expected for well-operated conventional CAF. Pre-chlorinated raw water quality and operational conditions relevant to all experiments, along with individual oocyst removal data, are provided in Appendix J.

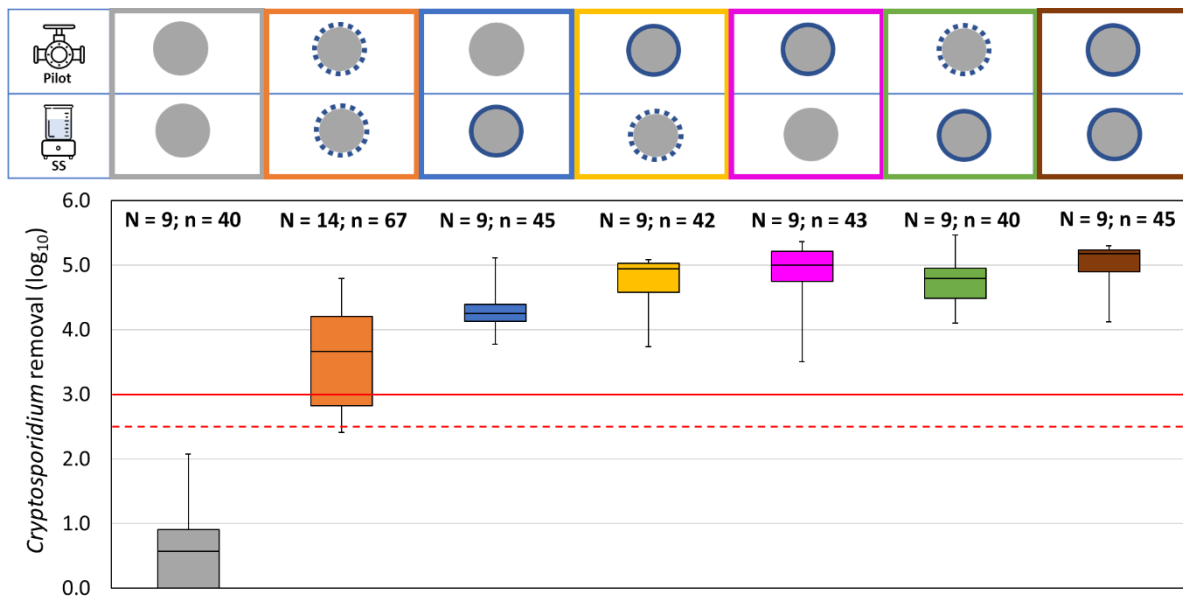


Figure 4.5 help illustrate whether the enhanced oocyst removals observed for direct in-line CAF depended on where particle destabilization occurred—within the pilot water, the seed suspension, or both. The top panel outlines eight destabilization scenarios, ranging from optimal to sub-optimal and to no destabilization, with all combinations in between. The green and orange boxes correspond to the conditions previously presented in Figures 4.3 and 4.4, respectively. As shown in the lower panel, when the seed suspension containing the oocysts was sufficiently destabilized (blue, green, and brown boxes), direct in-line CAF consistently achieved ≥ 3 -log removal of *Cryptosporidium* oocysts, as expected, regardless of the pilot destabilization condition (Chapter 3). This is because oocysts were already sufficiently destabilized prior to introduction at the filter influent (Figure 4.1). Notably, during experiments when seed suspension destabilization was sub-optimal or absent, but the pilot influent stream was adequately destabilized *Cryptosporidium* oocysts removals still exceeded 3-log (yellow and pink boxes).

Even when oocysts were sub-optimally destabilized or not destabilized at the point of introduction, sufficient coagulant addition in the pilot influent stream likely generated micro-precipitates that increased contact opportunities between oocysts, micro-precipitates, and filter media. Similar to what was observed in previous findings, these additional contact opportunities, supported by the reduced residence time and minimized coagulant losses to upstream basins under direct in-line conditions, likely promoted destabilization, attachment, and ultimately improved removal by CAF. Taken together, these findings also help confirm the performance advantage of direct in-line CAF relative to conventional CAF—more of the

applied coagulant reaches the filter influent, supporting more effective oocyst attachment. It is also important to note that the removal significantly dropped and varied when destabilization was absent or sub-optimal for both the pilot and the seed suspension (grey and orange boxes) reinforcing that particle destabilization is a key factor in ensuring *Cryptosporidium* oocysts removal by CAF.

4.4 Conclusions and Implications

During this study several significant insights were revealed.

1. Direct in-line CAF consistently achieved *Cryptosporidium* oocyst removal exceeding 3-log when particles were sufficiently destabilized, as indicated by a zeta potential within ± 5 mV of 0. In several cases, removals approached 5-log, substantially exceeding the 3-log regulatory expectations for “well-operated” treatment performance. Although current U.S. EPA SWTRs and Canadian guidelines assign only a 2.5-log treatment credit to direct filtration systems (EPA, 2006a; Health Canada, 2012), the results from this work demonstrate that well-operated direct in-line CAF can reliably achieve *Cryptosporidium* removals ≥ 3 -log.

Collectively, the findings indicate that treatment credit for direct in-line CAF should be based on demonstrated performance rather than inferred from the presence or absence of specific treatment units (e.g., sedimentation), thereby supporting reconsideration of the 2.5-log removal credit currently assigned to direct in-line CAF systems. For high-quality source waters, direct in-line CAF—when supported by operational tools such as zeta-potential analysis—represents an effective and robust approach for pathogen removal and warrants broader consideration in future treatment design.

2. Well-operated direct in-line CAF consistently exhibited equivalent or higher *Cryptosporidium* oocyst removal than conventional CAF when supported by adequate coagulant dosing for sufficient particle destabilization. Results from Figures 4.2 through 4.5 indicate that, for high-quality source waters, sedimentation provides limited additional removal benefit. Under these conditions, direct in-line CAF consistently achieved—and frequently exceeded—the 3-log *Cryptosporidium* removal target currently credited to conventional CAF, with average removals approximately 1.5-log higher under otherwise comparable operating conditions.

This performance advantage reflects the design and operational characteristics of direct in-line CAF, which is likely to promote more effective delivery of alum hydrolysis species to the filter.

The shortened residence time between coagulant addition and filtration reduces losses to upstream surfaces, enables improved control of coagulant hydrolysis endpoints, and ensures that micro-precipitates reach the filter influent. Together, these factors increase collision frequency between oocysts, micro-precipitates, and filter media, enhancing particle destabilization, attachment, and overall filter performance. Collectively, the results underscore that particle (including oocysts), removal is governed by an appropriate combination of infrastructure design, operational control, and mechanistic understanding of treatment processes.

3. Minimum zeta potential value required for achieving ≥ 3 -log *Cryptosporidium* oocyst removal may differ between treatment configurations (i.e., direct in-line and conventional CAF). During this work, experiments achieved ≥ 3 -log removal even at zeta potentials as low as -10 mV, indicating that the operational range for sufficient particle destabilization may be broader in direct in-line systems. This may be partly explained by residual alum in the pilot influent stream enhancing oocyst destabilization and removal (Emelko, 2001, Huck et al., 2001), even when the seed suspension itself was at -10 mV.

These findings reinforce that although zeta potential values within a few millivolts of 0 typically reflect maximal destabilization, the minimum zeta potential threshold corresponding to the minimum coagulant dose required for achieving ≥ 3 -log removal is system specific. Differences in hydraulics, contact opportunities, and coagulant availability across treatment configurations can shift the zeta-potential value at which adequate destabilization and ≥ 3 -log removal is achieved.

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Chapter 5. Microplastics behave like other particulate contaminants treated by drinking water filtration

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Summary

Microplastics (MPs) are increasingly recognized as emerging contaminants in drinking water; however, uncertainties remain regarding their behavior in treatment systems and the extent to which existing drinking water technologies can remove them. In the absence of health-based regulatory targets or routine monitoring frameworks, understanding MP removal mechanisms is essential for future risk assessment. Yet, despite the perception that MP removal remains poorly understood, the fundamental principles governing their fate in treatment processes (i.e., filtration) may not be as uncertain as commonly assumed. This study evaluated the removal of pristine and weathered polystyrene MPs, alongside *Cryptosporidium* oocysts, using pilot-scale chemically assisted filtration (CAF) operated under varying destabilization conditions. Under optimal destabilization, MPs were consistently removed at 3.5- to 4-log, comparable to oocyst removal. Sub-optimal destabilization resulted in reduced and variable removal for all particle types. Across all scenarios, sufficient destabilization was a significant driver of particle (including MPs and oocysts) removal by CAF. These findings demonstrate that MPs behave similarly to other colloidal particles and can be effectively removed by CAF when sufficiently destabilized consistent with colloidal filtration theory. The work also shows that existing protozoan-based analytical and performance frameworks may be applicable for evaluating MP removal once health-based treatment targets are established.

5.1 Introduction

Microplastics (MPs), generally defined as plastic particles smaller than 5 mm (NOAA, 2015; ISO/TR 21960, 2020), are receiving increasing attention as an emerging contaminant of concern. MPs are persistent, bioaccumulative, and potentially toxic, and evidence indicates that humans are exposed through water, food, and air (EFSA, 2016; Prata, 2018; WHO, 2019; Li et al., 2023). Despite this growing recognition, major gaps remain regarding their long-term health impacts, ecological risks, and behavior in natural and engineered systems (Wang et al., 2021; WHO, 2019). MPs originate both from the breakdown of larger plastics and from intentionally manufactured microbeads (Wang et al., 2021; Acarer, 2023; Li et al., 2023),

with their widespread use contributing to increasing MP loads in most water bodies (i.e., rivers, lakes, and oceans) (Eriksen et al., 2013; Pivokonsky et al., 2018; Eerkes-Medrano et al., 2019; Chowdhury et al., 2023). As such, the detection of MPs in both source and treated drinking water worldwide has heightened public concern and stimulated discussion among regulatory bodies (WHO, U.S. EPA, EU) regarding future monitoring and control strategies (NOAA, 2015; WHO, 2019; EU, 2020).

Despite this attention, no standardized regulations or routine monitoring frameworks currently exist (WHO, 2019). Analytical challenges—including non-standardized sampling and extraction methods, inconsistent size detection limits, and divergent polymer identification techniques (FTIR, Raman, pyrolysis-GC/MS)—result in inconsistent and incomparable occurrence data (Li et al., 2018; Koelmans et al., 2019; WHO, 2019). Consequently, major knowledge gaps persist regarding the concentrations of MPs across different water matrices, the forms in which they occur, their behavior within treatment processes, and the health risks associated with exposure. These gaps highlight the need for a clearer understanding of how existing drinking water treatment processes can manage MPs, even though MPs are not presently included in routine monitoring or regulatory frameworks, yet drinking water remains a direct and potentially continuous exposure route.

Historically, when particulate contaminants with potential or direct health-based endpoints have been shown to pose especially high risks (such as protozoan pathogens) treatment performance has been evaluated through performance demonstration studies that inform regulatory standards (LeChevallier et al., 1991; LeChevallier and Norton, 1992; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; States et al., 1997; Edzwald and Kelley, 1998; Emelko, 2001; Huck et al., 2001, 2002; Emelko, 2003; Emelko et al., 2005; Hendricks et al., 2005; Assavasilavasukul et al., 2008). For fine colloidal particles that are often insufficiently removed by clarification alone, physico-chemical filtration (also known as chemically assisted filtration; CAF) represents a key barrier for achieving effective removal. Regulatory frameworks are therefore grounded in the performance of CAF, which serves as the polishing step for particles that persist beyond sedimentation. For these processes, coagulation plays a critical role in destabilizing fine particles and enhancing particle attachment during CAF (O'Melia, 1985; Amirtharajah and O'Melia, 1990; Edzwald, 1993; Crittenden et al., 2012; Edzwald, 2013).

Importantly, regulatory compliance is not based on direct measurement of pathogen removal, which is not feasible during routine operations (Regli et al., 1991; Haas et al., 1996). Instead, it is founded on a treatment technique (TT) based approach (EPA, 2006a). This framework operates on the premise that a “well-operated” treatment process, measured through surrogate performance indicators (i.e., filter effluent

turbidity in the case of CAF) can reliably ensure a prescribed level of pathogen removal (EPA, 2006a; Health Canada, 2012). Health-based endpoints are not established for all contaminants; they are introduced only when a contaminant presents a clearly defined and significant health risk supported by sufficient toxicological and exposure evidence (WHO, 2017). Therefore, a comparable framework does not yet exist for MPs, which currently fall outside monitoring and regulatory requirements. Emerging work, such as the Threshold Microplastics Concentration (TMC) proposed by Chowdhury et al., (2024), offers an early health-based reference point. The TMC represents the source water MP concentration below which treated water adsorbed regulated contaminant concentrations are not expected to pose health concerns under well-operated conventional treatment achieving ~3-log removal (Chowdhury et al., 2024). However, even for such thresholds, the lack of treatment performance data for MPs limits their practical application and the confidence with which they can inform risk assessment.

MPs share several characteristics with other colloidal particles relevant to CAF, including small size, surface charge, and physicochemical heterogeneity (Ma et al., 2019b; Yao et al., 2023a). Although MPs differ in polymer composition, shape, density, and hydrophobicity, established colloidal filtration theory suggests that adequate coagulant addition can overcome these surface-property differences (Stumm and O'Melia 1967; Ives, 1970; Yao et al., 1971; Tufenkji and Elimelech, 2004). This principle is well established for *Cryptosporidium* oocysts, which despite unique surface attributes are consistently removed once destabilized (Ballantyne et al., 2024; Chapter 3; Chapter 4). Given that particle destabilization and attachment are governed primarily by electrostatic interactions, zeta potential helps inform particle destabilization by coagulant addition (Chapter 3).

While MP removal has been investigated across bench-, pilot-, and full-scale drinking water treatment systems, much of this work occurred before MPs were recognized as a distinct contaminant of concern. In earlier studies, MPs were introduced primarily to support evaluations of CAF performance for protozoan removal, particularly *Cryptosporidium*, rather than to assess MP behavior (Dai and Hozalski, 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Amburgey et al., 2012; Liu et al., 2019). Their use was therefore indirect, intended to represent (bio)particle transport rather than to characterize MP removal itself. As research has begun to explicitly target MPs, most studies remain dose-driven and primarily report aggregate removal efficiencies, often emphasizing coagulation-induced aggregation (Pivokonsky et al., 2018; Ma et al., 2019; Lapointe et al., 2020; Skaf et al., 2020; Peyadesh et al., 2021; Zhou et al., 2021; Khan et al., 2023; Yu et al., 2024). As a result, reported removal efficiencies do not explicitly address whether MPs behave in accordance with established principles of particle destabilization, transport, and attachment, key

processes for the removal of other colloidal particles such as *Cryptosporidium* oocysts. Confirming whether these coagulation–CAF principles apply to MPs in the same way is therefore essential for understanding how effectively drinking water treatment technologies can remove them.

The present study addresses these gaps by evaluating removal of MPs alongside *Cryptosporidium* oocysts and by characterizing their removal during CAF at pilot-scale across both optimal and sub-optimal destabilization conditions by coagulant addition. These findings also offer insight into analytical approaches suited for evaluating MP removal by CAF and clarify the extent to which existing drinking water treatment infrastructure can effectively manage MPs, supporting broader efforts in public health risk assessment, treatment optimization, and the development of future monitoring and regulatory strategies.

5.2 Results and discussion

5.2.1 MP and oocyst removal by CAF under varying destabilization conditions

Figure 5.1 illustrates the removal of MPs and *Cryptosporidium* oocysts by CAF using high-quality Lake Ontario source water. Results are shown for a direct in-line CAF configuration under stable pilot-scale operating conditions at a hydraulic loading rate of 4.6 m/h. MP removal is shown for pristine blue (BB) particles and functionalized carboxylated yellow–green (YG) particles, the latter used to simulate weathered MPs (Sarkar et al., 2021; Borgmeyer et al., 2024), alongside *Cryptosporidium* oocyst removal to enable comparison with other colloidal particles. Data are grouped to compare removal performance under optimal (zeta potential within ± 5 mV of zero) and sub-optimal (< -5 mV) particle destabilization following coagulant addition. Results are presented for two representative filter configurations: Filter 2A, a shallow-dual-media filter comprising 450 mm of anthracite over 300 mm of sand, and Filter 3-1, a deep dual-media filter comprising 1000 mm of anthracite over 300 mm of sand. Further experimental details are provided in Methods (Section 5.4).

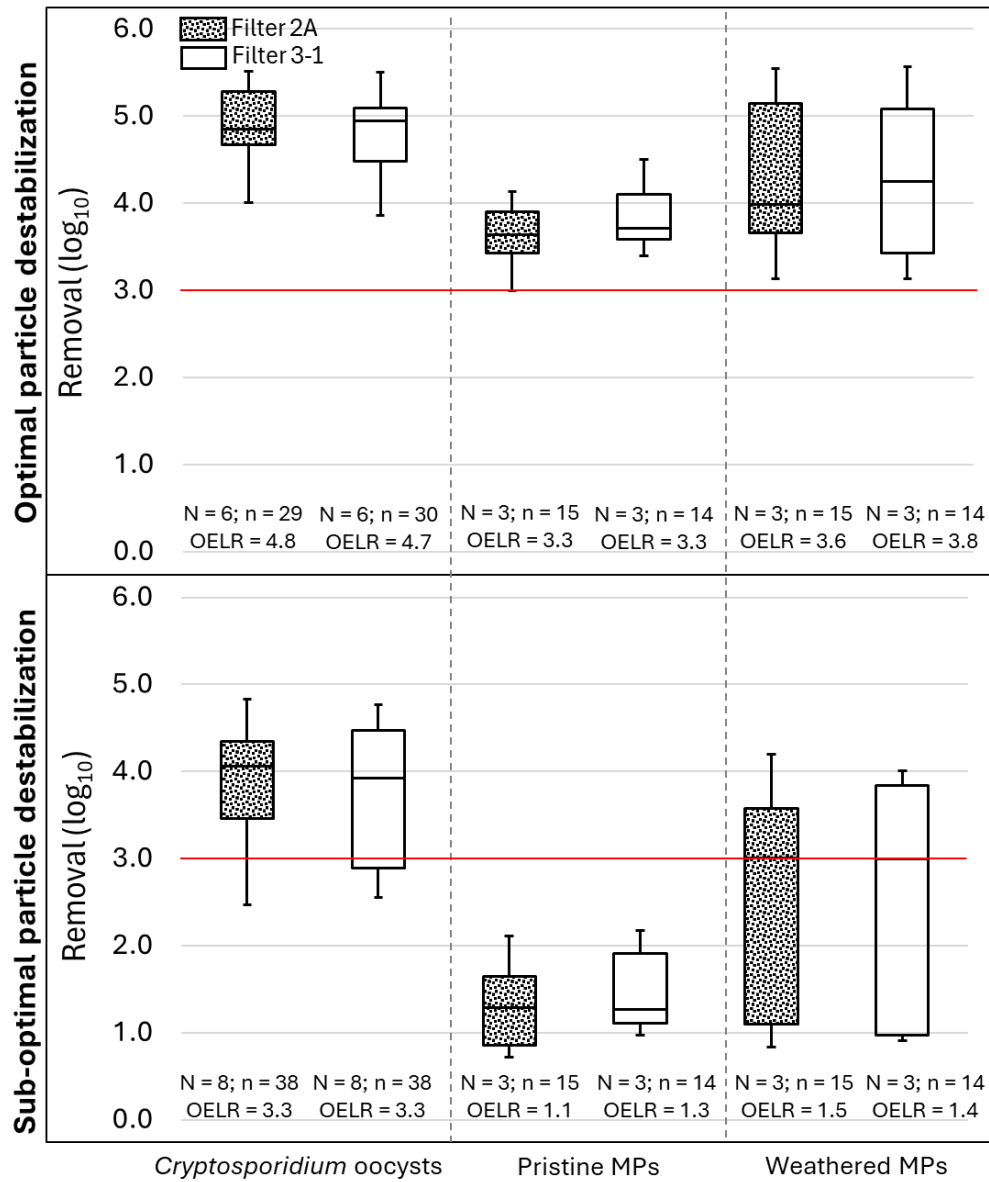


Figure 5.1. MP and *Cryptosporidium* oocyst removal by pilot-scale CAF configurations under optimal and sub-optimal particle destabilization by coagulant addition. The top panel presents removal achieved under optimal destabilization conditions (zeta potential within ± 5 mV of 0), and the bottom panel shows removal under sub-optimal destabilization (zeta potential < -5 mV). Dashed vertical lines separate the three particle types evaluated. Each boxplot integrates multiple experimental runs; N indicates the number of filter runs and n the number of filter effluent samples analyzed. The overall effective log reduction (OELR; Schmidt et al., 2020) is shown below each boxplot. Boxes represent the interquartile range (25th–75th percentile),

whiskers show the minimum and maximum values, and horizontal lines indicate medians. The horizontal red line shows the 3.0-log (99.9%) removal performance associated with “well-operated” CAF for *Cryptosporidium* oocysts (as credited by the USEPA and Health Canada). Pattern-filled boxplots correspond to Filter 2A and solid (no-fill) boxplots to Filter 3-1. Pattern-filled boxplots correspond to Filter 2A, and solid (no-fill) boxplots correspond to Filter 3-1. Pre-chlorinated raw water quality and operational conditions relevant to all experiments, along with individual oocyst removal data, are provided in Appendix K.

5.2.1.1 Optimal particle destabilization

Under optimal particle destabilization, both pristine and weathered MPs achieved consistently ≥ 3 -log (99.9%) removal, on average around 3.5- to 4-log, as indicated by the OELRs. The OELR summarizes reduction or passage rates and expresses these as a log reduction rather than averaging individual log removals, providing a better representation of the overall performance of the treatment technology (Schmidt et al., 2020). Pristine MPs exhibited narrow interquartile ranges and short whiskers, indicating minimal variability. This stability is likely attributable to their rigid, uniform polystyrene surfaces and consistent hydrophobicity and charge characteristics. Similar behavior of pristine polystyrene particles has been documented in previous coagulation studies (Lapointe et al., 2020; Yao et al., 2023b; Gomes, 2024).

Weathered (carboxylated) MPs also exhibited similar removals, though with larger interquartile ranges and longer whiskers. This greater variability likely reflects the heterogeneous surface properties introduced through weathering or functionalization, specifically, oxygen-containing surface groups, increased roughness, and broader distributions of surface charge. These traits have been shown to influence coagulant–particle interactions and increase variability in aggregation and particle destabilization (Amirtharajah and O’Melia, 1990; P. Liu et al., 2019; Ma et al., 2019a; Duan et al., 2021; Gomes, 2024). Even so, the consistent removals ≥ 3 -log observed demonstrate that surface oxidation can affect MP behavior and its subsequent removal by CAF, but they can be overcome through adequate coagulant dosing to maximize destabilization.

Consistent with prior pilot-scale findings, oocyst removal was high and typically ≥ 4 -log when coagulation–CAF performance was optimized, with an OELR of 4.8-log (Emelko and Huck, 2004; Lee, 2018; Ballantyne et al., 2024; Chapter 4). In this study, oocyst removals were slightly higher than those of the MPs as indicated by the calculated OELRs; however, this aligns with established observations in the literature when microspheres were used as surrogates for pathogen removal (Emelko et al., 2003; Emelko

and Huck, 2004; Brown and Emelko, 2009). Importantly, variability of approximately one order of magnitude (~ 1 -log) among replicate filters operated under identical conditions is well documented for oocysts (Emelko, 2001; Huck et al., 2001; Xagorarakis and Harrington, 2004; Emelko et al., 2005; Assavasilavasukul et al., 2008; Chapter 2; Chapter 3; Chapter 4). Thus, the ≤ 1 -log differences observed between particle types here fall well within expected operational variability and are not considered significant. The two filter media configurations were evaluated primarily to demonstrate that, when particle destabilization is optimized, they exhibit no discernible differences in performance—rather than conducting an in-depth comparison of media design. This is supported by the nearly identical OELRs observed for each particle type across filters 2A and 3-1. This further emphasizes that, given that filters are well designed and well operated, sufficient particle destabilization through appropriate coagulant addition is far more critical to achieving high CAF removals than the specific filter configuration.

At optimal destabilization conditions under stable filter operation, MPs behaved similarly to other colloidal particles and were removed by CAF, consistent with coagulation-CAF principles (O'Melia and Stumm, 1967; Ives, 1970; Amiratharajah, 1988; Tobiasson and O'Melia, 1988). Although no health-based removal targets currently exist for MPs, the observed removals consistently exceeded the 3-log benchmark used for protozoan pathogen control (EPA, 2006a; Health Canada, 2012).

5.2.1.2 Sub-optimal particle destabilization

Under sub-optimal destabilization (zeta potential < -5 mV after coagulant addition), removals decreased and became more variable across all particle types (Figure 5.1, bottom panel). Pristine MPs showed substantially reduced removal, with OELRs of 1.1-log (Filter 2A) and 1.3-log (Filter 3-1). Under these conditions, pristine MPs likely remained colloidally stable, experienced limited aggregation, which led to reduced attachment efficiency during CAF, consistent with colloidal filtration theory and findings in literature indicating that insufficient destabilization results in increased electrostatic repulsion (Stumm and O'Melia 1967; Ives, 1970; Yao et al., 1971; Edzwald, 2013; Lee, 2018; Ballantyne et al., 2024). While pristine MP removal varied slightly more than under optimal destabilization conditions, the limited dataset in this study did not exhibit increased variability. Nevertheless, potential variability in MP removal under such conditions remains an important consideration.

In contrast, weathered MPs exhibited noticeably greater variability at sub-optimal destabilization conditions, similar to optimal conditions but more pronounced. Removal spanned approximately 1- to 4-log, with most values below 3-log, resulting in OELRs of 1.5-log (Filter 2A) and 1.4-log (Filter 3-1). This

highlights the broader range of destabilization experienced by weathered MPs under poor coagulation conditions, reflecting their heterogeneous oxidation states, functional group density, and localized surface-charge and destabilization variability as explained before. These traits amplify differences in particle behavior when insufficient coagulant is added, resulting in wider boxplots and reduced reproducibility.

Cryptosporidium oocyst removal decreased under sub-optimal destabilization but remained higher than MP removal. This trend mirrors what was observed under optimal destabilization and is consistent with reported findings in the literature (Emelko and Huck, 2004; Brown and Emelko, 2009). Although this variability is not explored in depth here, one plausible explanation is that oocysts typically exhibit less negative surface charge than MPs, enabling more effective destabilization and attachment under adequate coagulation. In addition, as biological particles, oocysts possess flexible surface structures that may facilitate deformation, interaction, or aggregation in ways that rigid, hydrophobic MPs cannot. However, this study was not designed to evaluate whether *Cryptosporidium* or MPs serve as surrogates for one another. Instead, the intention was to demonstrate how coagulation chemistry governs removal across different colloidal particles and to highlight the applicability of these principles for enhancing their removal by CAF.

Achieving sufficient destabilization in low-DOC, low-turbidity source waters such as Lake Ontario is inherently challenging (Chapter 2; Chapter 3; Chapter 4). With few particles and little organic matter, there are limited surfaces for hydrolyzed coagulant species to interact with, reducing the efficiency of particle destabilization as described in Chapter 4. Because hydrolysis reactions determine which destabilization mechanisms dominate at a given pH and dose, high-quality source waters with pH around 8 often require higher-than-expected alum dose for effective pathogen removal as discussed by in Chapter 3 and Chapter 4. This same relationship was observed for MPs, where increased quantities of metal-hydroxide micro-precipitates were needed to create sufficient collision and attachment opportunities for MPs for increased CAF performance.

This behavior was also demonstrated in Figure 5.2. MPs experienced sub-optimal destabilization due to insufficient coagulant addition and micro-precipitate formation which likely limited opportunities for collision, resulting in lower and more variable removals. In contrast, higher alum doses shifted particle surface charge toward 0 mV due to increased collision opportunities, enhanced the likelihood of effective attachment, and produced increased MP removal across particle types. Because destabilization is an electrostatic process, achieving sufficient charge reduction enables attachment regardless of MP composition, hydrophobicity, or surface roughness.

5.2.2 Extending performance-based treatment approaches to MPs

MPs can be reasonably removed by CAF under stable pilot-scale operation; however, in the absence of a health-based target, we cannot yet determine whether this level of removal is “sufficient.” Unlike *Cryptosporidium* oocysts, for which a 3-log removal target exists, no such treatment target currently exists for MPs (WHO, 2019). Therefore, while CAF can remove MPs, it remains unknown whether future regulatory targets may require lower, equal, or even higher log-removals (e.g., 5-log instead of 3-log). Therefore, the current results do not show that MPs are being removed to any specific acceptable level; instead, they demonstrate that MPs can be effectively (3-log or 99.9%) removed and that their behavior during treatment aligns with established physico-chemical principles that underlie the removal of other colloidal particles.

Importantly, this does not imply that *Cryptosporidium* oocysts serve as an indicator or analogous for MP behavior. Instead, it shows that the performance demonstration approaches, quantitative evaluation methods, and drinking water treatment frameworks used for protozoa are likely applicable to MPs, once health-based targets for MPs are established. CAF removal is critically governed by particle destabilization and attachment, and because these mechanisms apply regardless of whether the particle is biological or polymeric, MPs can be incorporated into similar evaluation frameworks once regulatory benchmarks are defined.

The findings also show that the analytical and operational tools needed to quantify and evaluate MP removal—such as log-removal calculations, tools to inform destabilization, and performance demonstrations—already exist within conventional drinking water practice. This provides a foundation for integrating MPs into treatment and regulatory decision-making as scientific understanding of their occurrence, toxicity, and health relevance continues to evolve.

By demonstrating the relationship between coagulant dose, destabilization (as indicated by zeta potential), and MP removal, this study confirms the process understanding for evaluating MP behavior and removal in CAF systems. More broadly, the consistency observed across particle types (i.e., oocysts, pristine MPs, and weathered MPs) indicates that existing treatment processes are inherently adaptable. With appropriate chemical pre-treatment and for sufficient destabilization, CAF infrastructure used for protozoa removal is capable of managing emerging particulate contaminants such as MPs as well, while acknowledging that the level of removal ultimately required remains to be defined. This reinforces confidence in established drinking water treatment technologies.

5.3 Key conclusions and implications

1. The results show that when particles are sufficiently destabilized with adequate coagulant addition, CAF achieves ≥ 3 -log removal of pristine and weathered MPs and *Cryptosporidium* oocysts, confirming that MPs follow the same coagulation-CAF principles of sufficient particle destabilization and attachment which underlie removal of other colloidal particles. However, in the absence of a health-based treatment target for MPs, it is not yet possible to determine whether this level of removal is “sufficient.” While the data demonstrates that MPs can be removed effectively (~ 3 -log or 99.9%) and consistently under well-operated conditions, future regulatory benchmarks may require equal or more stringent removal targets than those currently applied to protozoa. It is entirely possible that acceptable MP removal could require higher levels of removal (e.g., 5-log instead of 3-log). Thus, the findings indicate that MPs can likely be removed effectively when adequately destabilized, but the level of removal ultimately required for public health protection is yet to be defined.
2. Treatment of MPs can be evaluated using similar performance-based framework used for other particulate contaminants, such as protozoa for which there are specific treatment targets, if health-based targets for MPs are established. This does not imply that *Cryptosporidium* is an indicator or analogous for MPs occurrence in raw water or treatment; rather, it demonstrates that the treatment strategies, performance demonstration approaches, and quantitative methods for reporting occurrence and treatment that has been used for protozoa can also be relevant for MPs, when health-based targets are defined.
3. With appropriate chemical pre-treatment and performance optimization, the conventional treatment infrastructure that is relied upon for public health protection against waterborne protozoa can manage particulate contaminants like MPs, given that health-based targets are established, reinforcing confidence in established drinking water treatment technologies.

5.4 Methods

5.4.1 Pilot-scale experimental set up

All experiments were conducted at the R.C. Harris Water Treatment Plant (Toronto, Ontario, Canada), which draws from Lake Ontario, a high-quality source characterized by low turbidity (< 2 NTU) and low

dissolved organic carbon (<2 mg/L). A pilot-scale filtration system representative of Great Lakes drinking water treatment plants was used (Figure 5.2).

The pilot consisted of two parallel filter columns (15 cm internal diameter, 5 m height) operated under constant-head, constant-flow conditions at a hydraulic loading rate of 4.6 m/h (approx. 1.5 L/min per filter). Two media configurations were evaluated: Filter 2A, a conventional shallow-bed filter with 45 cm anthracite (effective size: 0.95 mm) over 30 cm sand (effective size: 0.48 mm), and Filter 3, a deep-bed configuration with 100 cm anthracite (effective size: 0.95 mm) over 30 cm sand (effective size: 0.48 mm). All experiments were conducted using a direct in-line CAF configuration in which flocculation and sedimentation units were bypassed and alum coagulant (aluminum sulfate $[\text{Al}_2(\text{SO}_4)_3 \cdot 14\text{H}_2\text{O}]$; ChemTrade Logistics, Toronto, Canada) was applied directly to the pre-chlorinated raw water. Operational parameters including influent and effluent turbidity, pH, and flow rate were recorded at one-minute intervals via the plant SCADA system.

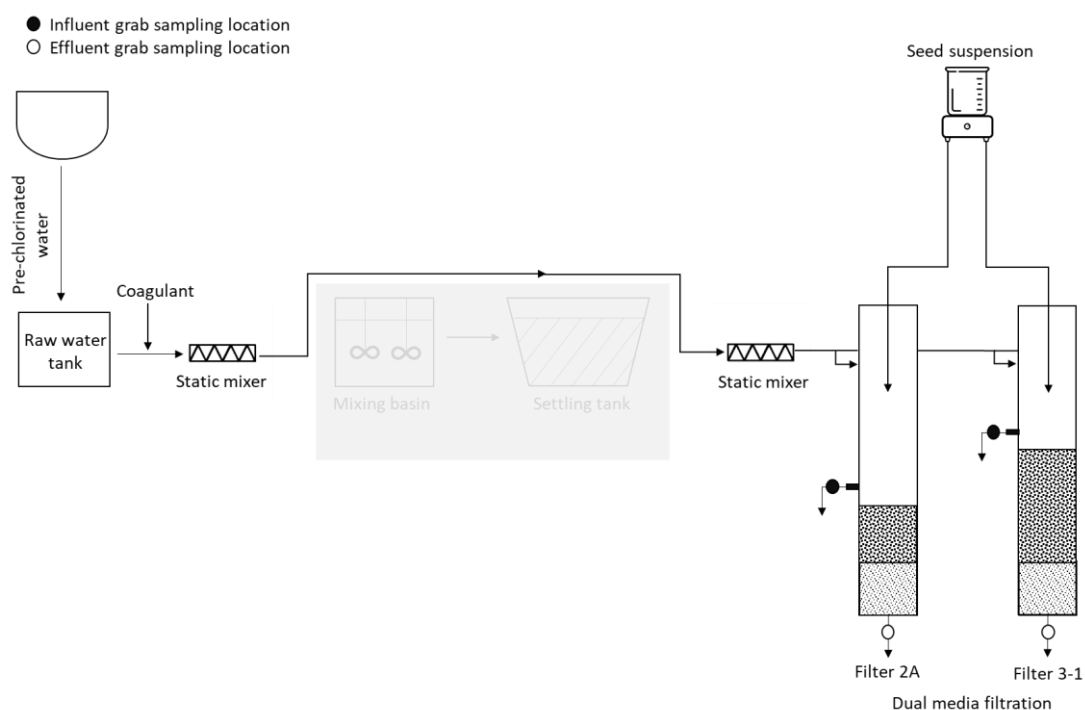


Figure 5.2. Schematic flow diagram of pilot-scale filtration plant at R.C. Harris WTP, Toronto. The study examined microsphere and *Cryptosporidium* oocyst removal by CAF with conventional filter media designs and loading rates comparable to those used by systems dependent on high-quality Great Lakes water. During the experiments, a continuous input of MPs (both pristine and weathered) and *Cryptosporidium*

oocyst seed suspension was introduced to the filters. Influent and effluent grab samples were collected to estimate particle removal by the filters.

The experimental design aimed to evaluate MP removal by CAF and determine whether they behaved similarly to oocysts under varying destabilization conditions. To minimize upstream particle losses and isolate CAF performance, particle suspensions were seeded directly at the filter influent as described in Chapter 4. A total of 12 direct in-line CAF runs were conducted, yielding 60 individual influent and effluent samples (total of 120 samples). Each experiment represented either optimal or suboptimal particle destabilization, defined using zeta potential measurements. Following previous pilot-scale (Chapter 3), zeta potential values within ± 5 mV of zero (after addition of coagulant) were classified as optimal destabilization, while values < -5 mV were classified as suboptimal. All experiments were conducted under stable filter operating conditions, and each condition was tested in triplicate.

5.4.2 Seed suspension preparation and introduction

Fluorescent polystyrene microspheres (surfactant-free; CD Bioparticles, New York, USA) were tested in two forms to represent MPs: plain BB and carboxylated YG. The carboxylated YG microspheres were considered as “weathered MPs” because their surface chemistry simulates oxidation and charge modifications typical of environmentally aged plastics, despite not undergoing actual environmental exposure. Formalin-inactivated *C. parvum* oocysts (P102C) were obtained from Waterborne Inc. (New Orleans, USA). These oocysts were preserved in 5% formalin (final concentration) in ~50 mL of 1× phosphate-buffered saline (PBS) without Tween®20. Particle characteristics of different particles used in these experiments are shown in Table 5.1.

Table 5.1. Characteristics of MPs and *Cryptosporidium* oocysts used in pilot-scale CAF experiments.

Particle type	Size (μm)	Color	Density (g/mL)	Zeta potential as supplied (mV)
Pristine(plain) polystyrene microspheres	5 ± 0.17	BB (bright blue)	1.045	~ -20
Carboxylated (weathered) polystyrene microspheres	4.7 ± 0.04	YG (yellow green)	1.045	~ -38
<i>Cryptosporidium</i> oocysts	3 to 6	-	-	~ -15

MPs and *Cryptosporidium* stock suspensions were refrigerated at 4°C in the dark until use. In this study, MPs (both pristine and weathered) and oocysts from the stock solution were vortexed and then added to

800 mL of pre-chlorinated raw water to prepare a seed suspension with a target concentration of approximately 10^7 number of particles for each particle type (i.e., MPs and oocysts), resulting in an expected concentration of $\sim 10^5$ particles/L for each particle type in the filter influent. This target was selected to ensure that an enumerable number of particles would be present in each filter effluent sample, thereby reducing uncertainty in particle concentration estimates (Emelko et al., 2008). The seed suspension was then mixed (PB-700, Phipps and Bird, Richmond, VA, USA) with alum to destabilize MPs and oocysts prior to introducing them to filter influent streams. Zeta potential analysis (detailed in 5.4.5) was used to evaluate MP and oocyst destabilization by alum addition.

All pilot-scale seeding experiments employed continuous seeding of particles at the filter influent during stable operation at a flow rate of 5 mL/min for 60 minutes for each filter run. Particle suspensions were introduced into each filter influent line using a Masterflex® peristaltic pump (Avantor, USA) equipped with ChemDurance® Bio tubing. ChemDurance® tubing was chosen because it minimized sorption losses of hydrophobic MPs and could be effectively cleaned with acetone between runs (detailed in 5.4.6). The pump was fitted with two heads to deliver identical flow to each of the three pilot filters. During seeding, suspensions were kept in constant motion on magnetic stir plates to prevent settling and maintain homogeneity.

5.4.3 Sample collection

Grab samples were collected from both filter influents and effluents (Figure 5.2) in sterilized clear glass bottles (Wheaton) using the approach described in (Chapter 3), where influent samples were collected directly above the filter media in 250 mL bottles and effluent samples were collected in 500 mL bottles from continuously running outlet lines. Sample collection commenced at time zero (T0) when seeding was initiated. The T0 samples also served as negative controls for each filter run. The subsequent effluent samples were collected at 15 minutes (T15) after seeding initiation. Additional samples were collected every 10 minutes through 65 minutes (T65). This schedule resulted in a total of 14 samples per filter run (seven influent samples and seven effluent samples from each of the two columns).

5.4.4 Particle enumeration and removal estimation

MP and *Cryptosporidium parvum* oocyst concentrations were quantified using direct membrane filtration followed by fluorescence microscopy. For each filter run, 500 mL effluent samples were processed, while influent concentrations were sufficiently high that only 1–5 mL of samples were required.

All samples were vacuum-filtered through 25 mm polycarbonate membranes with a nominal pore size of 1 μm (Whatman Nuclepore®, GE Healthcare Life Sciences, Mississauga, ON, Canada) using a filtration manifold operated at -21 in Hg (-533 mmHg). After filtration, membranes containing captured particles were stained for microscopic enumeration. Since the polystyrene MPs used in this study were intrinsically fluorescent, no additional staining was required. However, *Cryptosporidium* oocysts were stained using an immunofluorescence assay (IFA; EasyStain™, Biopoint, Narabang Way Belrose, Sydney, Australia). For oocysts, EasyStain™ was applied evenly across the membrane surface and incubated in a dark, humidified chamber at 35 °C for at least 30 minutes.

Following staining, membranes were mounted onto glass slides and enumerated by fluorescence microscopy at 400x magnification (Axioskop 2 plus, Zeiss, Göttingen, Germany). Excitation and emission filter sets matched the fluorophores associated with each bead type BB pristine MPs were visualized using a DAPI filter set (excitation ~ 360 – 405 nm, emission ~ 420 – 480 nm), and YG weathered MPs were visualized using a FITC filter set (excitation ~ 488 – 505 nm, emission ~ 515 – 540 nm), consistent with the filter sets used for *Cryptosporidium* oocysts. To reduce counting uncertainty, MP and *Cryptosporidium* enumeration targeted 30–100 particles per slide (Emelko et al., 2008). Average influent and effluent particle concentrations were used to calculate the effective log reduction of the two different MPs and *Cryptosporidium* oocysts during each filter run (Teunis et al., 2009; Schmidt et al., 2020).

Consistent with regulatory practice, which evaluates treatment performance based on average log-removal credits rather than statistical bounds (EPA, 2006a; Health Canada, 2012), log removal values herein are reported as point estimates. Confidence intervals were not calculated for *Cryptosporidium* oocyst removal because oocyst count data are discrete, non-normally distributed, and exhibit concentration-dependent (heteroscedastic) uncertainty (Emelko et al., 2008, 2010), limiting the applicability of conventional statistical approaches. While approaches such as Bayesian methods have been proposed (Emelko et al., 2010), no standardized approach currently exists for their application to oocyst removal data. As a result, removal performance is commonly reported without statistical intervals in the literature (LeChevallier et al., 1991; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2001, 2002; Emelko et al., 2005; Hashimoto et al., 2001; Mazoua and Chauveheid, 2005; Ballantyne et al., 2024).

5.4.5 Zeta potential measurements

Zeta potential was measured using a Zetasizer Nano Z (Malvern Panalytical, Mississauga, Canada). Three independent measurements were averaged per a sample of 0.75 mL used in cuvette for measurement. All cuvettes and syringes were rinsed with Milli-Q™ ultrapure water (resistivity >18 MΩ·cm; conductivity <0.056 μS/cm; <50 ppb total organic carbon [TOC]) between samples. For each sample, three zeta potential readings were measured. Each reading was based on 50 individual zeta potential readings (though the maximum number of readings was not always required). The average of the three readings per sample was used as the zeta potential for each experiment during this work.

Quantitative analysis of zeta potential data is not possible because the raw data are not available. Although the instrument used herein reports a “zeta deviation,” it cannot be readily used because the underlying distribution is unknown. This is especially relevant following coagulant addition because some particles may be preferentially destabilized thereby altering the underlying distribution of particle (including *Cryptosporidium* oocyst) zeta potentials. Variability among replicate runs was insignificant (typically within 1–2 mV); therefore, zeta potential results are reported as average values only.

5.4.6 Cleaning and contamination control

Between experimental runs, all tubing, sampling bottles, and filter manifolds were thoroughly cleaned and rinsed to prevent carryover of MPs or oocysts. Equipment was rinsed with a diluted acetone solution (50% dilution) to dissolve any residual MPs, followed by multiple rinses with ultrapure water. Prior to use and after use, all glassware was rinsed with detergent solution (1×PBS with Tween 80 [PBST]) and with acetone. Negative controls were collected at the beginning of each run (T0) from both influent and effluent ports to confirm the absence of contamination.

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Chapter 6. Demonstrating pathogen removal by filtration: Conducting challenge tests with confidence

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Summary

Waterborne protozoa continue to drive drinking water risk management, and pilot-scale performance demonstrations remain essential for verifying treatment effectiveness. Natural protozoan pathogen concentrations are too low for direct measurement of log-removal; therefore, performance demonstrations rely on introducing protozoa concentrations at defined points within the treatment train. Despite decades of study and use for regulatory and risk assessment purposes, uncertainty remains regarding how methodological decisions, including (but not limited to) the necessarily elevated concentrations in seed suspensions, the location at which pathogens are introduced, and the analytical approaches used to quantify them—influence measured performance and the confidence placed in these demonstrations. This study systematically evaluated some of these key methodological questions and their effects on CAF performance with consideration of the factors that drive uncertainty and variability (i.e., non-detects, quantification methods involving the analysis of variable volume water samples, and the influence of coagulation chemistry). Results showed that when particles were sufficiently destabilized, filtration consistently achieved ≥ 3 -log *Cryptosporidium* oocyst removal independent of the methodological approaches tested within this study, whereas sub-optimal destabilization yielded reduced and more variable performance. These findings clarify when methodological differences meaningfully influence measured log-removal and strengthen the interpretability of performance demonstration data that underpin treatment credits, regulatory expectations, and risk-based decision-making.

6.1 Introduction

Waterborne protozoa remain a key driver of drinking water risk management. For decades, understanding the occurrence of pathogens in source water and the effectiveness of treatment processes in removing them has been central to ensuring the provision of safe drinking water. Since pathogens like *Cryptosporidium* are difficult to disinfect with chlorine, physico-chemical or chemically assisted filtration (CAF) remains a critical and required treatment barrier to preventing their passage into drinking water supplies (EPA, 2006a;

Health Canada 2012; WHO, 2017). While UV irradiation can inactivate pathogens (Linden et al., 2002), it is only effective if CAF sufficiently reduces particle loads to prevent shielding effects (Templeton et al., 2005; Mamane and Linden, 2006), highlighting the importance of well-operated CAF performance. Accordingly, pilot-scale performance demonstrations are foundational to confirming the sufficiency of protozoa treatment by CAF.

Direct pathogen monitoring in treated water is rarely feasible. *Cryptosporidium* concentrations in source waters are typically <1 oocyst per 100 L, analytical recovery is highly variable, and the sample volumes required for precise enumeration are logistically impractical (LeChevallier et al., 1991; Regli et al., 1991; Haas et al., 1996). Accordingly, regulatory frameworks rely on treatment technique-based approaches (e.g., well-operated CAF as indicated by filter effluent turbidity values, CT, chlorine residuals, etc.) to manage threats from waterborne pathogens (EPA, 2006a; Health Canada, 2012), an approach also adopted by WHO, the European Union, Australia, New Zealand, and other national regulators (Ministry of Health–Manatū Hauora, 2005; NHMRC and NRMCC, 2011; WHO, 2017; European Union, 2020). Over several decades, evidence from performance demonstrations at pilot-scale and full-scale has shown that well-operated CAF can achieve approximately 3-log removal of *Cryptosporidium* oocysts, a level of removal that has proven sufficient to protect public health (LeChevallier et al., 1991; Nieminski and Ongerth, 1995; Patania et al., 1995; Bandin and Laine, 1998; Edzwald and Kelley, 1998; Huck et al., 2001; Emelko, 2003; Emelko et al., 2005). These demonstrations form the empirical foundation for filtration regulations, optimization of treatment, and the multi-barrier approach to public health protection (CCME, 2004).

Since natural oocyst levels are too low for direct measurement of log removal, performance demonstrations introduce a concentration of many orders of magnitude higher than what is typically observed in source waters (Nieminski and Ongerth, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2001; Harrington et al., 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Emelko et al., 2005; Assavasilavasukul et al., 2008; Scott, 2008; Lee, 2018; Ballantyne et al., 2024), often assuming that removal efficiency is independent of influent concentration. Some studies have suggested that influent oocyst concentration may also affect measured removal efficiencies, indicating that assumptions of concentration independent performance should be interpreted cautiously (Hendricks et al., 2005; Assavasilavasukul et al., 2008). Questions related to variability and uncertainty also persist for other methodological factors—such as pathogen-seeding location and the analytical approaches used for enumeration (EPA, 2012b; Health Canada, 2019)—yet it remains unclear whether these differences meaningfully influence the performance estimates that have been generated and relied upon for decades.

More recent advances in understanding analytical uncertainties, particularly those associated with handling non-detects and quantification methods involving the analysis of variable volume water samples, have shown that these factors can confound measured performance estimates and contribute to uncertainty in reported performance estimates (Emelko et al., 2008; Chik et al., 2018; Schmidt et al., 2020).

Findings from previous studies further emphasize that particle destabilization through adequate coagulant addition is the primary driver of CAF performance for systems treating low turbidity, low DOC water (Ballantyne et al., 2024; Chapter 3; Chapter 4), underscoring the need to account for coagulation chemistry when interpreting performance demonstration results. However, a systematic evaluation of methodological factors of performance demonstrations with consideration of factors that can confound performance estimates (i.e., non detects variable-volume water samples, and coagulation chemistry) has not been conducted. At the same time, increasing and more variable turbidity and dissolved organic carbon concentrations, along with the associated challenges for coagulant dosing and particle destabilization, driven by climate related disturbances such as wildfires, hurricanes, and extreme precipitation events (Emelko et al., 2011; IPCC, 2021; Emelko, 2024), further emphasize the need to develop guidance that supports maintaining reliable CAF performance under changing source water conditions.

These considerations carry direct implications for public health protection. Performance demonstration data drive treatment plant design and form the foundation for regulatory expectations, including treatment credits, compliance assessments, and risk-based decision frameworks (EPA, 2006a; Medema et al., 2009; WHO, 2017; Health Canada, 2019). Variability introduced by methodological choices can affect the confidence with which utilities are credited for pathogen removal or required to implement additional treatment. Furthermore, many of these same methodological challenges encountered in evaluating pathogen removal can also apply to emerging particulate contaminants, including microplastics. Strengthening the interpretability and reliability of CAF performance demonstrations therefore supports not only pathogen control but also broader efforts to evaluate the removal of emerging contaminants within existing drinking water treatment frameworks.

A systematic evaluation of some of the key methodological factors and their influence on CAF performance demonstrations was therefore conducted. Using new and previously reported pilot-scale data, the effects of *Cryptosporidium* oocyst concentrations, the points of oocyst addition, and analytical approaches were assessed to determine the extent to which these factors affect measured log removal. This work helps strengthen the interpretability of performance demonstration data and provides a clearer empirical basis for the application of pathogen removal credits. These insights also support more consistent decision making

for both established protozoan pathogens and emerging particulate contaminants, reinforcing confidence in the methods used to evaluate CAF performance in drinking water treatment.

6.2 Methods

This study evaluated some of the key methodological factors influencing CAF performance demonstrations. Experiments conducted from 2021 to 2025 are included in this study, which includes data from previous work (Chapter 3; Chapter 4) incorporated to contextualize and compare results across different seeding and analytical approaches. All methodological details for previously published datasets can be found in Chapters 3 and 4, respectively; only methods for experiments conducted outside of these two papers specifically for this study in 2024–2025 are described in full in this section. As such, data from previous studies are used for comparison but their experimental procedures are not repeated here.

6.2.2 Pilot-scale treatment system

All pilot-scale experiments were performed at the R.C. Harris Water Treatment Plant (WTP) in Toronto, Ontario, which draws raw water directly from Lake Ontario and is pre-chlorinated before directed to the pilot-plant. The source water was characterized by low turbidity (<2 NTU) and low dissolved organic carbon concentrations (<2 mg/L) and is considered as high-quality water source based on particle concentrations. The pilot plant operates within a two-story enclosed structure on site and is designed and operated to closely mirror the hydraulic and operational conditions of the full-scale Harris WTP and other WTPs operated by Toronto Water (i.e., Clark, Horgan, Island WTPs).

Experiments were conducted using Train 1 of the pilot plant. Train 1 contained three filters representing full-scale media configurations used at the Harris and Clark WTPs in Toronto, representative of systems treating high-quality source waters (Table 6.1). Filter 2A represents a shallow-bed configuration (Harris WTP), while Filters 3-1 and 3-2 represent deep-bed configurations (Clark WTP). Filters 3-1 and 3-2 were operated in duplicate to assess inter-filter column variability.

Table 6.1. Filter configurations and operational conditions for Train 1.

Filter	Pilot being simulated	Coagulant	Hydraulic loading rate (m/h)	Column diameter (cm)	Column height (m)	Filter media depth	
						Anthracite (mm)	Sand (mm)
2A	Harris	alum	4.6	15	5	450	300
3-1 & 3-2	Clark	alum	4.6	15	5	1000	300

All filters were operated at 1.5 L/min under constant-head, constant-flow conditions. Backwashing was conducted the day prior to each experimental run using air scour followed by water wash. Turbidity, pH, headloss, and flow were continuously monitored via SCADA instrumentation.

Train 1 can operate in both a conventional CAF configuration and a direct in-line CAF configuration. In the conventional mode, a portion of pre-chlorinated raw water was pumped to a constant-head reservoir from which water was gravity fed into a pipe to which coagulant is added and then directed through an in-line static mixer, flocculation basin, and sedimentation basin before entering the filters. For direct in-line CAF experiments, the flocculation and sedimentation stages were bypassed so that coagulated raw water flowed directly to the filters. A schematic of configurations used is provided in Figure 6.1 and Figure 6.2.

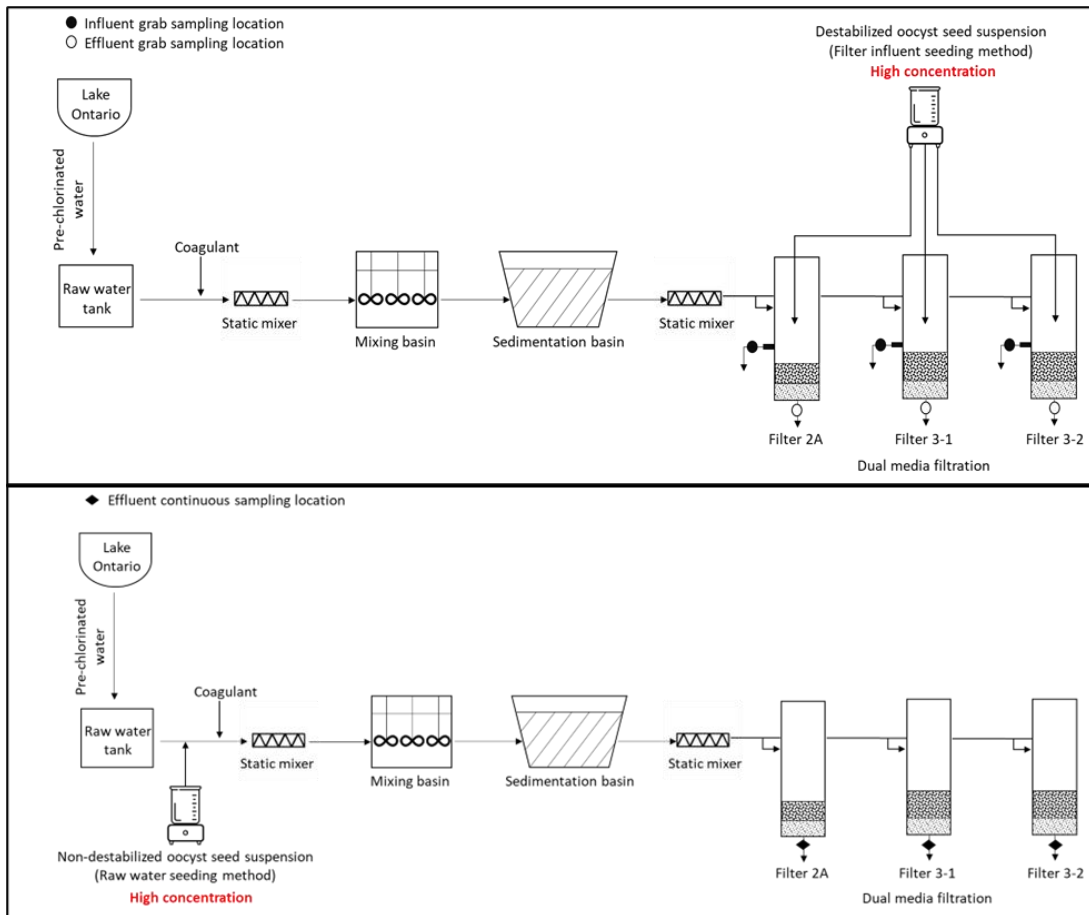


Figure 6.1. Schematic of the seeding and sampling approaches used for conventional CAF. (a) Filter influent seeding method shown here to facilitate comparison (approach described in Chapter 3); (b) Raw water seeding method using conventional CAF with high oocyst concentration and continuous sample collection. Not to scale

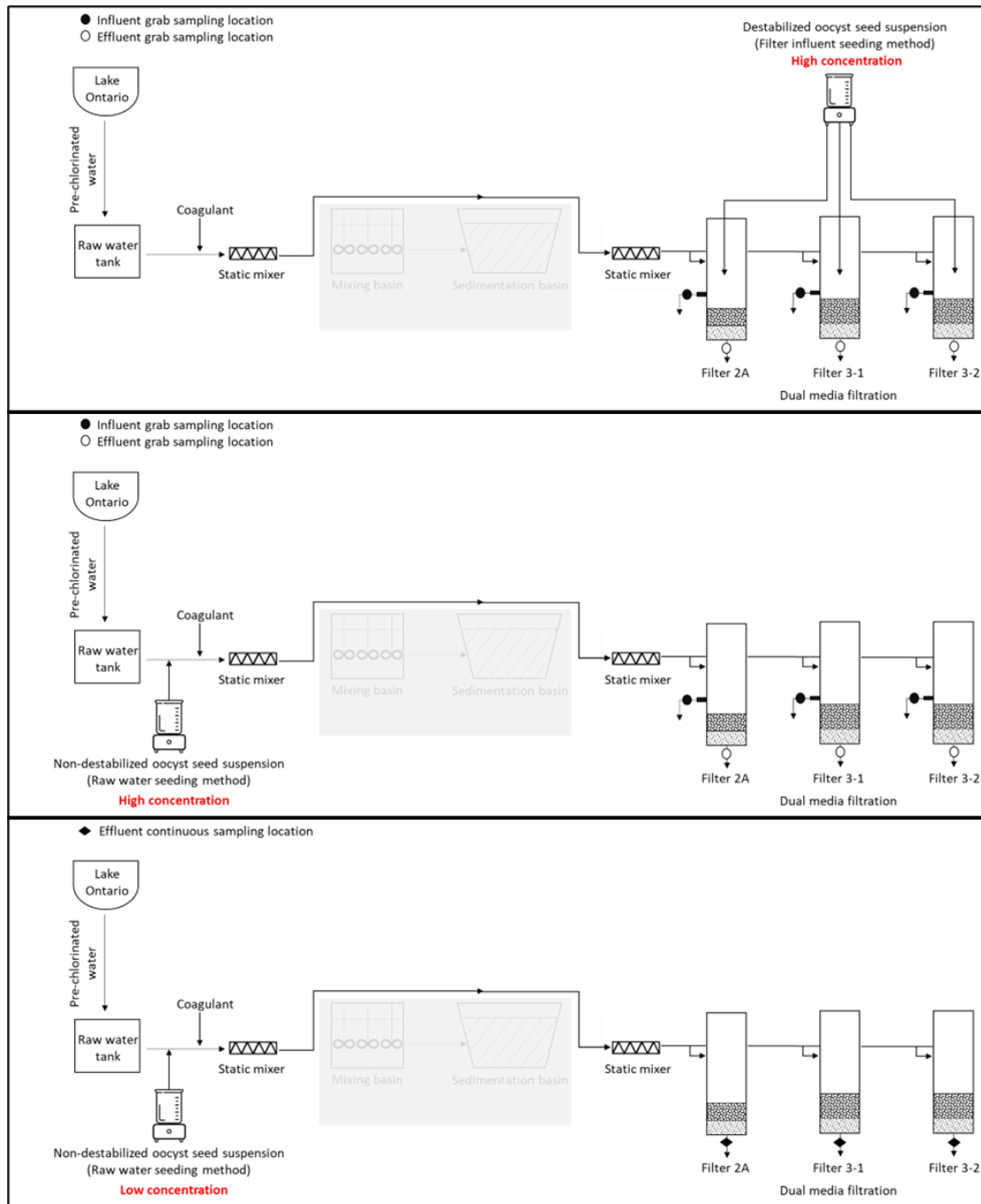


Figure 6.2. Schematic of the seeding and sampling approaches used for direct in-line CAF. (a) Filter influent seeding method shown here to facilitate comparison (approach described in Chapter 4); (b) Raw water seeding method using direct in-line CAF with high oocyst concentration and grab sample collection; (c) Raw water seeding method using direct in-line CAF with low oocyst concentration and continuous sample collection. Not to scale.

6.2.3 *Cryptosporidium* oocyst seeding approaches

Two seeding approaches were evaluated for conventional CAF and direct in-line CAF (Figure 6.1 and Figure 6.2). These approaches reflect commonly used methodologies in CAF performance demonstrations and were selected to understand how seeding method influences measured oocyst removal.

6.2.3.1 Filter influent seeding

In the filter influent seeding approach, the destabilized oocyst seed suspension (i.e., coagulant added to achieve target zeta potential) was introduced to the filter influent (Figure 6.1a and Figure 6.2a). This is the most widely used method in performance demonstrations (Nieminski and Ongerth, 1995; Emelko, 2003; Harrington et al., 2003; Ballantyne et al., 2024; Chapter 2; Chapter 3; Chapter 4; Chapter 5) to assess pathogen removal by CAF. High-concentration oocyst seed suspensions were typically used to obtain reliable effluent counts and minimize sampling error, which can otherwise exceed 1-log uncertainty (Emelko et al., 2008). All methodological details for these previous experiments can be found in Chapters 3 and Chapter 4; only their resulting data are utilized here for comparison.

6.2.3.2 Raw water seeding

In the raw water seeding approach, non-destabilized oocyst seed suspension was introduced to raw water upstream of coagulant addition, allowing oocysts to pass through plant coagulation process and for conventional CAF, flocculation and sedimentation processes before CAF. This approach is laborious, costly, and prone to oocyst losses that can result in non-detects (NDs) in effluent samples, but it provides a more representative assessment of oocyst removal through the treatment train.

For conventional CAF, only high-concentration suspensions were used (Figure 6.1b) due to anticipated upstream losses and the high cost and labour required for these experiments. For direct in-line CAF, both high- and low-concentration seed suspensions were evaluated (Fig. 6.2b and 6.2c).

6.2.4 *Cryptosporidium* oocyst seed suspension preparation

Cryptosporidium oocysts inactivated with 5% formalin (final concentration) in phosphate-buffered saline (PBS) were obtained from Waterborne, Inc. (New Orleans, LA). The oocysts were bovine in origin and supplied in a clean, purified form. Stock suspensions were stored at 4 °C in the dark until use. Prior to each experiment, the required number of oocysts from the stock suspension was added to 800 mL of raw water to prepare the seed suspension. This suspension was mixed using a PB-700 jar tester (Phipps & Bird, Richmond, VA). For experiments using filter influent seeding approach, coagulant was added to destabilize

oocysts before introduction at the filter influent and for raw water seeding approach, oocysts were not pre-destabilized in the suspension and were coagulated and destabilized through the pilot coagulation as described in Section 6.2.3. Zeta potential analysis (Section 6.2.7) was used to confirm the degree of oocyst destabilization following coagulant addition for both approaches. The seed suspension was delivered continuously for 60 min using a Masterflex peristaltic pump (Avantor, ON, Canada) at the seeding locations investigated in this study. To maintain homogeneity, the seed suspension was continuously stirred using a magnetic stirrer.

6.2.5 *Cryptosporidium* oocyst sampling approaches

For the different seeding methods and concentrations that were employed, two sampling strategies were used as described below.

6.2.5.1 Grab sampling

For all filter influent seeding method experiments, grab sampling was used following the approach described in Chapter 3 and Chapter 4. Grab samples were collected at filter influent and effluent ports and used to calculate effective log removal values. More details of experiments conducted for these approaches can be found in Chapters 3 and 4.

For raw water seeding method experiments under direct in-line CAF with high concentrations, grab sampling approach was applicable due to high magnitude of oocysts introduced and minimal upstream losses. For these experiments, influent and effluent samples were systematically collected in sterilized plastic (PP) bottles (Fisher Scientific, Thermo Fisher Scientific Inc., Massachusetts, USA). The sampling commenced at time zero (T0) when seeding was initiated. Subsequently, samples were collected from the filter effluent port (Figure 6.2b) at regular intervals, specifically every 10 minutes starting from 15 minutes (T15) and continuing up to 85 minutes (T85) following the start of the seeding process. In total, 18 samples (including influent and effluent samples) were collected for each filter/experiment throughout the experimental duration. Each filter effluent sample was collected in a 500 mL bottle over 5-minute period from a continuously running effluent line. The entire filter effluent sample was analyzed for *Cryptosporidium* oocysts. In contrast, influent samples were collected in 125 mL bottles over a brief 0.5-minute period from a port directly above the filter media (Figure 6.2b). The filter influent stream flowed for at least 15 seconds before each sample collection to ensure a representative sample.

6.2.5.2 Continuous sampling

For all other raw water seeding method experiments, particularly those involving conventional CAF or lower influent concentrations for direct in-line CAF, continuous sampling was used. In these runs, Envirochek HV™ capsules (Pall Corporation, New York, USA) were connected to the filter effluent and sample was collected for approximately 7 h in the conventional CAF configuration collecting ~600 L of water (Figure 6.1b) and 4 h in the direct in-line configuration, collecting ~400 L of water (Figure 6.2c). The longer sampling duration for the conventional configuration reflects the additional residence time associated with passage through the flocculation and sedimentation basins. This was confirmed through tracer testing performed for each configuration and simple time series modeling (Appendix B and Appendix M).

6.2.6 *Cryptosporidium* oocyst enumeration and removal estimation

6.2.6.1 Grab sample enumeration

Grab samples were processed using membrane filtration followed by immunofluorescence assay (IFA) staining (EasyStain™, Biopoint, Narabang Way Belrose, Sydney, Australia). Oocysts were enumerated at 400× magnification using an Axioskop 2 Plus epifluorescence microscope (Zeiss, Germany). All glassware was rinsed with 1x phosphate buffered saline (PBS) with Tween®80 [PBST]) before use. Effluent samples (1 L volumes) were filtered through 25 mm polycarbonate membranes (1 µm), whereas only 1–5 mL of influent samples were filtered through 12 mm membranes due to higher concentrations. Vacuum filtration was conducted at –21 in Hg (–533 mmHg). After staining, membranes were incubated at 35 °C for at least 30 min and mounted for enumeration.

Influent concentrations were averaged for each run, and percent reductions for all effluent samples (except T0) were calculated. The log of the average percent reduction was used to determine effective log removal (Teunis et al., 2009; Schmidt et al., 2020).

Cryptosporidium oocyst removal results are commonly reported without statistical intervals (LeChevallier et al., 1991; Nieminski and Ongerth, 1995; Ongerth and Pecoraro, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2001, 2002; Emelko et al., 2005; Hashimoto et al., 2001; Mazoua and Chauveheid, 2005; Ballantyne et al., 2024), reflecting limitations inherent to the data. Oocyst counts are discrete and concentration-dependent, resulting in non-normal distributions, asymmetric uncertainty at low counts, and heteroscedastic variance (Emelko et al., 2008, 2010), which limit the

suitability of conventional confidence interval methods. Although Bayesian approaches using credible intervals have been proposed to better represent analytical uncertainty associated with oocyst enumeration (Emelko et al., 2010), no single, widely accepted method currently exists for their application to oocyst removal data. Accordingly, and consistent with broader regulatory practice—which evaluates treatment performance based on average log-removal credits rather than statistically bounded estimates (EPA, 2006a; Health Canada, 2012)—log removal values in this study are reported as point estimates.

6.2.6.2 Continuous sample enumeration

Envirochek HV™ capsule samples collected for continuous samples were processed by an accredited laboratory in Canada using EPA Method 1623.1. This method involves elution, concentration, immunomagnetic separation, and IFA based enumeration (EPA, 2012). Resulting effluent concentrations were paired with average influent concentrations to calculate effective log removal (Teunis et al., 2009; Schmidt et al., 2020). Recovery efficiencies were within the acceptable range (i.e., 33–100%) specified by Method 1623.1 (EPA, 2012). Although Method 1623.1 requires recovery efficiencies to be measured as a quality assurance metric, the method does not provide a standardized or recommended approach for incorporating recovery into concentration or log-removal calculations. Consequently, recovery corrections were not applied to the reported removal data. Moreover, variability in recovery efficiency was assumed to fall within the inherent variability of performance observed in similar studies and was therefore not expected to alter the interpretation of results.

A summary of all experimental conditions, including seeding method, target concentration, sampling method, and analytical approach, is provided in Table 6.2. More details regarding each individual experiment can be found in Appendices F, J, and L.

Table 6.2. Summary of experimental approaches evaluated during the study

Experimental scenario (Figure #)	CAF Type		Point of oocyst addition		Oocyst target concentration (oocysts/L)		Oocyst sample collection method		Sample enumeration method	
	Direct in-line	Conventional	Raw water	Filter influent	Low	High	Grab	Continuous	Membrane filtration	Method 1623.1
					(10^3 - 10^4) ^a	(10^5 - 10^6)				
1a*		✓		✓		✓	✓		✓	
1b		✓	✓			✓		✓		✓
2a*	✓			✓		✓	✓		✓	
2b	✓		✓			✓	✓		✓	
2c	✓		✓		✓			✓		✓

*Data from previous studies and details reported in Chapter 3 and Chapter 4.

6.2.7 Zeta potential analysis

Zeta potential measurements were performed using a Zetasizer Nano Z Analyzer (Malvern Panalytical, Mississauga, ON), where a 10 mL aliquot was taken from the main sample and passed through the measurement cuvette for rinsing and 0.75 mL was retained in the cuvette for the measurement. Zetasizer analyzer performed three runs per sample (triplicate), with each run consisting of multiple runs (maximum 50 runs). The reported value herein represents the average of triplicate runs only. Zeta potential of the seed suspension was measured before and after coagulant addition. Destabilization was considered “optimal” when values were within ± 5 mV of 0, “sub-optimal” when more negative than -5 mV after coagulant addition, and “no destabilization” when coagulant was not added, consistent with Chapter 3. Between measurements, syringes and instrument cartridges were thoroughly rinsed with ultrapure MilliQ™ Type I water (resistivity >18 M Ω -cm; conductivity <0.056 μ S/cm; TOC <50 ppb).

Although some instruments like the one used herein reports a “zeta deviation,” it cannot be readily used because the raw data and the underlying distribution is unknown. Therefore, quantitative analysis of zeta potential data not possible. This is especially relevant following coagulant addition because some particles may be preferentially destabilized thereby altering the underlying distribution of particle (including *Cryptosporidium* oocyst) zeta potentials. Variability between repeated runs was evaluated and found insignificant (i.e., typically within 1-2 mV).

6.3 Results and discussion

6.3.1 Influence of seeding methods on oocyst removal by direct in-line CAF

This section compares CAF performance observed using two oocyst seeding approaches: filter influent seeding (Figure 6.2a) and raw water seeding (Figure 6.2b). By comparing results generated under otherwise consistent treatment conditions, the analysis isolates the influence of the point of oocyst addition on measured removal performance. Results from filter influent seeding, drawn from previously published work Chapter 4, are presented alongside raw water seeding data generated in this study to enable direct comparison. Together, these results allow evaluation of whether the location of oocyst introduction influences measured removal or affects the interpretation of direct in-line CAF performance.

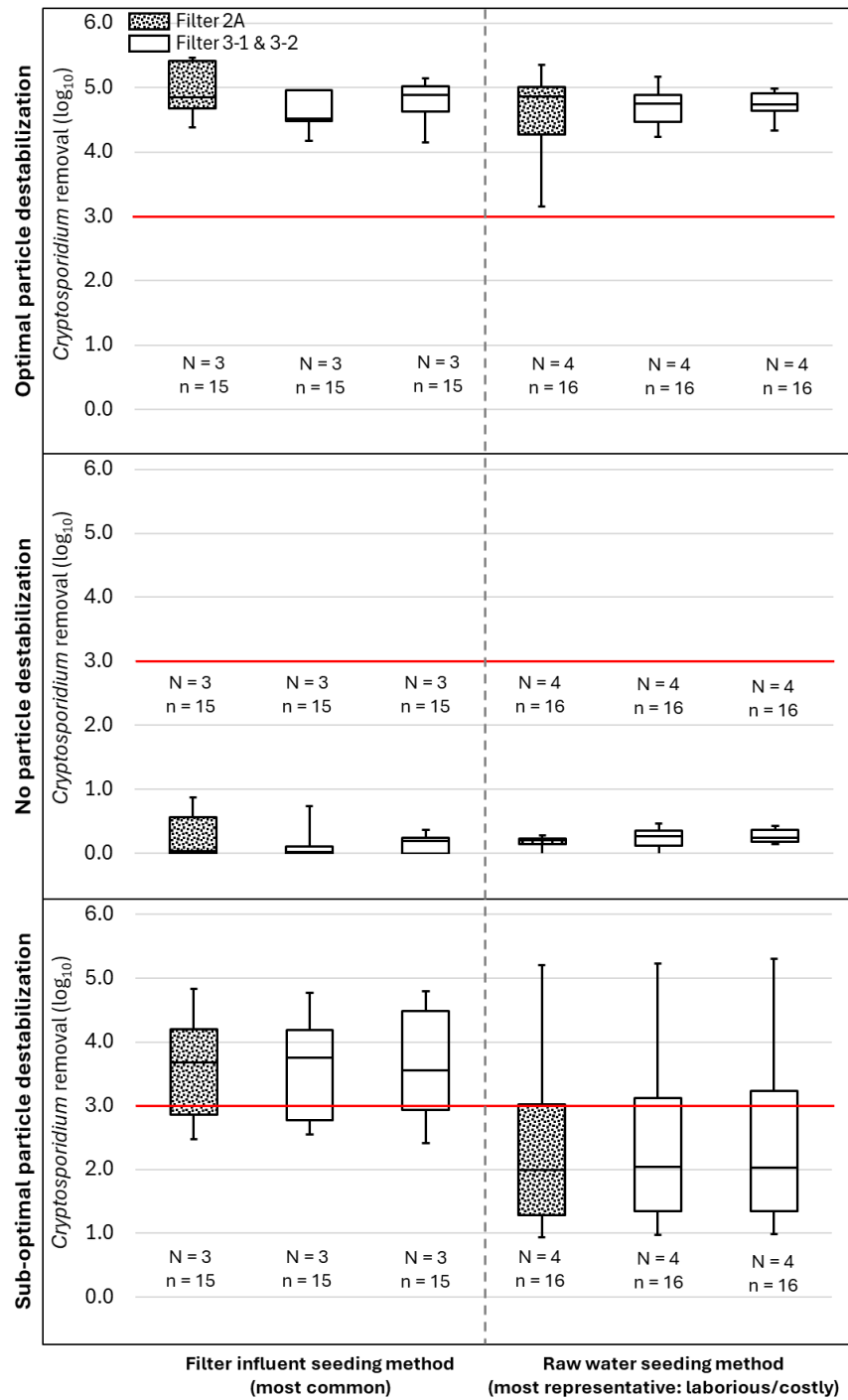


Figure 6.3. Performance comparison of *Cryptosporidium* oocyst removal by pilot-scale direct in-line CAF with high concentrations of optimally destabilized, non-destabilized, and sub-optimally destabilized oocysts added using different seeding methods; filter influent seeding method (most common) and raw

water seeding method (most representative: laborious/costly). Each box plot summarizes data from multiple experiments, where N signifies the count of individual filter runs/experiments, and n denotes the number of filter effluent samples considered. The pattern-filled box plots indicate Filter 2A and no-fill boxplots indicate duplicate Filters 3-1 and 3-2. The red horizontal line indicates the 3-log *Cryptosporidium* oocyst removal performance expected from "well-operated" CAF.

When oocysts were optimally destabilized (top panel on Figure 6.3) both seeding approaches produced consistently high removals. Regardless of filter configuration, log removals typically ranged from 4- to 5-log, exceeding the widely accepted 3-log benchmark for well-operated direct in-line CAF. These results are consistent with previous pilot-scale studies demonstrating that CAF reliably achieves ≥ 3 -log removal of *Cryptosporidium* oocysts when particle destabilization is effectively controlled (Ballantyne et al., 2024; Chapter 3; Chapter 4), illustrating that when coagulation chemistry is well optimized, the choice of seeding point exerts little influence on performance. Sufficient particle destabilization is a governing factor in the removal by CAF, and upstream mixing differences when seeded to raw water (raw water seeding method) do not meaningfully alter outcomes. This confirms that under optimal destabilization conditions, CAF performance is consistent and the methodological differences inherent to each seeding approach do not bias removal estimates.

Under conditions with no coagulant addition, and therefore no particle destabilization, the influence of point of oocyst addition on measured performance was similarly evaluated and the resulting removals are shown in the middle panel of Figure 6.3. In the absence of alum addition (raw water zeta potential ranged from -6 to -20 mV), oocyst removal was uniformly poor across all seeding methods and filter designs (Figure 6.3). Removals remained in 0- to 1-log range, consistent with colloidal filtration theory, which describes that in the absence of destabilization to overcome electrostatic repulsion, oocysts behave as stable colloids and pass through the filter bed with minimal attachment (Stumm and O'Melia, 1967; Ives, 1970; Yao et al., 1971; O'Melia, 1985; Tobiasson and O'Melia, 1988; Amirtharajah and O'Melia, 1990; Letterman et al., 1999; Crittenden et al., 2012). These results further emphasize that differences in the point of oocyst addition do not artificially increase measured removal under chemically unfavorable conditions.

Under sub-optimal destabilization, the influence of the seeding method became more pronounced (bottom panel Figure 6.3), and measurable differences emerged between the removals achieved with filter influent seeding method and raw water seeding methods (overall effective log removals [OLERs] shown in Table 6.3). For raw water seeding method, oocysts entered upstream of pilot coagulation and experienced longer residence times. However, because coagulation was sub-optimal, upstream conditions of raw water seeding

method amplified variability in removal. Real time fluctuations in particle charge, incomplete or inconsistent interactions with coagulant species, and evolving hydrolysis and transport dynamics likely contributed to the broader spread of observed log-removals. In contrast, filter-influent seeding method bypassed upstream processes by introducing destabilized oocysts directly at the filter influent. In these experiments, residual alum present in the pilot influent stream may have further contributed to particle destabilization (Emelko et al., 2001; Huck et al., 2001; Chapter 4), an effect that may have become more pronounced under sub-optimal destabilization conditions but was not evident under optimal destabilization conditions. As a result, the chemistry and residence time differed for raw water seeding scenarios, and the measured removals were influenced more by experimental handling (e.g., seed suspension addition point, mixing effects). These methodological influences on observed levels and ranges of oocyst removal were magnified by the unstable coagulation chemistry, resulting in a wide distribution of log-removal values, reflected in the extended whiskers in the bottom panel of Figure 6.3.

Importantly, because sub-optimal destabilization generally corresponds to wide range of particle destabilization (<-5 mV), the system spans a broad continuum of partially destabilized states. Under these conditions, destabilization occurs inconsistently, and electrostatic patch mechanisms may develop but only on parts of particle surfaces rather than uniformly (Amirtharajah and O'Melia, 1990; Duan and Gregory, 2003). This intrinsic chemical variability limits reproducibility from one experiment to the next, and the challenge is further amplified by natural variability in raw water characteristics. These combined effects become particularly evident under sub-optimal coagulant doses. As a result, differences in observed performance cannot be attributed solely to operational factors such as the seeding point or the point of oocyst addition, because variability in the extent of destabilization itself contributes substantially to the wide variability in removal outcomes.

Collectively, these observations indicate that sub-optimal destabilization conditions can magnify the relative influence of methodological changes in the observed oocyst removal by CAF. When coagulation is not fully optimized, the point at which particles are introduced governs the chemistry (i.e., residence times and subsequent hydrolysis reactions, contact opportunities) they experience and therefore the degree of destabilization achieved prior to CAF. As a result, reproducibility under these conditions is inherently more challenging. Experiments conducted under sub-optimal coagulation can yield more variable data and increased uncertainty, underscoring the need for careful consideration of the methods used and correct interpretation of the resulting performance data. The overall effective log removals (OELRs), which summarize reduction or passage rates expressed as a log-reduction value (Schmidt et al., 2010), are

presented in Table 6.3 for each filter type and experimental method to illustrate these differences. Importantly, the results also show that the pilot-scale performance demonstration approaches commonly used in practice (filter influent seeding method), remained informative and produced removal estimates consistent with those generated using more representative but resource-intensive approaches (e.g., raw water seeding), providing confidence in methods used in such studies.

Table 6.3. OELR achieved by Filters 2A and 3-1 for *Cryptosporidium* oocysts for data illustrated in Figures 6.3, 6.4, and 6.5. Raw water data and individual removal results for all experiments are provided in Appendices F, J, and L.

CAF type	Point of oocyst addition	Oocyst target concentration	Oocyst sample collection	Overall effective log reduction (OELR)								
				Optimal particle destabilization			No particle destabilization			Sub-optimal particle destabilization		
				2A	3-1	3-2	2A	3-1	3-2	2A	3-1	3-2
Direct in-line CAF	Filter influent seeding	High	Grab samples	4.8	4.7	4.9	-0.3	-0.3	-0.4	3.1	3.1	3.1
	Raw water seeding	High	Grab samples	3.9	4.6	4.7	0.1	0.2	0.3	1.6	1.6	1.7
	Raw water seeding	Low	Continuous samples	3.9	4.9	5	1.7	1.4	1.5	3.1	3.4	3.1
Conventional CAF	Filter influent seeding	High	Grab samples	3.4	3.7	3.3	-0.3	-0.3	-0.4	1.5	1.6	1.6
	Raw water seeding		Continuous samples	7.4	7.3	7.5	0.3	0.3	0.3	2.1	2.3	2.4

6.3.2 Influence of seed concentration and analytical approach on oocyst removal by direct in-line CAF

The influence of oocyst seeding concentration and analytical approach on measured CAF performance was evaluated next. Results were generated using a consistent raw water seeding approach for direct in-line CAF, allowing differences in observed performance to be attributed to oocyst concentration and analytical method rather than the point of seeding. Comparisons therefore reflect conditions with differing oocyst concentrations and associated analytical approaches, while all other aspects of treatment configuration remained consistent. Figure 6.4 summarizes removal performance across the range of particle destabilization scenarios evaluated.

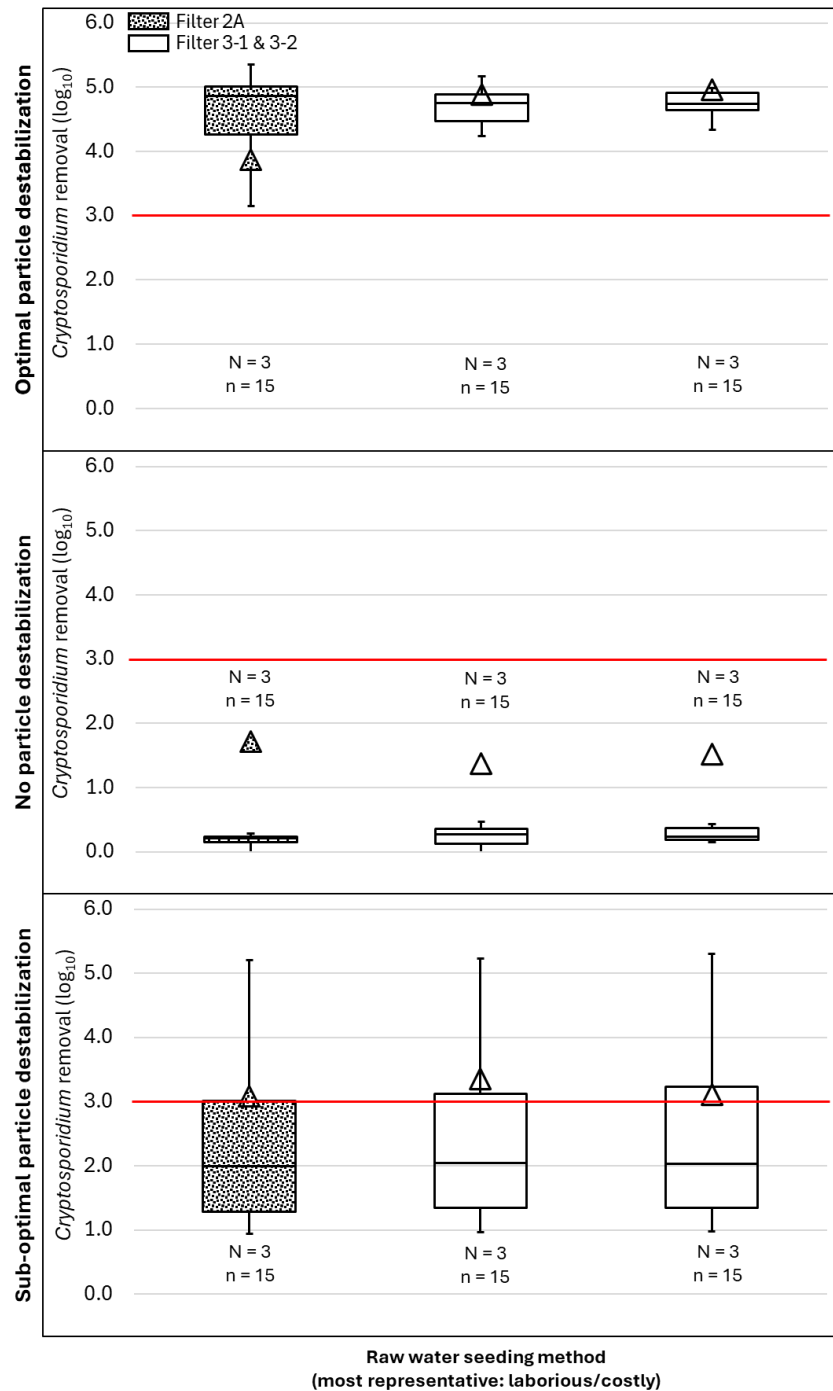


Figure 6.4. Performance comparison of *Cryptosporidium* oocyst removal by pilot-scale direct in-line CAF with optimally destabilized, non-destabilized, and sub-optimally destabilized oocysts added using the raw water seeding method. The boxplots represent removals from high concentration experiments using

multiple grab samples for membrane filtration analysis; each boxplot summarizes data from multiple experiments, where N denotes the number of filter runs and n denotes the number of effluent samples included. Triangles represent low concentration experiments evaluated using continuous sampling for EPA Method 1623.1 analysis, in which approximately 400 L of filter effluent were collected and analyzed, yielding a single data point per run. Pattern-filled symbols indicate Filter 2A, and no-fill symbols indicate duplicate Filters 3-1 and 3-2. The red horizontal line indicates the 3-log *Cryptosporidium* oocyst removal performance expected from "well-operated" CAF.

Consistent with what was observed previously, optimal destabilization consistently resulted in high removals (>3-log, typically 4- to 5-log) regardless of oocyst concentration or analytical method employed (Figure 6.4). This reinforces that sufficient destabilization is a significant driver in CAF performance in *Cryptosporidium* oocyst removal and methodological factors have limited impact. The slightly higher removals noted in the low concentration experiments likely reflect the limitations of single-point estimates produced by Method 1623.1, which cannot capture the range of variability. This should be considered when interpreting results from such methods. However, these differences fall within the well-documented natural variability (approximately 1-log) observed in replicate filters operated under identical conditions (Huck et al., 2001; Emelko, 2001; Xagorarakis and Harrington, 2004; Emelko et al., 2005; Assavasilavasukul et al., 2008; Chapter 3; Chapter 4). Thus, they do not reflect meaningful differences in CAF performance but rather analytical limitations of the sampling method. Further details on the OELRs achieved by each of these experiments can be found in Table 6.3.

To assess whether these patterns persisted under chemically unfavorable conditions, performance was next evaluated under no-coagulant addition, where particle destabilization did not occur. Removal under no-destabilization conditions shown in the middle panel of Figure 6.4 was uniformly poor (≤ 3 -log) across all concentrations and sampling approaches. Again, experiments with low concentration appeared slightly higher (1.4 to 1.7; Table 6.3), whereas high concentrations had removals closer to 0-log (-0.3 to 0.3), but this can be attributable to analytical uncertainty associated with Method 1623.1, discussed previously. Especially when removals are poor, small differences in oocyst counts can translate into large shifts in estimated performance. Additionally, increased number of oocysts on prepared microscope slides (>5000 counts) due to poor removal under these destabilization conditions necessitated enumeration of only a portion of the microscopic field of view with subsequent extrapolation, introducing additional uncertainty. For these reasons, differences in removal under no-destabilization should not be over interpreted as they do

not indicate improved performance, but rather reflect methodological limitations under high count, poor performance conditions.

Sub-optimal destabilization produced the highest variability across all scenarios. Experiments showed broader spread in removal values, reflecting the sensitivity of particle–coagulant interactions to operational and analytical factors as explained previously (bottom panel on Figure 6.4). As with the point of oocyst addition comparison in Figure 6.3, removals under sub-optimal destabilization frequently fell below 3-log and exhibited considerable spread in data. Low concentration experiments occasionally approached 2-log, but these values lack associated measures of variability and are further affected by partial field-of-view enumeration, limiting their interpretability. In contrast, grab samples analyzed using membrane filtration approach captured distributions more clearly as they are based on multiple samples with complete field-of-view enumeration of the microscope slide.

Similar to the variability introduced by differences in the number of oocysts counted, handling non-detects (NDs) can also contribute to the variability observed between different concentrations and analytical approaches. The inherently variable analytical recovery of oocyst enumeration methods (EPA, 2012b; Health Canada, 2019), combined with the occurrence of NDs, can introduce additional uncertainty and can act as a factor contributing to the wide range of reported treatment efficiencies in literature. How NDs are handled therefore have important implications for interpreting removal performance. Consistent with Chik et al. (2018), NDs in this study were not treated as censored values or interpreted as evidence of complete removal; instead, a count of one was assigned as a conservative adjustment. This preserves the discrete nature of the method while avoiding overestimation of performance. This approach is appropriate given that NDs can arise from sampling error at low concentrations (Chik et al., 2018).

Moreover, the similarity between high and low concentration removals under optimal destabilization in Figure 6.4 demonstrates that oocyst removal is independent of influent concentration when destabilization is sufficient. This addresses longstanding question whether higher seeding concentrations overestimate measured removal (Hendricks et al., 2005; Assavasilavasukul et al., 2008). The observed behavior aligns with clean-bed filtration theory, which predicts concentration independent log removal when attachment kinetics are first-order (Iwasaki, 1937; Ives, 1970; Yao et al., 1971; Crittenden et al., 2012). Under optimal destabilization and stable hydraulic conditions, both transport efficiency and attachment efficiency remain stable, and first-order behavior is preserved. In contrast, the broader spread observed under sub-optimal conditions reflects deviations from clean-bed filtration theory. Incomplete or uneven destabilization alters attachment efficiency, while localized breakthrough, preferential pathways, and blocking can further

exacerbate variability (Tufenkji and Elimelech, 2004; Tufenkji and Elimelech, 2005; Papineau, 2013). Under such sub-optimal conditions, small differences in oocyst concentration or count uncertainty can produce apparent differences in performance and amplify analytical and operational variability observed. This work also suggests that limited insight into the extent of destabilization, especially in cases where zeta potential was not assessed, may confound reported performance estimates for systems treating low turbidity and low DOC water. Without an indication of the extent of particle destabilization, it is difficult to determine whether poor or variable removals arose from other factors or were simply the result of insufficient coagulant addition and incomplete destabilization. Incorporating measures of destabilization and accounting for coagulation chemistry can reduce these uncertainties and improve the interpretability and confidence of CAF performance data. It is also important to note that optimal particle destabilization alone is not sufficient to ensure a specific level of *Cryptosporidium* oocyst removal. Hydrodynamic conditions within the filter can influence removal efficiency because changes in fluid velocity between media grains affect particle deposition and detachment (Ives, 1970; Tobiasson and O'Melia, 1988). Hydraulic changes such as filter ripening, flow disturbances, or hydraulic surges can also cause particle release when shear forces exceed the attractive forces responsible for attachment to filter media (Amirtharajah, 1988; Huck et al., 2001; Emelko, 2003; Chapter 3). In addition, particle surface interactions governed by media size, depth, and surface roughness can further influence particle attachment and removal by CAF (Kau and Lawler, 1995; Jin et al., 2015a). Together, these considerations highlight the need to integrate both destabilization mechanisms and hydraulic performance when interpreting treatment performance.

6.3.3 Influence of seeding method and analytical approach on oocyst removal by conventional CAF

The final set of experiments evaluated the performance of conventional CAF using two different oocyst seeding methods: (i) filter influent seeding method (Figure 6.2a), data from Chapter 3 for comparison, and (ii) raw water seeding method, in which oocysts passed through the static mixer, flocculation, and sedimentation basins before entering the filters (Figure 6.2d). These experiments were designed to evaluate whether the performance patterns observed under direct in-line CAF evaluations (Figures 6.3 and 6.4) persisted when upstream clarification processes were present for conventional CAF, and to assess whether the data generated using different methodological approaches for conventional CAF were similarly reliable and informative. The resulting oocyst removals under varying destabilization conditions are shown in Figure 6.5.

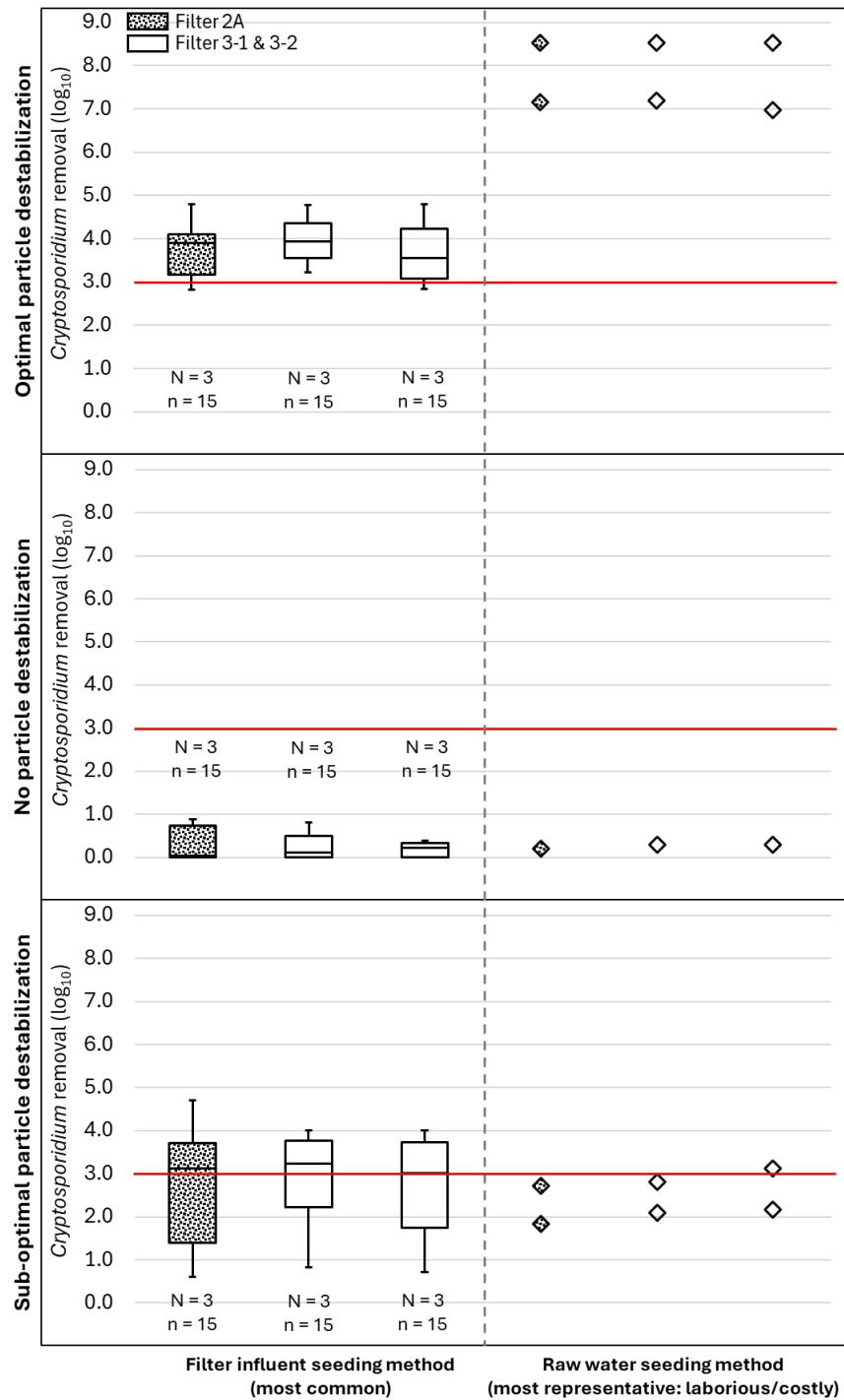


Figure 6.5. Performance comparison of *Cryptosporidium* oocyst removal by pilot-scale conventional CAF with high concentrations of optimally destabilized, non-destabilized, and sub-optimally destabilized oocysts added using different seeding methods; filter influent seeding method (most common) and raw

water seeding method (most representative: laborious/costly). The boxplots represent removals from high concentration experiments using multiple grab samples for membrane filtration analysis; each boxplot summarizes data from multiple experiments, where N denotes the number of filter runs and n denotes the number of effluent samples included. Diamond symbol represent high concentration experiments evaluated using continuous sampling for EPA Method 1623.1 analysis, in which approximately 600 L of water were collected and analyzed, yielding a single data point per run. Pattern-filled symbols indicate Filter 2A, and no-fill symbols indicate duplicate Filters 3-1 and 3-2. The red horizontal line indicates the 3-log oocyst removal performance expected from "well-operated" CAF.

Under optimal destabilization, removals achieved using the filter influent seeding method ranged from 3- to 4-log, consistent with expectations for particles sufficiently destabilized by adequate coagulant addition (Chapter 3). However, these removals were lower than those observed for direct in-line CAF, which achieved approximately 5-log removal under comparable chemical and operational conditions (as shown in Figure 6.3). While a direct experiment-to-experiment comparison of conventional and direct in-line CAF was not conducted in the present study, this has been examined in detail in Chapter 4, and likely attributes to increased contact opportunities for sufficient particle destabilization under direct in-line CAF as opposed to conventional CAF for high-quality source waters.

For the raw water seeding approach under optimal destabilization, oocyst removals reached 7- to 8-log, reflecting the combined contributions of sedimentation followed by CAF. Because oocysts were introduced upstream of the clarification processes, the measured removal incorporated performance achieved by all treatment barriers (i.e., sedimentation and CAF) present in conventional CAF treatment configuration. For these experiments, only a single effluent sample was collected for a 7h run; therefore, variability associated with individual experiments cannot be directly assessed from these results, as discussed previously. However, to better understand the contribution of each treatment stage, an individual influent grab sample of ~10 mL was collected at the filter influent for only the optimal destabilization experiments and were processed using membrane filtration method described Section 6.2.6.1. These measurements indicated that sedimentation alone provided approximately 1.5- to 2-log removal, implying that CAF consistently contributed an additional 5- to 6-log. The clustering of high removals under optimal conditions reinforces that this performance was reproducible, and highlights that for high-quality source waters, CAF provides the majority of pathogen removal once particles are sufficiently destabilized. This finding is consistent with longstanding evidence that CAF represents a key barrier for *Cryptosporidium* oocyst removal when coagulant demand is adequately met (Patania et al., 1995; Nieminski and Ongerth, 1995; Edzwald and

Kelley, 1998; Emelko, 2001; Huck et al., 2002; Emelko, 2003; Lee, 2018; Ballantyne et al., 2024; Chapter 2; Chapter 3; Chapter 4). Further details on the overall effective log removal achieved by each of these experiments can be found in Table 6.3.

Under no-destabilization conditions, removals declined to approximately 0- to 1-log for both seeding and analytical approaches, reflecting the expected behaviour of stable oocysts that neither aggregate, settle, nor attach to filter media in the absence of coagulant addition. These observations are consistent with the findings presented in Sections 6.3.1 and 6.3.2 and align with colloidal filtration theory (Tufenkji and Elimelech, 2004, Tufenkji and Elimelech, 2005; Stumm and O'Melia, 1967), which predicts negligible removal of stable colloids under unfavorable coagulation and destabilization conditions.

Under sub-optimal destabilization, removals decreased substantially and exhibited greater variability for the filter influent seeding method, typically falling within the 1- to 3-log removal. This variability emphasizes the inherent instability of partially destabilized conditions, where small deviations in coagulant dose can lead to large differences in filter performance as explained previously. For the raw water seeding method, removals in the same 1- to 3-log range were observed; however, variability was less apparent due to the use of single effluent samples. Importantly, the presence of a sedimentation basin did not compensate for inadequate particle destabilization, as removals remained less than 3-log. This behaviour closely mirrors the trends observed for the direct in-line CAF under equivalent operational conditions and reinforces that sub-optimal destabilization, rather than treatment configuration and methodological differences, impacted measured CAF performance.

Across all data presented in this study: different seeding methods, seeding concentrations, analytical approaches, and both direct in-line and conventional CAF configurations, a consistent pattern emerged: CAF performance was governed primarily by the extent of particle destabilization. When destabilization was absent or sub-optimal, removals remained well below the 3-log benchmark irrespective of performance demonstration method used, indicating that neither treatment configuration nor methodological variations could compensate for inadequate coagulation. In contrast, when optimal destabilization was achieved, removals were uniformly high across all configurations and approaches, with sedimentation and CAF together providing cumulative removals of 7- to 8-log and CAF alone contributing the majority of pathogen removal.

These findings indicate that the pilot-scale performance demonstration approaches currently used to evaluate pathogen removal by CAF are generally robust and capable of producing reliable and consistent

performance estimates. However, the interpretation of these results must account for factors that can introduce uncertainty and variability into methodological approaches used in performance demonstrations—specifically, the appropriate handling of non-detects, variability associated with analyzing different sample volumes and their corresponding enumeration methods, and the influence of coagulation chemistry (i.e., particle destabilization). Each of these factors has the potential to confound measured performance estimates and therefore must be considered carefully when interpreting data.

6.4 Conclusions

In this systematic evaluation of *Cryptosporidium* oocyst removal by CAF using various performance demonstration approaches significant insights were revealed.

1. Filtration can consistently achieve ≥ 3 -log oocyst removal when oocysts are sufficiently destabilized, regardless of different performance demonstration approaches (i.e., oocyst addition point, concentration, or analytical method).
2. Pilot-scale performance demonstration approaches currently in use to evaluate *Cryptosporidium* passage through filtration are reasonable and can yield generally consistent results between replicates. While each method has analytical limitations, particularly the handling of non-detects and the reliance on single point estimates, the primary performance trends remained consistent. Greater variability emerged only under sub-optimal or no destabilization conditions, underscoring that lack of consideration of degree of particle destabilization can confound generated performance estimates. When interpreted with appropriate awareness of these constraints, existing pilot-scale performance demonstration methods remain informative and reliable tools for assessing pathogen removal.
3. Current treatment infrastructure, CAF or equivalent, can reliably achieve 3-log of protozoan removal by CAF, and likely emerging contaminants (i.e., microplastics). The consistent removals demonstrated in this study reinforce the reliability of CAF for achieving the levels of protozoan reduction required to protect public health. These results highlight the essential role of performance demonstrations in informing treatment plant design, validating treatment credits, supporting risk-based regulatory decision-making, and ensuring that utilities can confidently meet pathogen removal expectations.

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Chapter 7. Conclusions, implications, and recommendations

7.1 Conclusions

The key conclusions from this thesis research are presented below.

1. Filter effluent turbidities of 0.3 NTU, 0.1 NTU, or lower do not ensure 3-log removal of *Cryptosporidium* oocysts by filtration without sufficient particle destabilization by coagulation.
2. Zeta potential analysis is a valuable operational tool for assessing coagulant dose sufficiency and supporting effective *Cryptosporidium* oocyst removal by filtration in systems reliant on high-quality (low turbidity, low dissolved organic carbon concentration) source water.
3. In Toronto's Lake Ontario source water, a post-coagulation filter influent zeta potential within ± 5 mV of 0 was associated with sufficient particle destabilization to achieve ≥ 3 -log *Cryptosporidium* oocyst removal by filtration.
4. Temperature and filter media depth were not primary drivers of oocyst removal by filtration; rather, performance was governed by the sufficiency of particle destabilization.
5. Direct in-line filtration consistently achieved *Cryptosporidium* oocyst removal exceeding 3-log when particles were sufficiently destabilized.
6. Direct in-line filtration consistently exhibited equivalent or higher *Cryptosporidium* oocyst removal than conventional filtration when particles were sufficiently destabilized.
7. Minimum zeta potential value required for achieving ≥ 3 -log *Cryptosporidium* oocyst removal can differ between treatment configurations and systems.
8. When sufficiently destabilized, microplastics achieved ≥ 3 -log removal similar to *Cryptosporidium* oocysts, confirming that microplastics follow the established coagulation-filtration principles of sufficient particle destabilization and attachment by filtration.
9. Treatment of microplastics can be evaluated using similar performance-based framework used for other particulate contaminants (i.e., protozoa) for which there are specific treatment targets, once health-based targets for them are established.
10. Despite inherent differences among seeding methods, seed concentrations, and analytical approaches used to conduct performance demonstrations of *Cryptosporidium* oocyst removal by CAF, all approaches yielded comparable and interpretable results during conditions of sufficient particle destabilization for both direct in-line and conventional filtration.

11. Pilot-scale performance demonstration approaches currently in use to evaluate *Cryptosporidium* passage through filtration are reasonable and can yield generally consistent results between replicates.

Collectively, these conclusions reaffirm why physico-chemical filtration is often referred to as “chemically assisted filtration” (CAF). The central finding of this work is unequivocal: adequate coagulation and particle destabilization remain a primary driver of particle removal by CAF. Destabilization is central to filtration, the polishing step where colloidal particles that are too small to settle, including protozoa and microplastics (MPs), are removed—and when particles are sufficiently destabilized, CAF behaves predictably across different particle types, treatment configurations, and methodological approaches. This is especially important for high-quality source waters, where CAF performance is central to protozoan pathogen removal and sedimentation offers little to no additional benefit. Under these conditions, zeta potential offers a practical operational tool to confirm sufficiency of particle destabilization by adequate coagulant addition. At the same time, the work here has shown that effective destabilization alone does not guarantee effective filtration; hydraulic conditions within the filter can also influence attachment and removal. These findings further reinforce that the principles underlying CAF are robust and transferable; once health-based treatment targets for MPs are established, the same process understanding that guides protozoan removal can be extended to support MPs regulation and management. As the drinking water sector faces increasingly variable source water conditions and evolving contaminant concerns, the process understanding of CAF reinforced here provides guidance for future treatment design, optimization, and risk-informed decision-making.

7.2 Implications

This work demonstrated that for high-quality (low turbidity and low DOC) source waters, higher than expected coagulant doses may be required to achieve sufficient particle destabilization for well-operated CAF capable of meeting regulatory expectations of 2.5-log or 3-log *Cryptosporidium* oocyst removal. While zeta potential values within a few millivolts of 0 are indicative of maximal destabilization, neither a single zeta potential value nor a coagulant dose can be universally defined. The minimum coagulant dose required to achieve ≥ 3 -log oocyst removal by CAF is inherently system-specific, reflecting source-water characteristics, filter design, and operational conditions.

Importantly, zeta potential must not be misinterpreted as a surrogate or predictor of removal, as it does not account for key factors such as filter design or hydraulic conditions that also govern filtration performance. For utilities, this implies that combining zeta potential analysis with filtered water turbidity monitoring can

support more consistent CAF performance, guide coagulant dosing in low-turbidity waters, and reduce the risk of sub-optimal destabilization, while recognizing that zeta potential complements, but does not replace, turbidity-based evaluation.

The findings also showed that when particles were sufficiently destabilized, direct in-line CAF consistently achieved oocyst removals equivalent to—or often greater than—the 3-log credit assigned to conventional CAF, despite receiving only 2.5-log credit in current regulatory frameworks due to omission of the sedimentation basin (EPA, 2006a; Health Canada, 2012). However, direct in-line CAF is specifically designed for high-quality source waters where sedimentation provides limited benefit. Accordingly, the findings support revisiting regulatory frameworks to ensure that treatment credits appropriately reflect the performance of CAF configurations treating high-quality source waters.

While MPs removal was ≥ 3 -log under optimized destabilization (similar to *Cryptosporidium* oocysts) this cannot yet be interpreted as “sufficient” without a health-based treatment target (WHO, 2019). Future targets may require equal or more stringent removal levels than those applied to protozoa. While these findings demonstrate that MPs can be removed by CAF in a manner consistent with colloidal filtration principles (O’Melia and Stumm, 1967; Ives, 1970; Yao et al., 1971; Tobiason and O’Melia, 1988), but the level of removal ultimately required to protect public health is currently unknown. Importantly, this does not imply that *Cryptosporidium* is an indicator or analogous for MPs. Rather, the results show that the same process understanding that governs protozoan removal can be extended to support the regulation and management of MPs once their health-based treatment targets are established. Accordingly, the conventional treatment infrastructure (i.e., CAF) relied upon for protozoan control can likely manage MP removal in the future.

When evaluating and interpreting measured performance estimates from pilot-scale demonstrations, it is essential to consider the factors that drive uncertainty and variability. To avoid analytical bias, non-detects should be reported as zero counts per sample volume (Chik et al., 2018), and oocyst enumeration should include at least 10 oocysts per sample to minimize measurement error associated with random sampling and variable analytical recovery (Emelko et al., 2008). Variability associated with single point estimates from single sample analytical approaches should also be interpreted cautiously, as the underlying distribution of uncertainty is unknown for such data. Increased variability across different methods emerged only under sub-optimal or no destabilization conditions. In contrast, when destabilization was optimized, all methods produced consistent and reasonable performance estimates, highlighting that the lack of consideration of degree of particle destabilization can confound generated performance. Therefore, when

interpreted with appropriate awareness of these constraints, existing pilot-scale performance demonstration methods remain reliable tools for assessing pathogen removal.

Finally, the consistency observed across all performance demonstration approaches under optimal destabilization reinforces confidence in CAF's ability to achieve the protozoan reduction levels required for public health protection and supports extending these same principles to emerging particulate contaminants such as MPs once health-based targets are established, reinforcing confidence in established drinking water treatment technologies.

7.2 Recommendations and future directions

The following research goals are recommended for further study:

- Develop use of zeta potential analysis through routine monitoring (online or via grab samples) to develop system-specific targets.

Under changing source-water quality, particularly for systems reliant on low-turbidity, low-dissolved organic carbon concentrations waters, routine monitoring of zeta potential and, where feasible, real-time control of coagulation application can provide critical insight into the effectiveness of coagulant application and support more consistent CAF performance.

- Progress toward establishing health-based treatment targets for microplastics will require improved analytical methods and standardized monitoring approaches that can reliably quantify particles across all relevant size ranges.

Given that this study only evaluated ~5 µm microplastics, future work should include smaller particles, including those approaching the nanoplastics range, to ensure that treatment performance frameworks used here is assessed across the various microplastics sizes.

Moreover, building a more comprehensive dataset on the fate of microplastics during drinking water treatment using explained approaches shown here will be essential for supporting evidence-based regulatory development.

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Appendix A

Pilot-scale Horgan Water Treatment Plant (WTP)

The Horgan WTP intake draws water from Lake Ontario, 3.2 km offshore at a depth of 8 m. Raw water quality during experiments was generally comparable to that at Harris WTP, with minor variations in key parameters (mean $\pm$ standard deviation): turbidity 0.29 ± 0.73 NTU, pH 8.1 ± 0.23 , and total organic carbon (TOC) 2.56 ± 0.26 mg/L. The Horgan pilot plant operated as a direct filtration CAF, similar to Train 2 of Harris WTP, incorporating coagulation, flocculation, and dual-media filtration at hydraulic loading rates (HLR) of 10–24 m/h. Raw water was diverted from the Horgan WTP raw water line, and coagulant (alum or PACl) was dosed using a positive displacement injection pump (Model Gala 1601 PPE, ProMinent Fluid Controls Ltd., Guelph, ON). The coagulated water then passed through four static mixers (models ½-, 1-, and 2-40C-4-12-2, Koflo Corp., Cary, IL) designed to simulate full-scale flocculation and provide adequate contact time. Water was subsequently directed to transparent PVC filter columns (Filters 2B and 4B) mounted on a stainless-steel frame. Each column was composed of three flanged sections, giving a total height of 3.96 m, with overflow drains located 31 cm from the top to provide 3.65 m of operational head. The columns had an internal diameter of 75 mm and were covered, but not sealed, to maintain constant-head conditions. Media configurations and characteristics for Filters 2B and 4B are summarized in Table A.1. Filter 2B was operated using engineered ceramic media designed to match the grain-size and hydraulic properties of conventional filter media. The rough engineered ceramic media used throughout the experimental program consisted of inert, kiln-fired clay aggregates that were generally spherical in shape (Scott, 2008). For filter 4B, anthracite and sand were used. In this study, the media configurations were not incorporated to evaluate filter design in detail, but rather to demonstrate that observed removal performance was independent of filter design and was instead governed by particle destabilization conditions.

Table A.1. Filter media and configuration details for Horgan WTP

Filter 2B	Filter 4B
45 cm (ES=0.89 mm) ceramic	45 cm (ES=0.89) mm anthracite
30 cm (ES=0.47 mm) ceramic	30 cm (ES=0.47) mm sand
20 cm graded gravel	20 cm graded gravel

Seed suspensions were introduced via an injection port located 61 cm above the media surface. A peristaltic pump (Model 7553-70, Cole-Parmer Instrument Canada Inc., Montreal, QC) delivered the suspension through a distributor nozzle fitted with six radial openings to ensure uniform dispersal into

the column center. A schematic of the overall pilot plant setup is shown in Figure A.1. Pilot-scale *Cryptosporidium* experiments at Horgan WTP followed the same procedures as at Harris, including seed suspension preparation, coagulant addition, and sample collection with minor differences in seeding duration and sampling intervals (Scott, 2008).

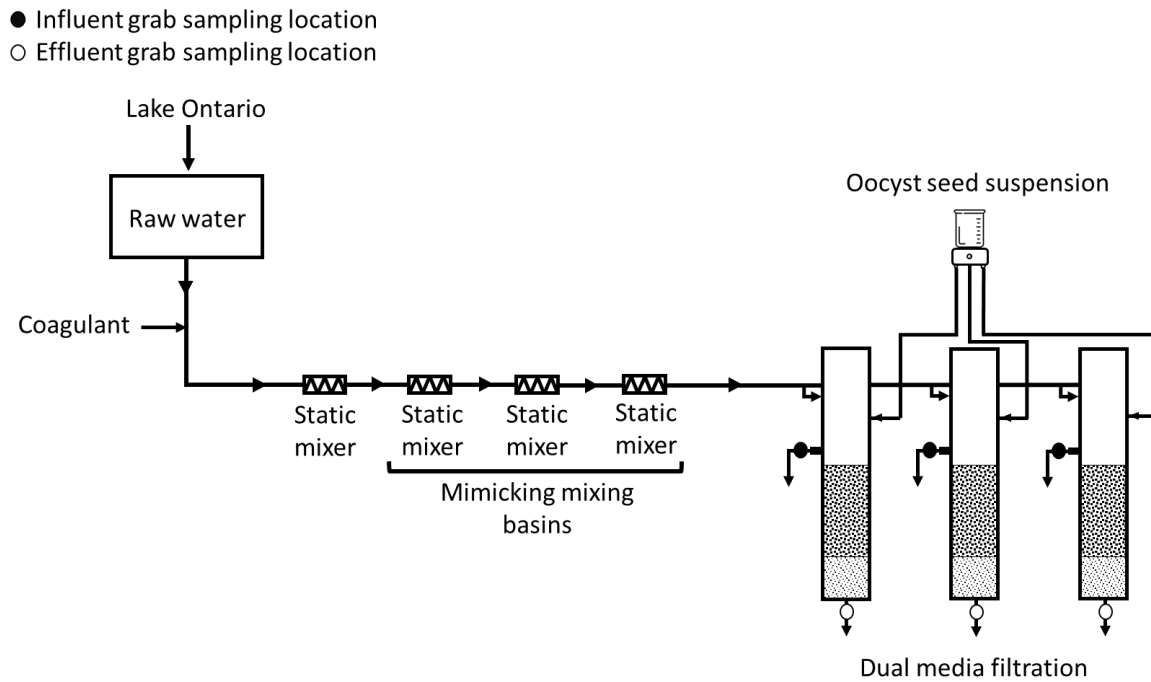


Figure A.1. Schematic flow diagram of pilot-scale filtration plant at Horgan WTP, Toronto. During the filter runs, a continuous input of *Cryptosporidium* oocyst seed suspension was introduced into the filters. Influent and effluent grab samples were collected to estimate *Cryptosporidium* oocyst removal by the filters.

Appendix B

Tracer studies

Tracer tests were conducted to (i) verify adequate mixing of oocysts introduced to the filter influents through visual assessment and (ii) estimate seed-suspension residence time in the filters to inform appropriate sample collection times. Two tracers were used in these experiments: a food-grade dye (Allura Red, Red No. 40) and sodium chloride (NaCl). The dye test enabled rapid visualization of flow paths and provided a qualitative indication of oocyst mixing and dispersion following introduction to the influent streams. In contrast, the salt test relied on conductivity measurements, which allowed quantitative determination of water residence time within the filters for the different seeding locations.

A continuous feed (step input) containing both tracers was introduced at the selected injection point. Filter effluent samples were collected at 2-minute intervals until tracer concentrations reached a stable plateau. Once stabilization occurred, tracer addition was discontinued, and samples were subsequently collected every 10–20 minutes until conductivity returned to baseline levels measured prior to the experiment. The general experimental configuration and the seeding points evaluated through tracer testing are shown in Figure B.1 and Figure B.2, respectively. The configurations illustrated in Figure B.2 represent the seed suspension addition approaches used throughout this thesis for the various performance demonstrations.

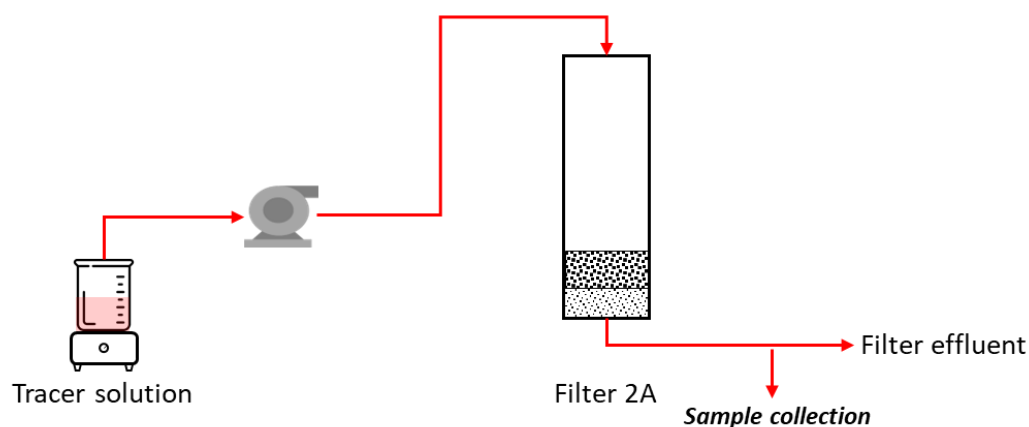


Figure B.1. Tracer study general experimental configuration.

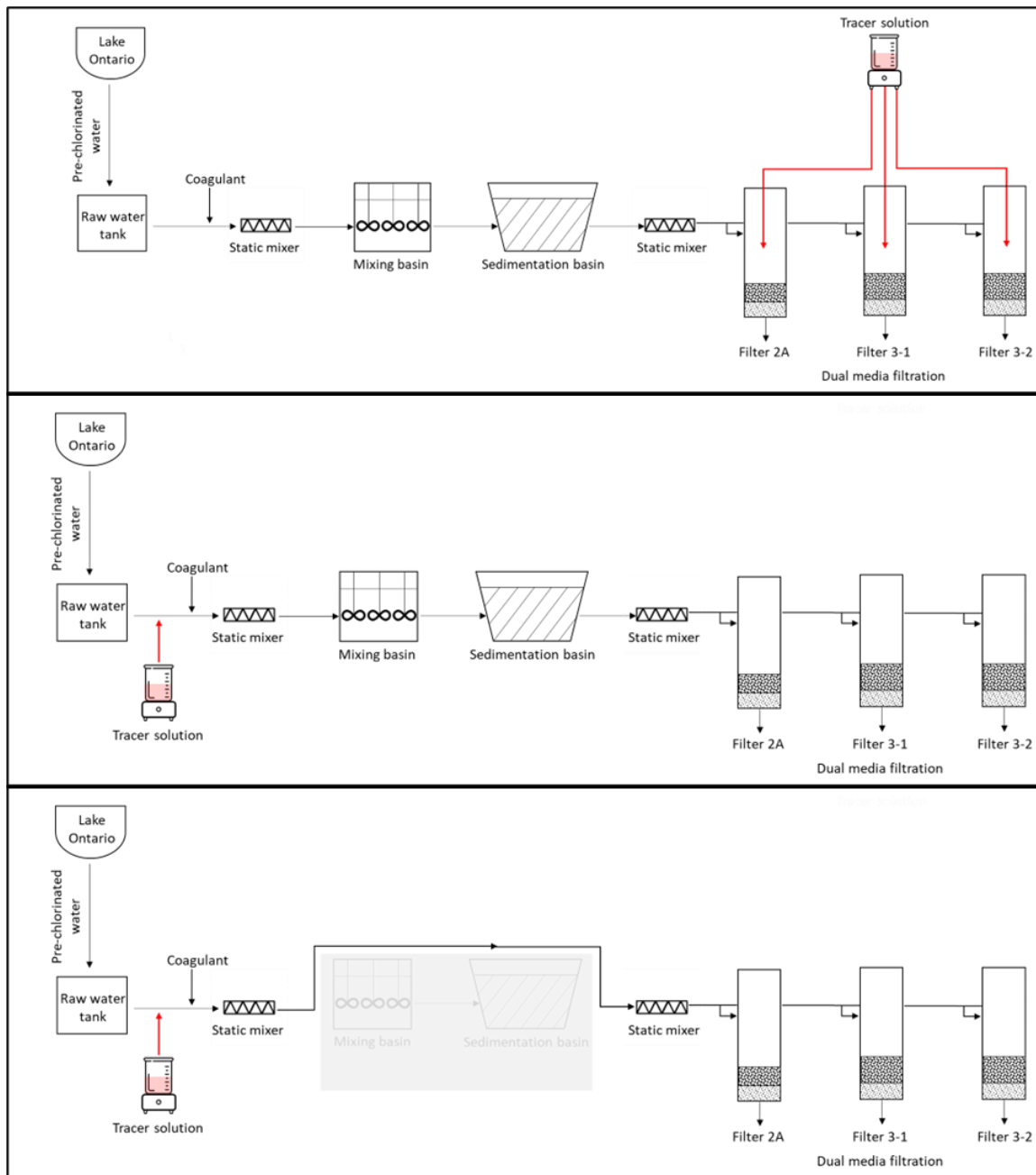


Figure B.2. Different seeding points evaluated using tracer testing. Top panel: Filter influent seeding method. Middle panel: Raw water seeding method for conventional CAF. Bottom panel: Raw water seeding method for direct in-line CAF.

The red dye tracer test demonstrated that seed suspension addition point ensured sufficient mixing and rapid, consistent dispersion of the tracer solution across all the filter columns. Some vertical dispersion was noted as the dye entered the filter column because the filter influent inflow was directly above the

injection point. This caused turbulence leading to upward dispersion. However, overall, the experiments demonstrated that seed suspension addition used for this study resulted in good mixing and oocyst dispersal in the filter influent streams.

Using conductivity measurements obtained during the NaCl tracer test, the mean filter residence time (T_{50}) corresponding to the three seed suspension addition points and the filter effluent was estimated through breakthrough curve analysis. An example of a conductivity breakthrough curve from the tracer test conducted on Filter 3-2 is shown in Figure B.3. The associated mean filter residence times (T_{50}) are presented in Table B.1.

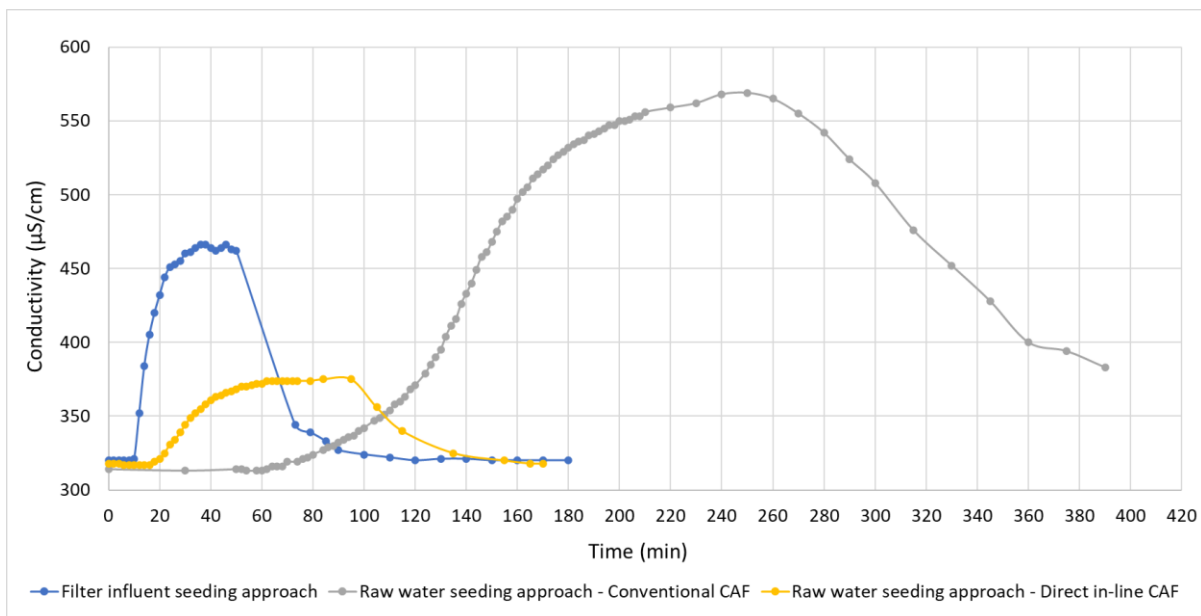


Figure B.3. Example conductivity breakthrough curves from the NaCl tracer test on Filter 3-2 using the three seeding approaches shown in Figure B.2.

The T_{50} value for the filter-influent seeding approach was approximately 15 minutes, whereas the raw-water seeding approach for direct in-line CAF resulted in a T_{50} of about 30 minutes. For the filter-influent approach, the tracer was introduced only 130 cm upstream of the media for Filters 3-1 and 3-2 and 180 cm upstream for Filter 2A, resulting in much shorter travel distances and therefore shorter residence times. In contrast, when the tracer was introduced at the raw-water line upstream of coagulant addition, it traveled a longer hydraulic path before reaching the filters, producing the longer T_{50} observed. The lower-amplitude tracer curve for this configuration reflects dilution occurring when introduced at the beginning of the treatment process.

For the raw water seeding approach in conventional CAF, the T_{50} was approximately 140 minutes. This longer residence time corresponds to the greater distance traveled when tracer is introduced at the very beginning of the treatment process, passing through the rapid-mix, flocculation, and sedimentation basin before entering the filters. The higher peak in the tracer curve reflects the larger initial tracer dose required to compensate for dilution through these units. As shown, conductivity required nearly seven hours or more to return to baseline for the used concentration. These tracer-derived residence times were essential for planning the duration of the pilot-scale challenge tests and selecting appropriate sampling intervals following oocyst seed-suspension addition.

Table B. 1. Mean Residence Time (T_{50}) in Filters 2A, 3-1, and 3-2 based on NaCl tracer tests using the three different seeding approaches. N/A indicates the data that is not available.

Filter	Residence Time (min)		
	Filter influent seeding approach	Raw water seeding approach – Conventional CAF	Raw water seeding approach – Direct in-line CAF
3-1	14.67	137.4	29.2
3-2	-	140.0	30.8
2A	19.67	139.3	29.6

Recognizing that filter hydraulics have the potential to result in different residence times in the individual filters, conductivity breakthrough curves were generated for each of the three filters used in Raw water seeding approaches for conventional CAF and direct in-line CAF are shown in Figures B.4 and B.5. The overlap of the curves for each filter demonstrates excellent hydraulic reproducibility between the filter columns, indicating consistent flow distribution, residence time, and mixing behavior across filters, and adding confidence that differences observed during challenge tests are attributable to treatment performance rather than hydraulic variability.

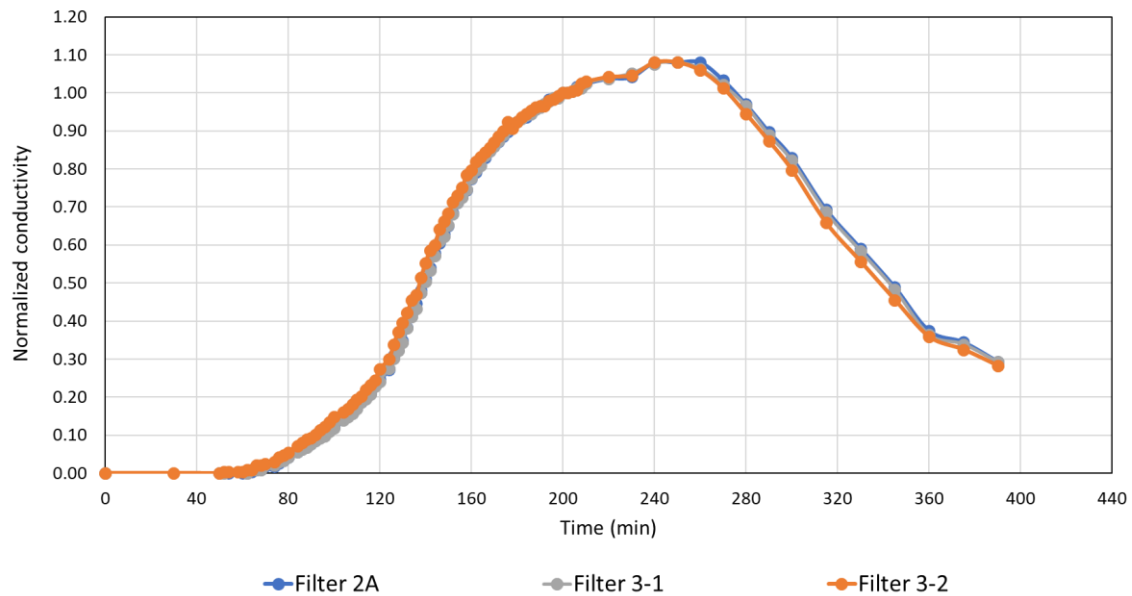


Figure B.4. Example conductivity breakthrough curves from the NaCl tracer test on Filters 2A, 3-1, and 3-2 when tracer was introduced using the raw water seeding approach for conventional CAF.

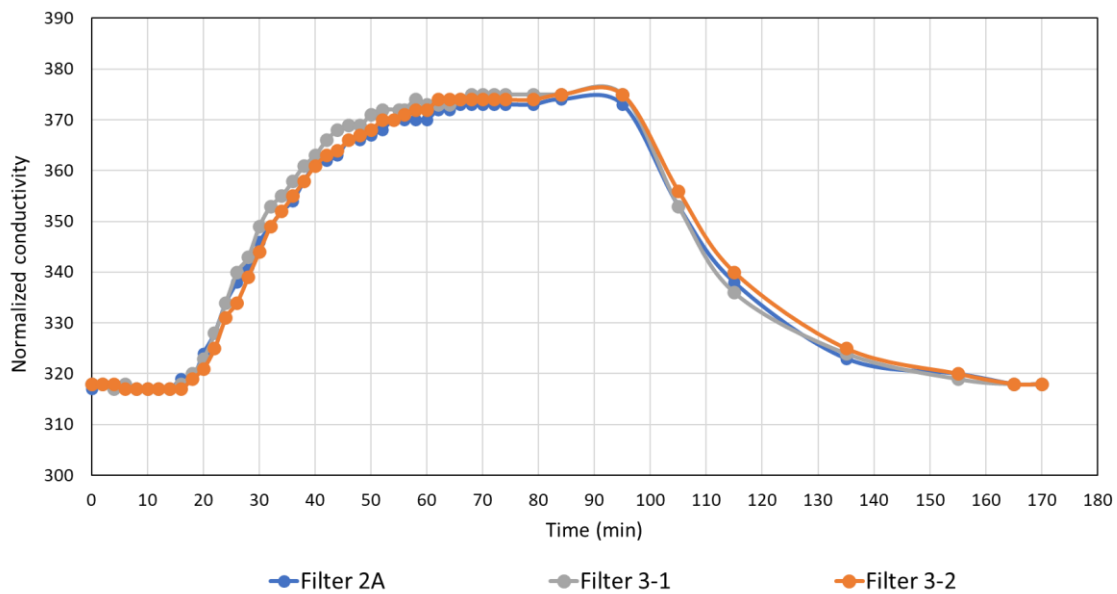


Figure B.5. Example conductivity breakthrough curves from the NaCl tracer test on Filters 2A, 3-1, and 3-2 when tracer was introduced using the raw water seeding approach for direct in-line CAF.

Appendix C

Influence of oocyst addition to raw water quality and coagulant demand for particle destabilization

Pilot-scale performance demonstrations involving the addition of destabilized *Cryptosporidium* oocysts to the filter influent streams—a method widely reported in the literature (Nieminski and Ongerth, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Emelko, 2001; Huck et al., 2001; Emelko, 2003; Emelko and Huck, 2004; Amburgey et al., 2005; Emelko et al., 2005; Assavasilavasukul et al., 2008; Scott, 2008; Brown and Emelko, 2009; Hijnen and Medema, 2010; Lee, 2018; Ballantyne et al., 2024)—was employed in this thesis (Chapters 2, 3, 4, and 5). Figure C.1 illustrates an example of possible changes in turbidity and zeta potential that can be observed during preparation of the *Cryptosporidium* oocyst seed suspension.

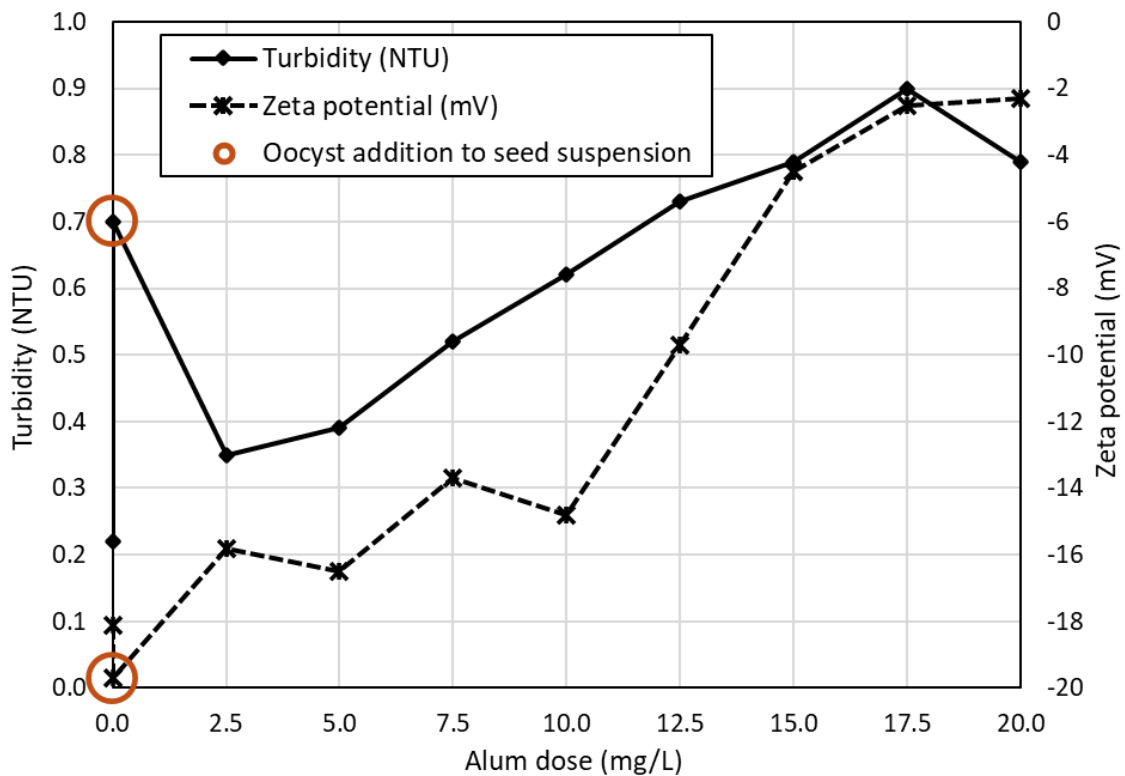


Figure C.1. Turbidity and zeta potential response to *Cryptosporidium* oocyst and incremental coagulant dosing in seed suspension. Coagulant was added in 2.5 mg/L increments, with periods of rapid mixing and settling occurring prior to turbidity and zeta potential readings. The initial alum addition dropped turbidity to 0.35 NTU. Consecutive 2.5 mg/L additions of alum to the seed suspension increased its

turbidity, until the target zeta potential and reduction in turbidity of the seed suspension was achieved (i.e., maintaining a zeta potential between -5 and 0 mV).

In this scenario, as *Cryptosporidium* oocysts were added to the source water (raw water) used to prepare the seed suspension a noticeable increase in turbidity, from 0.22 NTU to 0.70 NTU, was observed. For high-quality source waters, this illustrates how oocyst addition alters raw-water quality, sometime so much that it can be measured as a change in turbidity. Regardless, it affects coagulant demand relative to raw water alone (Appendix C). Therefore, the coagulant dose used for pilot operation may not always reflect the dose required to sufficiently destabilize the seed suspension. For example, the coagulant requirement for water at 0.70 NTU differs from that required for 0.22 NTU.

It was also observed that although the initial coagulant dose reduced turbidity, the particles were not yet sufficiently destabilized (-16 mV). As additional coagulant was added, turbidity increased due to the formation of micro precipitates and hydrolyzed coagulant species, while the zeta potential moved closer to 0 mV. This behavior is consistent with findings from this thesis and established coagulation chemistry for low-turbidity systems, where insufficient particle density limits contact opportunities for destabilization until micro precipitates form and create additional contact opportunities for particle destabilization (Amirtharajah and O'Melia, 1990; O'Melia, 1985; O'Melia and Stumm, 1967). At approximately 20 mg/L, the zeta potential approached 0 mV and turbidity again decreased, indicating that particle destabilization had become sufficient.

Appendix D

Review of *Cryptosporidium* oocyst removal by CAF

Table D.1. Summary of reported *Cryptosporidium* oocyst removal by CAF across various source water turbidity ranges and treatment configurations.

Raw water turbidity				Source water quality		Operational period(s) investigated			<i>Cryptosporidium</i> oocysts			Filter effluent turbidity during investigation	
	Investigation	Scale	Filtration type	Turbidity (NTU)	DOC (mg/L)	Stable operation	Ripening, hydraulic surge or step	End-of-run, breakthrough	Origin or point of addition	Removal range (log ₁₀)	Non-detects observed	<0.3 NTU	<0.1 NTU
<1.0 NTU	West et al., 1994	pilot	direct	0.3-0.7	not reported	✓			seeded into influent stream	1.9-3.4	✓	✓	✓
	Ongerth & Pecoraro, 1995	pilot	direct	0.3-0.6*	not reported	✓			seeded into influent stream	1.5-3.1*		✓	✓
	Edzwald et al., 2000	pilot	conventional	0.7-0.9	not reported		not reported		seeded up-front of clarification	5.4-5.5	✓	✓	✓
		pilot	conventional							5.3-5.5	✓	✓	✓
		pilot	conventional							5.4-5.5	✓	✓	✓
	Dugan & Williams, 2004	pilot	in-line	0.2-0.3*	not reported	✓	✓		seeded into influent stream	0.8-3.7	✓		
≥1.0 NTU	LeChevallier et al., 1991	full	varied	various	not reported	✓			environmental	0.1-4.6	✓	✓	
	LeChevallier & Norton, 1992	full	conventional	0.4-120	not reported	✓			environmental	2.3-2.5*	✓	✓	

Hall et al., 1995	pilot	conventional	2.5-11*	not reported	✓	✓	seeded into influent stream	2.9-4.4	✓			
Kelley et al., 1995	full	conventional	1.7-99.0	not reported	not reported		environmental	1.8*	✓	✓		
	full	conventional						1.4*	✓	✓		
Nieminski, 1994; Nieminski & Ongerth, 1995	pilot	conventional	4.0-23.0	not reported	✓		seeded into influent stream	1.9-4.0*	✓	✓		
		direct						1.3-4.0*	✓	✓		
	full	conventional	2.5-28.0					✓	1.9-2.8*	✓	✓	
		direct						✓	2.6-2.9*	✓	✓	
Patania et al., 1995	pilot	conventional	1.0	not reported	✓		seeded into influent stream	4.3-5.2		✓	✓	
	pilot	conventional	10.0-13.0					✓	✓	5.0		
	pilot	conventional	4.0					✓	✓	4.2-4.7		
	pilot	conventional	1.4					✓	✓	2.7-3.1		
	pilot	conventional	2.0-2.5					✓	✓	5.1-5.9		
Edzwald et al., 1996	pilot	conventional	0.5-1.5	not reported	not reported		seeded into influent stream	4.3-5.5*	✓	✓	✓	
Van Duser et al., 1996	full	conventional	29.0*	not reported	not reported		environmental	3.2*		✓	✓	
	pilot	conventional						2.9*		✓	✓	
Scott et al., 1997	pilot	conventional	0.7-8.0	not reported	not reported		seeded into influent stream	1.7-4.3				

States et al., 1997	full	conventional	not reported	not reported	not reported			environmental	1.5	✓	✓	✓	
Yates et al., 1997	pilot	direct	not reported	not reported	not reported			seeded into influent stream	3.7-4.5*		✓	✓	
Edzwald & Kelley, 1998	pilot	conventional	1.6-2.1	2.7-2.8	not reported			seeded into influent stream	4.2-5.0*		✓	✓	
Baudin & Lainé, 1998	full	conventional	10.0*	not reported	✓	✓		environmental	N/A	✓	✓		
	full	direct	1.0*		✓	✓			3.0-4.0	✓	✓		
	full	conventional	15.0*		✓	✓			1.3-3.0		✓		
Swertfeger et al., 1999	pilot	conventional	7.7-196.0*	not reported	✓			seeded into influent stream	1.6-4.2*	✓	✓		
Amburgey et al., 2001	pilot	direct	1.8*	not reported	✓	✓		seeded into influent stream	0.9-1.8*		✓		
Dugan et al., 2001	pilot	conventional	30.3*	not reported	not reported			seeded into influent stream	0.2-4.4*	✓			
Hashimoto et al., 2001	full	conventional	17.7*	not reported	not reported			environmental	2.5*	✓			
Huck et al.,	2001	pilot	conventional	1.1*	3.0*	✓	✓	✓	seeded into influent stream	0.5-5.0	✓	✓	
		pilot	conventional	3.0*	6.0*	✓	✓	✓		1.0-5.5	✓		
	2002a	pilot	conventional	3.0**	not reported	✓	✓	✓	seeded into influent stream	5.5*		✓	✓
		pilot	conventional	2.0**		✓	✓	✓		3.0*		✓	✓
		pilot	conventional	1.5**		✓				4.2*		✓	✓

	2002b	pilot	conventional	1.0-2.7	not reported	✓	✓	✓	seeded into influent stream	1.0-5.5*	✓	
		pilot	conventional	0.4-2.4		✓	✓	✓		0.5-5.0*	✓	
Harrington et al.,	2001	pilot	conventional	5.5*	not reported	✓	✓		seeded up-front of clarification	1.4-1.8		
	2003	pilot	conventional	8.6*	not reported	✓			seeded up-front of clarification	1.2-2.1	✓	
Emelko et al.; Emelko & Huck,	2000	pilot	conventional	3.0**	not reported	✓	✓	✓	seeded into influent stream	1.3-5.8*	✓	✓
	2001	pilot	conventional	3.0**	not reported	✓		✓	seeded into influent stream	3.9-5.8*	✓	✓
	2003	pilot	conventional	3.0**	not reported	✓		✓	seeded into influent stream	1.3-5.8*	✓	✓
	2004	pilot	conventional	3.0*	6.0*	✓	✓	✓	seeded into influent stream	0.3-5.8*	✓	
		pilot	conventional	1.5*	<1.0*	✓	✓	✓		4.3-5.3*	✓	✓
	Xagarorarakis et al., 2004	pilot	conventional	0.5-5.0	not reported		not reported		seeded up-front of clarification	0.3-2.6*	✓	
Hendricks et al., 2005		pilot	conventional	1.2-3.5	not reported	✓			seeded into influent stream	2.5-4.3*	✓	✓
Amburgey et al., 2005		pilot	conventional	1.5-2.6	not reported	✓	✓		seeded into influent stream	1.4-1.9*	✓	✓
Mazoua & Chauvheid, 2006		full	conventional	not reported	not reported		not reported		environmental	1.5-3.8	✓	✓
Assavasilavasukul et al.,	2008a	pilot	conventional	0.5-3.6*	3.0-6.0	✓			seeded up-front of clarification	0.7-5.2*	✓	✓

NTU	2008b	pilot	conventional	2.0-5.0*	3.0-6.0	✓	seeded up-front of clarification	0.3-5.2*	✓	✓	✓
	Brown & Emelko, 2009	pilot	in-line	2.5-5.0	1.9-2.2	✓	seeded into influent stream	0.2-4.4*			

* Averaged parameter
 ** Estimated parameter
 ‡ Often due to multiple sites reported in a single paper

Appendix E

Raw data for Chapter 2

Table E.1. Raw water quality, pilot plant operational data, seed suspension data, and average *Cryptosporidium* oocyst removal for Chapter 2.

Date	Raw Water Quality				Pilot Plant Coagulation		Oocyst Seed Suspension Coagulation			Pilot Plant CAF			
	Temperature (°C)	Turbidity (NTU)	pH	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Coagulant Type	Dose (mg/L)	Final Zeta Potential (mV)	Filter Operational Condition	Filter Effluent Turbidity (NTU)	Filter Configuration	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
06-Sep-06	20.0	0.7	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	0.50 0.37	2B 4B	1.1 1.2
11-Sep-06	21.0	0.5	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	0.48 0.40	2B 4B	0.6 0.3
12-Sep-06	20.0	0.4	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	0.33 0.28	2B 4B	0.2 0.2
25-Sep-06	9.0	0.2	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	0.13 0.10	2B 4B	0.1 0.5
29-Jan-07	2.0	0.2	-	-	PACl	0.8	PACl	0.8	-	Stable	0.06 0.06	2B 4B	4.6 5.1
02-Apr-07	5.5	0.2	-	-	PACl	0.6	PACl	0.6	-	Stable	0.11 0.10	2B 4B	2.1 2.1
06-Apr-07	6.5	0.2	-	-	PACl	1.6	PACl	1.6	-	Stable	0.16 0.06	2B 4B	1.6 1.5
11-Apr-07	6.5	0.2	-	-	PACl	2.6	PACl	2.6	-	Stable	0.12 0.10	2B 4B	1.0 1.5
16-Apr-07	7.0	0.3	-	-	PACl	3.6	PACl	3.6	-	Stable	0.10 0.08	2B 4B	1.3 1.8
20-Apr-07	6.0	0.1	-	-	PACl	0.3	PACl	0.3	-8.8	Stable	0.09 0.08	2B 4B	0.9 1.3
20-Apr-07	6.0	0.1	-	-	PACl	0.3	PACl	0.3	-	Stable	0.10 0.09	2B 4B	1.1 1.2
24-Apr-07	7.0	0.2	-	-	PACl	0.3	PACl	1.3	-8.0	Stable	0.12 0.11	2B 4B	1.0 0.9
12-Sep-07	22.0	0.3	-	-	alum	5.0	alum	5.0	-	Stable	0.11 0.09	2B 4B	0.3 0.3
13-Sep-07	22.0	0.3	-	-	alum	3.7	alum	3.7	-	Stable	0.06 0.06	2B 4B	2.2 1.9
11-Dec-07	4.0	0.2	-	-	No Coagulant	0.0	No Coagulant	4.0	-	Stable	0.19 0.21	2B 4B	0.4 0.0
18-Sep-08	22.0	0.3	-	-	alum	5.0	alum	5.0	-	Stable	0.06 0.05	2B 4B	1.6 2.1

19-Sep-08	22.0	0.4	-	-	alum	5.0	alum	5.0	-	Stable	0.08 0.06	2B 4B	1.6 1.7
29-Sep-08	22.0	1.0	-	-	alum	5.0	alum	5.0	-	Stable	0.15 0.10	2B 4B	0.9 1.3
05-Oct-17	16.0	0.5	7.2	-	alum	5.5	alum	40.0	-	Stable	0.02 0.02	1 2A	3.8 4.0
23-Oct-17	9.7	0.2	7.0	-	alum	4.5	alum	40.0	-	Stable	0.02 0.02	1 2A	4.3 4.7
13-Nov-17	13.1	0.2	6.8	-	alum	4.8	alum	40.0	-	Hydraulic surge	0.02 0.02	1 2A	4.2 4.7
28-Nov-17	12.5	0.2	6.9	-	alum	6.0	alum	40.0	-	Hydraulic surge	0.01 0.02	1 2A	3.4 2.6
22-Jan-18	4.3	0.2	6.8	-	alum	4.3	alum	40.0	-	Hydraulic surge	0.02 0.02	1 2A	4.7 4.7
06-Feb-18	4.3	0.2	4.9	-	alum	4.5	alum	40.0	-	Hydraulic surge	0.01 0.02	1 2A	4.2 4.6
21-Feb-18	5.3	0.2	6.9	-	alum	4.0	alum	40.0	-	Hydraulic surge	0.02 0.02	1 2A	4.4 4.8
06-Mar-18	4.5	0.1	6.9	-	alum	4.5	alum	40.0	0.1	Stable	0.02 0.02	1 2A	4.8 4.7
19-Mar-18	4.6	0.2	6.9	-	alum	4.5	alum	40.0	2.0	Stable	0.02 0.02	1 2A	4.4 4.1
10-Apr-18	4.9	0.2	7.0	-	alum	4.3	alum	5.0	-10.0	Stable	0.02 0.02	1 2A	2.3 1.9
23-Apr-18	5.0	0.5	7.1	-	alum	5.0	alum	0.0	-7.4	Stable	0.03 0.03	1 2A	1.3 0.8
29-May-18	8.9	0.1	8.35	-	alum	5.0	alum	40.0	-2.3	End of the run	0.04 0.04	1 2A	3.1 3.3
									1.3	Rippening	0.04 0.04	1 2A	3.0 3.4
19-Jun-18	8.8	0.2	7.2	-	alum	4.5	alum	40.0	0.5	Hydraulic surge	0.02 0.02	1 2A	3.1 3.2
16-Oct-18	8.0	0.1	6.95	-	alum	5.0	alum	40.0	2.63	Stable	0.02	3	3.9
23-Oct-18	7.9	0.3	6.99	-	alum	4.5	alum	40.0	1.67	End of the run	0.02	3	4.3
06-Nov-18	11.4	0.3	7.12	-	alum	4.5	alum	40.0	1.71	Rippening	0.03	3	4.8
10-Dec-18	6.6	0.1	7.03	-	alum	4.0	alum	40.0	0.89	End of the run	0.02	3	4.1
20-Feb-19	3.9	0.3	7	-	alum	4.5	alum	40.0		Stable	0.02	3	3.5
	2.2	1.0	8.36	-	PACI	0.9	PACI	12.5	-8.88	Stable	0.05	4A	4.3
08-Mar-19	3.7	0.2	7	-	alum	4.0	alum	40.0	1.84	Stable	0.02 0.02	3 3	3.9 3.6
	2.1	1.0	8.33	-	PACI	0.9	PACI	12.5	-7.8	Stable	0.04	4A	4.2
26-Apr-19	6.3	0.4	7.06	-	alum	4.5	alum	40.0	0.6	Rippening	0.03 0.03	3 3	2.1 2.6
	6.0	0.2	8.44	-	PACI	0.9	PACI	12.5	-1.07	Rippening	0.05	4A	3.2

30-May-19	10.5	0.8	7.18	-	alum	4.0	alum	40.0	-3.4	End of the run	0.03	3	3.6
	7.7	0.3	8.5	-	PACI	0.9	PACI	12.5	-7.8		0.04	3	4.0
02-Aug-19	10.2	0.5	8.68	-	alum	4.0	alum	0.0	-15.27	Stable	0.04	4A	4.7
13-Oct-21	18.0	0.5	8.0	-9.7	alum	5.0	alum	5.0	-6.3	Stable	0.15	3	0.5
					PACI	1.0	PACI	1.0	-7.3		0.17	3	1.4
10-Nov-21	6.7	0.2	8.0	-7.7	alum	4.0	alum	6.0	-9.7	Stable	0.07	3	1.1
					PACI	0.9	PACI	1.4	-12.2		0.07	3	0.9
19-Nov-21	4.9	0.2	8.0	-6.0	alum	4.0	alum	10.0	-10.0	Stable	0.07	2A	0.8
					PACI	0.9	PACI	1.2	-13.3		0.10	4A	0.5
14-Dec-21	4.8	0.4	8.0	-12.9	alum	4.0	alum	6.0	-8.3	Stable	0.04	3	3.1
					PACI	0.9	PACI	2.4	-4.5		0.04	3	3.5
15-Dec-21	4.9	0.4	8.0	-11.1	alum	4.0	alum	6.0	-13.9	Stable	0.04	2A	3.1
					PACI	0.9	PACI	2.0	-11.1		0.04	4A	1.0
16-Dec-21	4.7	1.8	8.0	-18.4	alum	4.0	alum	10.0	-12.7	Stable	0.07	4C	0.9
					PACI	0.9	PACI	2.4	-15.0		0.07	4C	0.9
16-Dec-21	4.7	1.8	8.0	-18.4	alum	4.0	alum	10.0	-11.8	Stable	0.04	3	3.9
					PACI	0.9	PACI	2.4	-16.5		0.04	3	4.0
04-Mar-22	2.0	0.4	7.9	-16.6	alum	5.0	alum	13.5	-0.8	Hydraulic surge	0.05	2A	3.0
12-Apr-22	4.5	0.2	8.0	-6.2	alum	5.0	alum	25.5	-1.5	Stable	0.04	4A	3.6
					alum	5.0	alum	25.5	-1.5		0.04	3	4.0

Table E.2. Detailed *Cryptosporidium* oocyst removal data for Chapter 2. For any counts with a zero (ND) (except for T0) a count of one was assigned as a conservative adjustment. This change for NDs is reflected in the “Filter Effluent *Cryptosporidium* (oocysts/L)” column.

Date	Pilot Plant CAF											
	Filter Configuration	Filter Operational Condition	Sample Time (min)	Filter Influent Sample Volume (L)	Filter Influent <i>Cryptosporidium</i> (# oocysts)	Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Average Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Filter Effluent Sample Volume (L)	Filter Effluent <i>Cryptosporidium</i> (# oocysts)	Filter Effluent <i>Cryptosporidium</i> (oocysts/L)	<i>Cryptosporidium</i> Removal (%)	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
06-Sep-06	2B	Stable	20	0.00500	124	2.48E+04	2.84E+04	0.05000	21	4.20E+02	1.48E-02	1.2
			30	0.00500	69	1.38E+04		0.05000	43	8.60E+02	3.03E-02	
			40	0.01000	214	2.14E+04		0.05000	268	5.36E+03	1.89E-01	
			50	0.01000	535	5.35E+04		0.05000	101	2.02E+03	7.12E-02	
06-Sep-06	4B	Stable	20	0.00500	192	3.84E+04	3.33E+04	0.05000	59	1.18E+03	3.54E-02	1.2
			30	0.00500	136	2.72E+04		0.05000	21	4.20E+02	1.26E-02	
			40	0.01000	356	3.56E+04		0.05000	193	3.86E+03	1.16E-01	
			50	0.01000	320	3.20E+04		0.05000	182	3.64E+03	1.09E-01	
11-Sep-06	2B	Stable	20	0.02000	1505	7.53E+04	3.49E+04	0.01000	127	1.27E+04	3.64E-01	0.6
			30	0.00200	43	2.15E+04		0.01000	79	7.90E+03	2.26E-01	
			40	0.00200	36	1.80E+04		0.02000	35	1.75E+03	5.01E-02	
			50	0.00200	50	2.50E+04		0.02000	263	1.32E+04	3.76E-01	
11-Sep-06	4B	Stable	20	0.02000	1469	7.35E+04	2.57E+04	0.10000	1898	1.90E+04	7.37E-01	0.3
			30	0.00200	34	1.70E+04		0.01000	90	9.00E+03	3.50E-01	
			40	0.00200	17	8.50E+03		0.01400	130	9.29E+03	3.61E-01	
			50	0.00200	8	4.00E+03		0.01400	203	1.45E+04	5.63E-01	
12-Sep-06	2B	Stable	20	0.00500	8	1.60E+03	1.20E+04	0.01000	33	3.30E+03	2.75E-01	0.2
			30	0.00500	69	1.38E+04		0.01000	0	7.50E+03	6.25E-01	
			40	0.00500	103	2.06E+04		0.01000	64	6.40E+03	5.33E-01	
			50	0.00500	0	1.20E+04		0.01000	128	1.28E+04	1.07E+00	
12-Sep-06	4B	Stable	20	0.00500	10	2.00E+03	7.05E+03	0.01000	39	3.90E+03	5.53E-01	0.2
			30	0.00500	46	9.20E+03		0.01000	34	3.40E+03	4.82E-01	
			40	0.00500	40	8.00E+03		0.01000	45	4.50E+03	6.38E-01	
			50	0.00500	45	9.00E+03		0.01000	66	6.60E+03	9.36E-01	
25-Sep-06	2B	Stable	20	0.00300	52	1.73E+04	2.18E+04	0.02000	270	1.35E+04	1.13E+00	0.1
			30	0.00300	65	2.17E+04		0.02000	167	8.35E+03	6.96E-01	
			40	0.01000	984	2.41E+04		0.02000	716	3.58E+04	2.98E+00	
			50	0.01000	1145	2.41E+04		0.02000	334	1.67E+04	1.39E+00	
25-Sep-06	4B	Stable	20	0.00300	85	2.83E+04	2.95E+04	0.01400	96	6.86E+03	9.73E-01	0.5
			30	0.00300	125	4.17E+04		0.02000	154	7.70E+03	1.09E+00	
			40	0.01000	1291	2.41E+04		0.01400	24	1.71E+03	2.43E-01	
			50	0.01000	904	2.41E+04		0.01400	295	2.11E+04	2.99E+00	
29-Jan-07	2B	Stable	20	0.00015	46	3.07E+05	3.51E+05	0.82300	16	1.94E+01	5.54E-05	4.6
			30	0.00015	70	4.67E+05		0.84600	6	7.09E+00	2.02E-05	
			40	0.00010	21	2.10E+05		0.73000	3	4.11E+00	1.17E-05	
			50	0.00010	42	4.20E+05		0.73000	1	1.37E+00	3.90E-06	
29-Jan-07	4B	Stable	20	0.00015	80	5.33E+05	4.38E+05	0.79000	1	1.27E+00	2.89E-06	5.2
			30	0.00015	111	7.40E+05		0.08100	330	4.07E+03	9.29E-03	
			40	0.00010	37	3.70E+05		0.69600	3	4.31E+00	9.83E-06	
			50	0.00010	11	1.10E+05		0.52400	1	1.91E+00	4.35E-06	
02-Apr-07	2B	Stable	20	0.00100	429	4.29E+05	5.33E+05	0.21500	984	4.58E+03	8.59E-03	2.1
			30	0.00100	767	7.67E+05		0.21600	775	3.59E+03	6.73E-03	
			40	0.00100	402	4.02E+05		0.21100	907	4.30E+03	8.07E-03	
			50	0.00100	533	5.33E+05		0.22200	852	3.84E+03	7.20E-03	
02-Apr-07	4B	Stable	20	0.00100	333	3.33E+05	5.33E+05	0.20400	881	4.32E+03	8.11E-03	2.1
			30	0.00100	753	7.53E+05		0.21400	737	3.44E+03	6.46E-03	
			40	0.00100	691	6.91E+05		0.21300	778	3.65E+03	6.86E-03	
			50	0.00100	354	3.54E+05		0.21300	889	4.17E+03	7.83E-03	

06-Apr-07	2B	Stable	20	0.00125	579	4.63E+05	5.22E+05	0.02000	161	8.05E+03	1.54E-02	1.6
			30	0.00125	481	3.85E+05		0.02000	120	6.00E+03	1.15E-02	
			40	0.00125	838	6.70E+05		0.02000	315	1.58E+04	3.02E-02	
			50	0.00125	712	5.70E+05		0.02000	355	1.78E+04	3.40E-02	
06-Apr-07	4B	Stable	20	0.00125	336	2.69E+05	5.35E+05	0.02000	80	4.00E+03	7.48E-03	1.5
			30	0.00125	851	6.81E+05		0.02000	122	6.10E+03	1.14E-02	
			40	0.00125	784	6.27E+05		0.02000	205	1.03E+04	1.92E-02	
			50	0.00125	702	5.62E+05		0.02000	911	4.56E+04	8.52E-02	
11-Apr-07	2B	Stable	20	0.00100	127	1.27E+05	9.98E+04	0.00500	24	4.80E+03	4.81E-02	1.0
			30	0.00100	51	5.10E+04		0.00500	41	8.20E+03	8.22E-02	
			40	0.00100	118	1.18E+05		0.00500	94	1.88E+04	1.88E-01	
			50	0.00100	103	1.03E+05		0.00500	45	9.00E+03	9.02E-02	
11-Apr-07	4B	Stable	20	0.00100	285	2.85E+05	2.16E+05	0.00500	35	7.00E+03	3.24E-02	1.5
			30	0.00100	145	1.45E+05		0.00500	29	5.80E+03	2.68E-02	
			40	0.00100	249	2.49E+05		0.00500	54	1.08E+04	4.99E-02	
			50	0.00100	186	1.86E+05		0.00500	31	6.20E+03	2.87E-02	
16-Apr-07	2B	Stable	20	0.00100	571	5.71E+05	3.67E+05	0.03000	370	1.23E+04	3.36E-02	1.3
			30	0.00100	389	3.89E+05		0.03000	586	1.95E+04	5.33E-02	
			40	0.00100	414	4.14E+05		0.03000	937	3.12E+04	8.51E-02	
			50	0.00400	373	9.33E+04		0.03000	219	7.30E+03	1.99E-02	
16-Apr-07	4B	Stable	20	0.00100	363	3.63E+05	5.01E+05	0.03000	163	5.43E+03	1.08E-02	1.8
			30	0.00100	233	2.33E+05		0.03000	234	7.80E+03	1.56E-02	
			40	0.00200	2611	1.31E+06		0.03000	544	1.81E+04	3.62E-02	
			50	0.00400	412	1.03E+05		0.03000	128	4.27E+03	8.51E-03	
20-Apr-07	2B	Stable	20	0.00045	421	9.36E+05	8.06E+05	0.00200	132	6.60E+04	8.19E-02	0.9
			30	0.00045	360	8.00E+05		0.00200	205	1.03E+05	1.27E-01	
			40	0.00050	451	9.02E+05		0.00200	247	1.24E+05	1.53E-01	
			50	0.00050	293	5.86E+05		0.00200	253	1.27E+05	1.57E-01	
20-Apr-07	4B	Stable	20	0.00045	371	8.24E+05	9.06E+05	0.00200	69	3.45E+04	3.81E-02	1.3
			30	0.00045	495	1.10E+06		0.00200	85	4.25E+04	4.69E-02	
			40	0.00050	358	7.16E+05		0.00200	112	5.60E+04	6.18E-02	
			50	0.00050	491	9.82E+05		0.00200	97	4.85E+04	5.36E-02	
20-Apr-07	2B	Stable	20	0.00075	436	5.81E+05	6.52E+05	0.00500	382	7.64E+04	1.17E-01	1.1
			30	0.00075	275	3.67E+05		0.00500	240	4.80E+04	7.36E-02	
			40	0.00075	706	9.41E+05		0.00400	37	9.25E+03	1.42E-02	
			50	0.00075	539	7.19E+05		0.00400	342	8.55E+04	1.31E-01	
20-Apr-07	4B	Stable	20	0.00075	567	7.56E+05	6.39E+05	0.00500	206	4.12E+04	6.44E-02	1.2
			30	0.00075	356	4.75E+05		0.00500	169	3.38E+04	5.29E-02	
			40	0.00075	453	6.04E+05		0.00400	135	3.38E+04	5.28E-02	
			50	0.00075	542	7.23E+05		0.00400	264	6.60E+04	1.03E-01	
24-Apr-07	2B	Stable	20	0.00050	541	1.08E+06	8.92E+05	0.00500	398	7.96E+04	8.93E-02	1.0
			30	0.00050	415	8.30E+05		0.00500	517	1.03E+05	1.16E-01	
			40	0.00050	279	5.58E+05		0.00500	634	1.27E+05	1.42E-01	
			50	0.00050	548	1.10E+06		0.00500	380	7.60E+04	8.52E-02	
24-Apr-07	4B	Stable	20	0.00050	262	5.24E+05	7.19E+05	0.00500	581	1.16E+05	1.62E-01	0.9
			30	0.00050	388	7.76E+05		0.00500	309	6.18E+04	8.60E-02	
			40	0.00050	237	4.74E+05		0.00500	608	1.22E+05	1.69E-01	
			50	0.00050	550	1.10E+06		0.00500	357	7.14E+04	9.94E-02	
12-Sep-07	2B	Stable	20	0.00075	2302	3.07E+06	1.20E+06	0.00100	1473	1.47E+06	1.23E+00	0.3
			30	0.00075	714	9.52E+05		0.02000	1499	7.50E+04	6.24E-02	
			40	0.00100	377	3.77E+05		0.00100	590	5.90E+05	4.91E-01	
			50	0.00100	408	4.08E+05		0.00100	308	3.08E+05	2.56E-01	
12-Sep-07	4B	Stable	20	0.00075	1928	2.57E+06	9.30E+05	0.00100	1157	1.16E+06	1.24E+00	0.3
			30	0.00075	385	5.13E+05		0.00100	298	2.98E+05	3.21E-01	
			40	0.00100	178	1.78E+05		0.00100	241	2.41E+05	2.59E-01	
			50	0.00100	457	4.57E+05		0.00100	247	2.47E+05	2.66E-01	
13-Sep-07	2B	Stable	30	0.00040	257	6.43E+05	1.48E+06	0.05000	700	1.40E+04	9.46E-03	2.2
			40	0.00040	596	1.49E+06		0.05000	102	2.04E+03	1.38E-03	
			50	0.00040	503	1.26E+06		0.05000	601	1.20E+04	8.12E-03	
			60	0.00040	1013	2.53E+06		0.05000	308	6.16E+03	4.16E-03	

13-Sep-07	4B	Stable	30 40 50 60	0.00040 0.00040 0.00040 0.00040	709 758 481 861	1.77E+06 1.90E+06 1.20E+06 2.15E+06	1.76E+06	0.10000 0.10000 0.10000 0.10000	1800 2735 2149 1469	1.80E+04 2.74E+04 2.15E+04 1.47E+04	1.03E-02 1.56E-02 1.22E-02 8.37E-03	1.9
11-Dec-07	2B	Stable	20 30 40 50	0.06100 0.10000 0.05000 0.05000	89 153 56 49	1.46E+03 1.53E+03 1.12E+03 9.80E+02	1.27E+03	0.20700 0.27000 0.41100 0.30400	164 197 72 73	7.92E+02 7.30E+02 1.75E+02 2.40E+02	6.23E-01 5.73E-01 1.38E-01 1.89E-01	0.0
11-Dec-07	4B	Stable	20 30 40 50	0.07700 0.09900 0.00500 0.00500	59 187 56 58	7.66E+02 1.89E+03 1.12E+03 1.16E+03	1.23E+03	0.21000 0.21000 0.28800 0.18500	112 950 18 23	5.33E+02 4.52E+03 6.25E+01 1.24E+02	4.32E-01 3.67E+00 5.07E-02 1.01E-01	0.4
18-Sep-08	2B	Stable	30 40 50 60	0.00120 0.00120 0.00120 0.00120	81 182 50 180	6.75E+04 1.52E+05 4.17E+04 1.50E+05	1.03E+05	0.03000 0.01500 0.01500 0.03000	33 25 69 72	1.10E+03 1.67E+03 4.60E+03 2.40E+03	1.07E-02 1.62E-02 4.48E-02 2.34E-02	1.6
18-Sep-08	4B	Stable	30 40 50 60	0.00120 0.00120 0.00120 0.00120	240 242 421 261	2.00E+05 2.02E+05 3.51E+05 2.18E+05	2.43E+05	0.01000 0.01000 0.00500 0.01000	10 4 16 23	1.00E+03 4.00E+02 3.20E+03 2.30E+03	4.12E-03 1.65E-03 1.32E-02 9.48E-03	2.2
19-Sep-08	2B	Stable	30 40 50 60	0.00120 0.00120 0.00120 0.00120	933 1413 1071 616	7.78E+05 1.18E+06 8.93E+05 5.13E+05	8.40E+05	0.05000 0.05000 0.05000 0.10000	1333 1410 1109 874	2.67E+04 2.82E+04 2.22E+04 8.74E+03	3.17E-02 3.36E-02 2.64E-02 1.04E-02	1.6
19-Sep-08	4B	Stable	30 40 50 60	0.00120 0.00120 0.00120 0.00120	1425 1235 1017 610	1.19E+06 1.03E+06 8.48E+05 5.08E+05	8.93E+05	0.05000 0.05000 0.10000 0.10000	993 1124 1657 676	1.99E+04 2.25E+04 1.66E+04 6.76E+03	2.22E-02 2.52E-02 1.86E-02 7.57E-03	1.7
29-Sep-08	2B	Stable	30 40 50 60	0.00120 0.00120 0.00120 0.00120	1390 1312 1354 525	1.16E+06 1.09E+06 1.13E+06 4.38E+05	9.54E+05	0.01000 0.01000 0.01000 0.02500	1461 1705 1289 1466	1.46E+05 1.71E+05 1.29E+05 5.86E+04	1.53E-01 1.79E-01 1.35E-01 6.14E-02	0.9
29-Sep-08	4B	Stable	30 40 50 60	0.00120 0.00120 0.00120 0.00120	853 785 499 1061	7.11E+05 6.54E+05 4.16E+05 8.84E+05	6.66E+05	0.00500 0.15000 0.02500 0.02500	178 6048 823 677	3.56E+04 4.03E+04 3.29E+04 2.71E+04	5.34E-02 6.05E-02 4.94E-02 4.06E-02	1.3
05-Oct-17	1	Stable	0 15 30 45 60 75	0.00600 0.00600 0.00300 0.00300 0.00300 0.00300	0 0 116 159 325 171	0.00E+00 0.00E+00 3.87E+04 5.30E+04 1.08E+05 5.68E+04	6.42E+04	0.70000 0.70000 0.70000 0.70000 0.70000 0.70000	0 0 3 8 2 16	0.00E+00 1.00E+00 4.00E+00 1.10E+01 3.00E+00 2.30E+01	0.00E+00 1.56E-05 6.23E-05 1.71E-04 4.68E-05 3.59E-04	3.8
05-Oct-17	2A	Stable	0 15 30 45 60 75	0.00600 0.00600 0.00300 0.00300 0.00300 0.00300	0 0 94 207 121 147	0.00E+00 0.00E+00 3.13E+04 6.90E+04 4.03E+04 4.90E+04	4.74E+04	0.70000 0.70000 0.70000 0.70000 0.70000 0.70000	0 0 0 2 2 3	0.00E+00 1.00E+00 1.00E+00 1.14E+01 3.00E+00 4.00E+00	0.00E+00 2.11E-05 2.11E-05 2.41E-04 6.33E-05 8.44E-05	4.0
23-Oct-17	1	Stable	0 15 30 45 60 75 90 105	0.00600 0.00600 0.00600 0.00300 0.00600 0.00300 0.00300 0.00300	0 3 180 129 486 270 358 392	0.00E+00 5.00E+02 3.00E+04 3.38E+04 1.27E+05 8.98E+04 1.19E+05 1.31E+05	8.83E+04	0.70000 0.70000 0.70000 0.70000 0.70000 0.70000 0.70000 0.70000	0 0 0 3 2 3 4 4	0.00E+00 1.00E+00 1.00E+00 4.30E+00 2.90E+00 4.30E+00 5.70E+00 5.70E+00	0.00E+00 1.13E-05 1.13E-05 4.87E-05 3.28E-05 4.87E-05 6.45E-05 6.45E-05	4.3

23-Oct-17	2A	Stable	0	0.00600	0	0.00E+00	8.23E+04	0.70000	0	0.00E+00	0.00E+00	4.7
			15	0.00600	2	2.50E+02		0.70000	1	1.00E+00	1.22E-05	
			30	0.00600	84	1.40E+04		0.70000	0	1.00E+00	1.22E-05	
			45	0.00300	337	5.62E+04		0.70000	0	1.00E+00	1.22E-05	
			60	0.00600	627	1.46E+05		0.70000	2	2.90E+00	3.53E-05	
			75	0.00300	138	4.58E+04		0.70000	2	2.90E+00	3.53E-05	
			90	0.00300	334	1.11E+05		0.70000	1	1.00E+00	1.22E-05	
			105	0.00300	278	1.21E+05		0.70000	1	1.00E+00	1.22E-05	
13-Nov-17	1	Hydraulic Surge	0	0.00600	4	5.84E+02	6.91E+04	0.70000	0	0.00E+00	0.00E+00	4.2
			50	0.00100	67	6.65E+04		0.70000	6	9.00E+00	1.30E-04	
			55	0.00100	55	5.50E+04		0.70000	1	1.40E+00	2.03E-05	
			61	0.00100	68	6.75E+04		0.70000	1	1.40E+00	2.03E-05	
			66	0.00100	94	9.40E+04		0.70000	8	1.10E+01	1.59E-04	
			71	0.00100	86	8.55E+04		0.70000	6	9.00E+00	1.30E-04	
			80	0.00100	61	6.10E+04		0.70000	0	1.00E+00	1.45E-05	
			100	0.00100	54	5.40E+04		0.70000	1	1.40E+00	2.03E-05	
13-Nov-17	2A	Hydraulic Surge	0	0.00600	1	8.35E+01	7.01E+04	0.70000	0	0.00E+00	0.00E+00	4.7
			50	0.00100	41	4.10E+04		0.70000	0	1.00E+00	1.43E-05	
			55	0.00100	55	5.45E+04		0.70000	0	1.00E+00	1.43E-05	
			61	0.00100	63	6.30E+04		0.70000	1	1.43E+00	2.04E-05	
			66	0.00100	66	6.55E+04		0.70000	2	2.90E+00	4.14E-05	
			71	0.00100	58	5.70E+04		0.70000	0	1.00E+00	1.43E-05	
			80	0.00100	108	1.08E+05		0.70000	0	1.00E+00	1.43E-05	
			100	0.00100	102	1.02E+05		0.70000	1	1.40E+00	2.00E-05	
28-Nov-17	1	Hydraulic Surge	0	0.00600	2	1.67E+02	8.61E+04	0.70000	0	0.00E+00	0.00E+00	3.4
			50	0.00100	74	7.40E+04		0.70000	1	1.40E+00	1.63E-05	
			55	0.00100	77	7.65E+04		0.70000	3	4.30E+00	5.00E-05	
			61	0.00100	72	7.15E+04		0.70000	1	1.40E+00	1.63E-05	
			68	0.00100	73	7.30E+04		0.70000	3	4.30E+00	5.00E-05	
			73	0.00100	94	9.40E+04		0.70000	5	7.10E+00	8.25E-05	
			80	0.00100	107	1.07E+05		0.70000	160	2.29E+02	2.66E-03	
			100	0.00100	107	1.07E+05		0.70000	9	1.29E+01	1.50E-04	
28-Nov-17	2A	Hydraulic Surge	0	0.00600	0	0.00E+00	8.58E+04	0.70000	0	0.00E+00	0.00E+00	2.6
			50	0.00100	59	5.90E+04		0.70000	1	1.00E+00	1.17E-05	
			55	0.00100	68	6.75E+04		0.70000	0	1.00E+00	1.17E-05	
			61	0.00100	61	6.10E+04		0.70000	1500	1.50E+03	1.75E-02	
			68	0.00100	80	8.00E+04		0.70000	10	1.00E+01	1.17E-04	
			71	0.00100	116	1.16E+05		0.70000	1	1.40E+00	1.63E-05	
			80	0.00100	118	1.18E+05		0.70000	1	1.40E+00	1.63E-05	
			100	0.00100	100	1.00E+05		0.70000	1	1.40E+00	1.63E-05	
22-Jan-18	1	Hydraulic Surge	0	0.00600	0	0.00E+00	8.20E+04	0.70000	0	0.00E+00	0.00E+00	4.7
			50	0.00100	49	4.90E+04		0.70000	1	1.00E+00	1.22E-05	
			55	0.00100	35	3.50E+04		0.70000	2	3.00E+00	3.66E-05	
			61	0.00100	56	5.55E+04		0.70000	2	3.00E+00	3.66E-05	
			66	0.00100	78	7.80E+04		0.70000	1	1.40E+00	1.71E-05	
			73	0.00100	87	8.70E+04		0.70000	1	1.40E+00	1.71E-05	
			80	0.00100	121	1.21E+05		0.70000	1	1.40E+00	1.71E-05	
			100	0.00100	149	1.49E+05		0.70000	1	1.40E+00	1.71E-05	
22-Jan-18	2A	Hydraulic Surge	0	0.00600	2	1.67E+02	1.09E+05	0.70000	0	0.00E+00	0.00E+00	4.7
			50	0.00100	59	5.90E+04		0.70000	0	1.00E+00	9.20E-06	
			55	0.00100	64	6.35E+04		0.70000	1	1.43E+00	1.32E-05	
			61	0.00100	79	7.85E+04		0.70000	1	1.43E+00	1.32E-05	
			66	0.00100	89	8.90E+04		0.70000	2	2.86E+00	2.63E-05	
			71	0.00100	104	1.04E+05		0.70000	1	1.43E+00	1.32E-05	
			80	0.00100	152	1.52E+05		0.70000	2	2.86E+00	2.63E-05	
			100	0.00100	215	2.15E+05		0.70000	2	2.86E+00	2.63E-05	

06-Feb-18	1	Hydraulic Surge	0	0.00600	0	0.00E+00	6.78E+04	0.70000	0	0.00E+00	0.00E+00	4.2
			50	0.00100	42	4.15E+04		0.70000	2	2.86E+00	4.22E-05	
			55	0.00100	45	4.50E+04		0.70000	2	2.86E+00	4.22E-05	
			61	0.00100	62	6.20E+04		0.70000	3	4.29E+00	6.33E-05	
			66	0.00100	81	8.05E+04		0.70000	3	4.29E+00	6.33E-05	
			73	0.00100	73	7.30E+04		0.70000	3	4.29E+00	6.33E-05	
			80	0.00100	84	8.35E+04		0.70000	4	5.71E+00	8.43E-05	
			100	0.00100	89	8.90E+04		0.70000	5	7.14E+00	1.05E-04	
06-Feb-18	2A	Hydraulic Surge	0	0.00600	0	0.00E+00	8.56E+04	0.70000	0	0.00E+00	0.00E+00	4.6
			50	0.00100	26	2.60E+04		0.70000	1	1.43E+00	1.67E-05	
			55	0.00100	35	3.50E+04		0.70000	1	1.43E+00	1.67E-05	
			61	0.00100	102	1.02E+05		0.70000	1	1.43E+00	1.67E-05	
			66	0.00100	57	5.70E+04		0.70000	2	2.86E+00	3.34E-05	
			71	0.00100	102	1.02E+05		0.70000	1	1.43E+00	1.67E-05	
			80	0.00100	119	1.19E+05		0.70000	2	2.86E+00	3.34E-05	
			100	0.00100	159	1.59E+05		0.70000	3	4.29E+00	5.01E-05	
21-Feb-18	1	Hydraulic Surge	0	0.00600	0	0.00E+00	1.01E+05	0.70000	0	0.00E+00	0.00E+00	4.4
			50	0.00100	60	6.00E+04		0.70000	9	1.29E+01	1.28E-04	
			55	0.00100	41	4.05E+04		0.70000	1	1.43E+00	1.42E-05	
			61	0.00100	136	1.36E+05		0.70000	2	2.86E+00	2.84E-05	
			66	0.00100	147	1.47E+05		0.70000	2	2.86E+00	2.84E-05	
			73	0.00100	111	1.11E+05		0.70000	2	2.86E+00	2.84E-05	
			80	0.00100	119	1.19E+05		0.70000	4	5.71E+00	5.68E-05	
			100	0.00100	92	9.15E+04		0.70000	2	2.86E+00	2.84E-05	
21-Feb-18	2A	Hydraulic Surge	0	0.00600	0	0.00E+00	1.12E+05	0.70000	0	0.00E+00	0.00E+00	4.8
			50	0.00100	73	7.25E+04		0.70000	0	1.00E+00	8.96E-06	
			55	0.00100	84	8.40E+04		0.70000	1	1.40E+00	1.25E-05	
			61	0.00100	124	1.24E+05		0.70000	1	1.40E+00	1.25E-05	
			66	0.00100	122	1.22E+05		0.70000	2	3.00E+00	2.69E-05	
			71	0.00100	122	1.22E+05		0.70000	2	3.00E+00	2.69E-05	
			80	0.00100	126	1.26E+05		0.70000	1	1.43E+00	1.28E-05	
			100	0.00100	131	1.31E+05		0.70000	1	1.43E+00	1.28E-05	
06-Mar-18	1	Stable	0	0.00600	0	0.00E+00	6.70E+04	0.70000	0	0.00E+00	0.00E+00	4.8
			15	0.00100	1	5.00E+02		0.70000	0	1.00E+00	1.49E-05	
			30	0.00100	16	1.60E+04		0.70000	1	1.43E+00	2.13E-05	
			45	0.00100	48	4.80E+04		0.70000	1	1.43E+00	2.13E-05	
			60	0.00100	63	6.25E+04		0.70000	0	1.00E+00	1.49E-05	
			75	0.00100	87	8.70E+04		0.70000	0	1.00E+00	1.49E-05	
			90	0.00100	89	8.85E+04		0.70000	0	1.00E+00	1.49E-05	
			105	0.00100	100	1.00E+05		0.70000	0	1.00E+00	1.49E-05	
06-Mar-18	2A	Stable	0	0.00600	0	0.00E+00	6.09E+04	0.70000	0	0.00E+00	0.00E+00	4.7
			15	0.00100	2	2.00E+03		0.70000	1	1.43E+00	2.35E-05	
			30	0.00100	29	2.85E+04		0.70000	1	1.43E+00	2.35E-05	
			45	0.00100	34	3.35E+04		0.70000	0	1.00E+00	1.64E-05	
			60	0.00100	48	4.80E+04		0.70000	0	1.00E+00	1.64E-05	
			75	0.00100	60	6.00E+04		0.70000	0	1.00E+00	1.64E-05	
			90	0.00100	92	9.15E+04		0.70000	1	1.43E+00	2.35E-05	
			105	0.00100	104	1.04E+05		0.70000	0	1.00E+00	1.64E-05	
19-Mar-18	1	Stable	0	0.00600	0	0.00E+00	5.23E+04	0.70000	0	0.00E+00	0.00E+00	4.4
			15	0.00100	3	3.00E+03		0.70000	1	1.43E+00	2.74E-05	
			30	0.00100	12	1.15E+04		0.70000	3	4.29E+00	8.21E-05	
			45	0.00100	31	3.05E+04		0.70000	2	2.86E+00	5.47E-05	
			60	0.00100	49	4.85E+04		0.70000	0	1.00E+00	1.91E-05	
			75	0.00100	62	6.20E+04		0.70000	1	1.43E+00	2.74E-05	
			90	0.00100	78	7.75E+04		0.70000	1	1.43E+00	2.74E-05	
			105	0.00100	84	8.35E+04		0.70000	0	1.00E+00	1.91E-05	

19-Mar-18	2A	Stable	0	0.00600	0	0.00E+00	2.81E+04	0.70000	0	0.00E+00	0.00E+00	4.1
			15	0.00100	1	5.00E+02		0.70000	1	1.00E+00	3.56E-05	
			30	0.00100	9	9.00E+03		0.70000	2	2.86E+00	1.02E-04	
			45	0.00100	6	6.00E+03		0.70000	1	1.43E+00	5.09E-05	
			60	0.00100	22	2.20E+04		0.70000	3	4.29E+00	1.53E-04	
			75	0.00100	40	3.95E+04		0.70000	-	-	-	
			90	0.00100	42	4.20E+04		0.70000	1	1.43E+00	5.09E-05	
			105	0.00100	50	5.00E+04		0.70000	1	1.43E+00	5.09E-05	
10-Apr-18	1	Stable	0	0.00600	0	0.00E+00	6.30E+04	0.03000	0	0.00E+00	0.00E+00	2.3
			15	0.00100	17	1.65E+04		0.03000	6	2.00E+02	3.17E-03	
			30	0.00100	31	3.05E+04		0.03000	8	2.67E+02	4.23E-03	
			45	0.00100	45	4.50E+04		0.03000	4	1.33E+02	2.12E-03	
			60	0.00100	61	6.05E+04		0.03000	15	5.00E+02	7.94E-03	
			75	0.00100	63	6.25E+04		0.03000	10	3.33E+02	5.29E-03	
			90	0.00100	84	8.35E+04		0.03000	4	1.33E+02	2.12E-03	
			105	0.00100	96	9.60E+04		0.03000	12	4.00E+02	6.35E-03	
10-Apr-18	2A	Stable	0	0.00600	0	0.00E+00	6.28E+04	0.03000	8	2.67E+02	4.25E-03	1.9
			15	0.00100	10	9.50E+03		0.03000	1	3.33E+01	5.31E-04	
			30	0.00100	19	1.85E+04		0.03000	2	6.67E+01	1.06E-03	
			45	0.00100	36	3.60E+04		0.03000	2	5.00E+01	7.97E-04	
			60	0.00100	43	4.30E+04		0.03000	1	3.33E+01	5.31E-04	
			75	0.00100	75	7.45E+04		0.03000	32	1.07E+03	1.70E-02	
			90	0.00100	96	9.55E+04		0.03000	47	1.57E+03	2.50E-02	
			105	0.00100	109	1.09E+05		0.03000	66	2.20E+03	3.51E-02	
23-Apr-18	1	Stable	0	0.00600	17	1.42E+03	7.80E+04	0.03000	4	1.33E+02	1.71E-03	1.3
			15	0.00100	0	0.00E+00		0.03000	48	1.60E+03	2.05E-02	
			30	0.00100	18	1.75E+04		0.03000	57	1.90E+03	2.44E-02	
			45	0.00100	35	3.50E+04		0.03000	59	1.83E+03	2.35E-02	
			60	0.00100	61	6.05E+04		0.03000	175	5.83E+03	7.48E-02	
			75	0.00100	89	8.90E+04		0.03000	153	5.10E+03	6.54E-02	
			90	0.00100	117	1.17E+05		0.03000	187	6.23E+03	7.99E-02	
			105	0.00100	150	1.50E+05		0.03000	87	2.90E+03	3.72E-02	
23-Apr-18	2A	Stable	0	0.00600	2	1.67E+02	6.28E+04	0.03000	118	3.93E+03	6.26E-02	0.8
			15	0.00100	11	5.50E+03		0.03000	79	2.63E+03	4.19E-02	
			30	0.00100	14	1.35E+04		0.03000	151	5.03E+03	8.01E-02	
			45	0.00100	32	3.20E+04		0.03000	45	1.50E+03	2.39E-02	
			60	0.00100	84	8.35E+04		0.03000	303	1.01E+04	1.61E-01	
			75	0.00100	72	7.20E+04		0.03000	382	1.27E+04	2.03E-01	
			90	0.00100	85	8.45E+04		0.03000	373	1.24E+04	1.98E-01	
			105	0.00100	92	9.15E+04		0.03000	381	1.27E+04	2.02E-01	
29-May-18	1	End of the run	0	0.00600	11	9.17E+02	3.24E+04	0.40000	38	9.50E+01	2.93E-03	3.1
			15	0.00100	2	1.00E+03		0.70000	29	4.14E+01	1.28E-03	
			30	0.00100	6	6.00E+03		0.70000	6	8.57E+00	2.64E-04	
			45	0.00100	18	1.75E+04		0.70000	1	1.00E+00	3.08E-05	
			60	0.00100	48	4.80E+04		0.70000	5	7.14E+00	2.20E-04	
			75	0.00100	25	2.50E+04		0.70000	23	3.29E+01	1.01E-03	
			90	0.00100	46	4.55E+04		0.70000	23	3.29E+01	1.01E-03	
			105	0.00100	53	5.25E+04		0.70000	41	5.86E+01	1.81E-03	
29-May-18	2A	End of the run	0	0.00600	3	5.00E+02	4.36E+04	0.70000	0	0.00E+00	0.00E+00	3.0
			15	0.00100	1	5.00E+02		0.70000	23	3.29E+01	7.53E-04	
			30	0.00100	17	1.70E+04		0.70000	28	4.00E+01	9.17E-04	
			45	0.00100	15	1.50E+04		0.70000	7	1.00E+01	2.29E-04	
			60	0.00100	46	4.60E+04		0.70000	28	4.00E+01	9.17E-04	
			75	0.00100	36	3.58E+04		0.70000	10	1.43E+01	3.27E-04	
			90	0.00100	67	6.70E+04		0.70000	8	1.14E+01	2.62E-04	
			105	0.00100	81	8.10E+04		0.70000	10	1.43E+01	3.27E-04	

29-May-18	1	Ripening	0	0.00800	64	5.33E+03	5.08E+04	0.70000	25	3.57E+01	7.03E-04	3.0
			5	0.00150	0	0.00E+00		0.68900	1	1.45E+00	2.86E-05	
			10	0.00150	41	2.85E+04		0.70000	37	5.29E+01	1.04E-03	
			15	0.00150	79	5.60E+04		0.70000	33	4.71E+01	9.28E-04	
			20	0.00150	103	7.23E+04		0.70000	21	3.00E+01	5.91E-04	
			25	0.00150	90	6.03E+04		0.70000	60	8.57E+01	1.69E-03	
29-May-18	2A	Ripening	30	0.00150	65	3.70E+04	7.91E+04	0.70000	18	2.57E+01	5.06E-04	3.4
			0	0.00800	0	0.00E+00		0.70000	9	1.29E+01	1.63E-04	
			15	0.00150	51	3.18E+04		0.70000	13	1.86E+01	2.35E-04	
			30	0.00150	53	3.53E+04		0.70000	11	1.57E+01	1.99E-04	
			45	0.00150	250	1.65E+05		0.70000	62	8.86E+01	1.12E-03	
			60	0.00150	150	9.50E+04		0.70000	20	2.86E+01	3.61E-04	
19-Jun-18	1	Hydraulic surge	75	0.00150	120	7.95E+04	5.06E+04	0.70000	22	3.14E+01	3.98E-04	3.1
			90	0.00150	27	2.03E+04		0.70000	8	1.14E+01	1.45E-04	
			0	0.00600	6	5.00E+02		0.70000	4	5.71E+00	1.13E-04	
			50	0.00100	31	3.10E+04		0.70000	27	3.86E+01	7.63E-04	
			55	0.00100	33	3.25E+04		0.70000	17	2.43E+01	4.80E-04	
			67	0.00100	56	5.60E+04		0.70000	9	1.29E+01	2.54E-04	
29-May-18	2A	Hydraulic surge	72	0.00100	53	5.30E+04	5.11E+04	0.70000	27	3.86E+01	7.63E-04	3.2
			77	0.00100	58	5.75E+04		0.70000	51	7.29E+01	1.44E-03	
			86	0.00100	50	5.00E+04		0.70000	26	3.71E+01	7.34E-04	
			106	0.00100	74	7.40E+04		0.70000	20	2.86E+01	5.65E-04	
			0	0.00600	0	0.00E+00		0.70000	134	1.91E+02	3.75E-03	
			50	0.00100	31	3.05E+04		0.70000	12	1.71E+01	3.36E-04	
16-Oct-18	3	Stable	55	0.00100	40	3.95E+04	2.26E+04	0.70000	11	1.57E+01	3.08E-04	3.9
			67	0.00100	32	3.20E+04		0.70000	6	8.57E+00	1.68E-04	
			72	0.00100	41	4.10E+04		0.70000	92	1.31E+02	2.57E-03	
			77	0.00100	53	5.30E+04		0.70000	5	7.14E+00	1.40E-04	
			86	0.00100	77	7.65E+04		0.70000	14	2.00E+01	3.92E-04	
			106	0.00100	85	8.50E+04		0.70000	10	1.43E+01	2.80E-04	
16-Oct-18	3	Stable	0	0.00600	2	3.33E+02	2.26E+04	0.70000	0	0.00E+00	0.00E+00	3.9
			15	0.00100	9	9.00E+03		0.80000	2	2.50E+00	1.10E-04	
			30	0.00100	21	2.05E+04		0.80000	5	6.25E+00	2.76E-04	
			45	0.00100	24	2.35E+04		0.70000	2	2.86E+00	1.26E-04	
			75	0.00100	24	2.35E+04		0.70000	0	1.00E+00	4.42E-05	
			105	0.00100	23	2.30E+04		0.80000	1	1.25E+00	5.52E-05	
23-Oct-18	3	End of the run	0	0.00500	5	1.00E+03	2.19E+04	0.70000	0	0.00E+00	0.00E+00	4.3
			15	0.00500	18	3.60E+03		0.80000	2	2.50E+00	1.10E-04	
			30	0.00500	71	1.42E+04		0.80000	5	6.25E+00	2.76E-04	
			45	0.00500	83	1.66E+04		0.70000	2	2.86E+00	1.26E-04	
			75	0.00500	116	2.31E+04		0.70000	0	1.00E+00	4.42E-05	
			105	0.00500	183	3.66E+04		0.80000	1	1.25E+00	5.52E-05	
06-Nov-18	3	Ripening	0	0.00600	0	0.00E+00	1.25E+05	0.80000	0	0.00E+00	0.00E+00	4.8
			5	0.00500	4	8.00E+02		0.80000	0	1.00E+00	4.57E-05	
			87	0.00500	64	1.27E+04		0.80000	0	1.00E+00	4.57E-05	
			83	0.00300	91	3.03E+04		0.80000	0	1.00E+00	4.57E-05	
			64	0.00300	114	3.80E+04		0.80000	0	1.00E+00	4.57E-05	
			67	0.00300	101	3.37E+04		0.80000	0	1.00E+00	4.57E-05	
10-Dec-18	3	End of the run	0	0.00500	0	0.00E+00	2.61E+04	0.80000	0	0.00E+00	0.00E+00	4.1
			5	0.00500	349	6.98E+04		0.80000	4	5.00E+00	4.00E-05	
			10	0.00500	185	3.69E+04		0.80000	0	1.00E+00	8.00E-06	
			20	0.00500	872	1.74E+05		0.80000	0	1.00E+00	8.00E-06	
			30	0.00500	830	1.66E+05		0.80000	3	3.75E+00	3.00E-05	
			0	0.00550	0	0.00E+00		0.80000	0	1.00E+00	0.00E+00	
10-Dec-18	3	End of the run	15	0.00400	4	1.00E+03	2.61E+04	0.80000	0	1.00E+00	3.84E-05	4.1
			30	0.00550	117	2.12E+04		0.80000	0	1.00E+00	3.84E-05	
			45	0.00550	705	1.28E+05		0.80000	0	1.00E+00	3.84E-05	
			75	0.00550	150	2.73E+04		0.80000	-	-	-	
			105	0.00550	125	2.27E+04		0.80000	3	3.75E+00	1.44E-04	

20-Feb-19	3	Stable	0	0.00500	6	1.10E+03	3.80E+04	0.80000	0	0.00E+00	0.00E+00	3.5
			15	0.00500	0	0.00E+00		0.80000	0	1.00E+00	2.63E-05	
			30	0.00500	46	9.10E+03		0.80000	0	1.00E+00	2.63E-05	
			45	0.00500	107	2.14E+04		0.80000	0	1.00E+00	2.63E-05	
			60	0.00500	184	3.67E+04		0.80000	56	7.00E+01	1.84E-03	
			75	0.00500	297	5.93E+04		0.80000	0	1.00E+00	2.63E-05	
			90	0.00500	289	5.78E+04		0.80000	0	1.00E+00	2.63E-05	
			105	0.00500	220	4.39E+04		0.80000	0	1.00E+00	2.63E-05	
20-Feb-19	4A	Stable	0	0.00500	41	8.20E+03	1.98E+04	0.80000	0	0.00E+00	0.00E+00	4.3
			15	0.00500	31	6.10E+03		0.80000	0	1.00E+00	5.04E-05	
			30	0.00500	104	2.07E+04		0.80000	0	1.00E+00	5.04E-05	
			45	0.00500	57	1.13E+04		0.80000	0	1.00E+00	5.04E-05	
			60	0.00500	103	2.05E+04		0.80000	0	1.00E+00	5.04E-05	
			75	0.00500	100	2.00E+04		0.80000	0	1.00E+00	5.04E-05	
			90	0.00500	114	2.28E+04		0.80000	0	1.00E+00	5.04E-05	
			105	0.00500	119	2.37E+04		0.80000	1	1.25E+00	6.30E-05	
08-Mar-19	3	Stable	0	0.00500	177	3.53E+04	5.87E+04	0.80000	0	0.00E+00	0.00E+00	3.9
			15	0.00500	0	0.00E+00		0.80000	0	1.00E+00	1.70E-05	
			30	0.00500	8	1.50E+03		0.80000	0	1.00E+00	1.70E-05	
			45	0.00500	311	6.21E+04		0.80000	12	1.50E+01	2.55E-04	
			60	0.00500	342	6.84E+04		0.80000	2	2.50E+00	4.26E-05	
			75	0.00500	334	6.68E+04		0.80000	18	2.25E+01	3.83E-04	
			90	0.00500	382	7.63E+04		0.80000	5	6.25E+00	1.06E-04	
			105	0.00500	386	7.72E+04		0.80000	0	1.00E+00	1.70E-05	
			0	0.00500	377	7.53E+04	6.36E+04	0.80000	1	1.25E+00	1.97E-05	3.6
			15	0.00500	240	4.80E+04		0.80000	0	1.00E+00	1.57E-05	
			30	0.00500	253	5.06E+04		0.80000	3	3.75E+00	5.90E-05	
			45	0.00500	467	9.34E+04		0.80000	33	4.13E+01	6.49E-04	
			60	0.00500	303	6.06E+04		0.80000	3	3.75E+00	5.90E-05	
			75	0.00500	474	9.48E+04		0.80000	28	3.50E+01	5.51E-04	
			90	0.00500	395	7.89E+04		0.80000	2	2.50E+00	3.93E-05	
			105	0.00500	400	8.00E+04		0.80000	0	1.00E+00	1.57E-05	
08-Mar-19	4A	Stable	0	0.00500	42	8.40E+03	2.47E+04	0.80000	0	0.00E+00	0.00E+00	4.2
			15	0.00500	4	8.00E+02		0.80000	0	1.00E+00	4.04E-05	
			30	0.00500	43	8.50E+03		0.80000	2	2.50E+00	1.01E-04	
			45	0.00500	132	2.64E+04		0.80000	2	2.50E+00	1.01E-04	
			60	0.00500	208	4.15E+04		0.80000	0	1.00E+00	4.04E-05	
			75	0.00500	162	3.24E+04		0.80000	0	1.00E+00	4.04E-05	
			90	0.00500	-	-		0.80000	0	1.00E+00	4.04E-05	
			105	0.00500	75	1.49E+04		0.80000	0	1.00E+00	4.04E-05	
26-Apr-19	3	Ripening	0	0.00500	27	5.40E+03	4.33E+03	0.80000	401	5.01E+02	1.16E-01	2.1
			5	0.00500	90	1.79E+04		0.80000	77	9.63E+01	2.22E-02	
			10	0.00500	39	7.70E+03		0.80000	32	4.00E+01	9.23E-03	
			15	0.00500	5	1.00E+03		0.80000	23	2.88E+01	6.63E-03	
			20	0.00500	30	5.90E+03		0.80000	83	1.04E+02	2.39E-02	
			25	0.00500	26	5.10E+03		0.80000	4	5.00E+00	1.15E-03	
			30	0.00500	3	6.00E+02		0.80000	0	1.00E+00	2.31E-04	
			0	0.00500	7	1.40E+03	6.14E+03	0.80000	52	6.50E+01	1.06E-02	2.6
			5	0.00500	8	1.50E+03		0.80000	2072	2.59E+03	4.22E-01	
			10	0.00500	15	2.90E+03		0.80000	18	2.25E+01	3.66E-03	
			15	0.00500	43	8.60E+03		0.80000	2	2.50E+00	4.07E-04	
			20	0.00500	49	9.80E+03		0.80000	2	2.50E+00	4.07E-04	
			25	0.00500	24	4.80E+03		0.80000	18	2.25E+01	3.66E-03	
			30	0.00500	23	4.60E+03		0.80000	15	1.88E+01	3.05E-03	

26-Mar-19	4A	Stable	0	0.00500	665	1.33E+05	1.05E+04	0.80000	0	0.00E+00	0.00E+00	3.2
			5	0.00500	359	7.17E+04		0.80000	0	1.00E+00	9.54E-05	
			10	0.00500	39	7.70E+03		0.80000	-	-	-	
			15	0.00500	109	2.17E+04		0.80000	1	1.25E+00	1.19E-04	
			20	0.00500	37	7.40E+03		0.80000	1	1.25E+00	1.19E-04	
			25	0.00500	41	8.10E+03		0.80000	3	3.75E+00	3.58E-04	
30-May-19	3	End of run	30	0.00500	38	7.50E+03	1.15E+05	0.80000	14	1.75E+01	1.67E-03	3.6
			0	0.00500	481	9.62E+04		0.80000	1	1.25E+00	1.09E-05	
			15	0.00500	452	9.03E+04		0.80000	2	2.50E+00	2.17E-05	
			30	0.00500	525	1.05E+05		0.80000	76	9.50E+01	8.25E-04	
			45	0.00500	689	1.38E+05		0.80000	2	2.50E+00	2.17E-05	
			60	0.00500	435	8.69E+04		0.80000	22	2.75E+01	2.39E-04	
			75	0.00500	446	8.92E+04	7.59E+04	0.80000	11	1.38E+01	1.19E-04	4.0
			90	0.00500	649	1.30E+05		0.80000	5	6.25E+00	5.43E-05	
			105	0.00500	712	1.42E+05		0.80000	9	1.13E+01	9.77E-05	
			0	0.00500	220	4.40E+04		0.80000	0	0.00E+00	0.00E+00	
			15	0.00500	120	2.40E+04		0.80000	0	1.00E+00	1.32E-05	
			30	0.00500	256	5.12E+04		0.80000	1	1.25E+00	1.65E-05	
			45	0.00500	313	6.26E+04		0.80000	7	8.75E+00	1.15E-04	
			60	0.00500	462	9.24E+04		0.80000	1	1.25E+00	1.65E-05	
			75	0.00500	472	9.43E+04	1.66E+05	0.80000	10	1.25E+01	1.65E-04	4.7
			90	0.00500	465	9.29E+04		0.80000	5	6.25E+00	8.23E-05	
			105	0.00500	310	6.20E+04		0.80000	9	1.13E+01	1.48E-04	
			0	0.00500	600	1.20E+05		0.80000	-	-	-	
			15	0.00500	393	7.86E+04		0.80000	2	2.50E+00	1.50E-05	
			30	0.00500	514	1.03E+05		0.80000	1	1.25E+00	7.52E-06	
02-Aug-19	3	Stable	45	0.00500	538	1.08E+05	3.27E+03	0.80000	6	7.50E+00	4.51E-05	0.5
			60	0.00500	856	1.71E+05		0.80000	2	2.50E+00	1.50E-05	
			75	0.00500	1452	2.90E+05		0.80000	0	1.00E+00	6.02E-06	
			90	0.00500	650	1.30E+05		0.80000	-	-	-	
			105	0.00500	979	1.96E+05		0.80000	5	6.25E+00	3.76E-05	
			0	0.00500	19	3.80E+03	1.40E+04	0.80000	13	1.63E+01	4.97E-03	1.4
			15	0.00500	7	1.30E+03		0.80000	2	2.50E+00	7.65E-04	
			30	0.00500	7	1.30E+03		0.80000	-	-	-	
			45	0.00500	5	9.00E+02		0.80000	460	5.75E+02	1.76E-01	
			60	0.00500	7	1.30E+03		0.80000	650	8.13E+02	2.49E-01	
			75	0.00500	34	6.70E+03		0.80000	1127	1.41E+03	4.31E-01	
13-Oct-21	3	Stable	90	0.00500	26	5.10E+03	1.85E+04	0.80000	536	6.70E+02	2.05E-01	1.10
			105	0.00500	22	4.30E+03		0.80000	1470	1.84E+03	5.63E-01	
			0	0.00500	3	6.00E+02		0.80000	2	2.50E+00	1.78E-04	
			15	0.00500	84	1.68E+04		0.80000	14	1.75E+01	1.25E-03	
			30	0.00500	39	7.80E+03		0.80000	-	-	-	
			45	0.00500	131	2.62E+04		0.80000	131	1.64E+02	1.17E-02	0.90
			60	0.00500	72	1.44E+04	1.16E+04	0.80000	1846	2.31E+03	1.64E-01	
			75	0.00500	30	5.90E+03		0.80000	26	3.25E+01	2.32E-03	
			90	0.00500	63	1.26E+04		0.80000	68	8.50E+01	6.06E-03	
			105	0.00500	87	1.73E+04		0.80000	3	3.75E+00	2.67E-04	
			0	0.00500	0	0.00E+00		0.80000	0	0.00E+00	0.00E+00	
			30	0.00500	36	7.20E+03	1.85E+04	0.80000	31	3.88E+01	2.10E-03	1.10
			45	0.00500	89	1.78E+04		0.80000	997	1.25E+03	6.74E-02	
			60	0.00500	72	1.44E+04		0.80000	2156	2.70E+03	1.46E-01	
			75	0.00500	166	3.32E+04		0.80000	2200	2.75E+03	1.49E-01	
			90	0.00500	99	1.98E+04		0.80000	515	6.44E+02	3.48E-02	
13-Oct-21	3	Stable	0	0.00500	0	0.00E+00	1.16E+04	0.50000	2	4.00E+00	3.46E-04	0.90
			30	0.00500	56	1.12E+04		0.50000	114	2.28E+02	1.97E-02	
			45	0.00500	52	1.04E+04		0.50000	748	1.50E+03	1.29E-01	
			60	0.00500	72	1.44E+04		0.30000	665	2.22E+03	1.92E-01	
			75	0.00500	55	1.10E+04		0.30000	652	2.17E+03	1.88E-01	
			90	0.00500	54	1.08E+04		0.30000	326	1.09E+03	9.40E-02	

13-Oct-21	2A	Stable	0	0.00500	0	0.00E+00	1.23E+04	0.50000	0	0.00E+00	0.00E+00	0.8
			30	0.00500	29	5.80E+03		0.50000	288	5.76E+02	4.69E-02	
			45	0.00500	65	1.30E+04		0.50000	553	1.11E+03	9.01E-02	
			60	0.00500	70	1.40E+04		0.30000	911	3.04E+03	2.47E-01	
			75	0.00500	64	1.28E+04		0.30000	684	2.28E+03	1.86E-01	
13-Oct-21	4A	Stable	90	0.00500	79	1.58E+04	8.20E+03	0.30000	775	2.58E+03	2.10E-01	0.5
			0	0.00500	0	0.00E+00		0.80000	0	0.00E+00	1.52E-04	
			30	0.00500	24	4.80E+03		0.80000	762	9.53E+02	1.16E-01	
			45	0.00500	73	1.46E+04		0.70000	2294	3.28E+03	4.00E-01	
			60	0.00500	21	4.20E+03		0.80000	1408	1.76E+03	2.15E-01	
10-Nov-21	3	Stable	75	0.00500	35	7.00E+03	6.22E+03	0.80000	2155	2.69E+03	3.29E-01	3.6
			90	0.00500	52	1.04E+04		0.80000	3056	3.82E+03	4.66E-01	
			0	0.01000	0	0.00E+00		0.80000	0	1.25E+00	0.00E+00	
			30	0.01000	38	3.80E+03		0.80000	1	1.25E+00	2.01E-04	
			45	0.01000	5	5.00E+02		0.80000	2	2.50E+00	4.02E-04	
10-Nov-21	4A	Stable	60	0.01000	78	7.80E+03	2.00E+03	0.80000	0	1.25E+00	2.01E-04	2.7
			75	0.01000	101	1.01E+04		0.80000	1	1.25E+00	2.01E-04	
			90	0.01000	89	8.90E+03		0.80000	0	1.25E+00	2.01E-04	
			0	0.01000	0	0.00E+00		0.80000	0	0.00E+00	6.25E-04	
			30	0.01000	12	1.20E+03		0.80000	5	6.25E+00	3.13E-03	
19-Nov-21	3	Stable	45	0.01000	15	1.50E+03	8.44E+03	0.80000	7	8.75E+00	4.38E-03	3.1
			60	0.01000	19	1.90E+03		0.80000	0	1.25E+00	6.25E-04	
			75	0.01000	23	2.30E+03		0.80000	1	1.25E+00	6.25E-04	
			90	0.01000	31	3.10E+03		0.80000	1	1.25E+00	6.25E-04	
			0	0.00500	0	0.00E+00		0.80000	0	0.00E+00	0.00E+00	
19-Nov-21	3	Stable	30	0.00500	19	3.80E+03	8.00E+03	0.80000	0	0.00E+00	1.48E-04	3.5
			45	0.00500	43	8.60E+03		0.80000	0	0.00E+00	1.48E-04	
			60	0.00500	49	9.80E+03		0.80000	19	2.38E+01	2.81E-03	
			75	0.00500	58	1.16E+04		0.80000	1	1.25E+00	1.48E-04	
			90	0.00500	42	8.40E+03		0.80000	4	5.00E+00	5.92E-04	
19-Nov-21	3	Stable	0	0.00500	0	0.00E+00	8.00E+03	0.80000	0	0.00E+00	0.00E+00	3.5
			30	0.00500	40	8.00E+03		0.80000	6	7.50E+00	9.38E-04	
			45	0.00500	21	4.20E+03		0.80000	2	2.50E+00	3.13E-04	
			60	0.00500	47	9.40E+03		0.80000	1	1.25E+00	1.56E-04	
			75	0.00500	37	7.40E+03		0.80000	1	1.25E+00	1.56E-04	
19-Nov-21	2A	Stable	90	0.00500	55	1.10E+04	7.36E+03	0.80000	1	1.25E+00	1.56E-04	3.1
			0	0.00500	0	0.00E+00		0.80000	0	0.00E+00	0.00E+00	
			30	0.00500	22	4.40E+03		0.80000	1	1.25E+00	1.70E-04	
			45	0.00500	33	6.60E+03		0.80000	2	2.50E+00	3.40E-04	
			60	0.00500	32	6.40E+03		0.80000	5	6.25E+00	8.49E-04	
19-Nov-21	4A	Stable	75	0.00500	30	6.00E+03	1.26E+04	0.80000	7	8.75E+00	1.19E-03	1.0
			90	0.00500	67	1.34E+04		0.80000	8	1.00E+01	1.36E-03	
			0	0.00500	0	0.00E+00		0.80000	0	0.00E+00	9.95E-05	
			30	0.00500	42	8.40E+03		0.80000	546	6.83E+02	5.43E-02	
			45	0.00500	71	1.42E+04		0.80000	1106	1.38E+03	1.10E-01	
19-Nov-21	4C	Stable	60	0.00500	62	1.24E+04	1.85E+04	0.80000	260	3.25E+02	2.59E-02	0.9
			75	0.00500	50	1.00E+04		0.80000	1475	1.84E+03	1.47E-01	
			90	0.00500	89	1.78E+04		0.80000	1421	1.78E+03	1.41E-01	
			0	0.00500	0	0.00E+00		0.80000	1	1.25E+00	6.76E-05	
			30	0.00500	72	1.44E+04		0.80000	1313	1.64E+03	8.88E-02	
19-Nov-21	4C	Stable	45	0.00500	69	1.38E+04	1.75E+04	0.80000	1954	2.44E+03	1.32E-01	0.9
			60	0.00500	111	2.22E+04		0.80000	1916	2.40E+03	1.30E-01	
			75	0.00500	81	1.62E+04		0.80000	2847	3.56E+03	1.93E-01	
			90	0.00500	129	2.58E+04		0.80000	1938	2.42E+03	1.31E-01	
			0	0.00500	0	0.00E+00		0.80000	1	1.25E+00	7.15E-05	
19-Nov-21	4C	Stable	30	0.00500	88	1.76E+04	1.75E+04	0.80000	1220	1.53E+03	8.72E-02	0.9
			45	0.00500	33	6.60E+03		0.80000	1540	1.93E+03	1.10E-01	
			60	0.00500	97	1.94E+04		0.80000	2218	2.77E+03	1.59E-01	
			75	0.00500	108	2.16E+04		0.80000	2546	3.18E+03	1.82E-01	
			90	0.00500	111	2.22E+04		0.80000	2108	2.64E+03	1.51E-01	

19-Nov-21	4C	Stable	0 30 45 60 75 90	0.00500 0.00500 0.00500 0.00500 0.00500	0 68 137 47 7 89	0.00E+00 1.36E+04 2.74E+04 9.40E+03 1.40E+03 1.78E+04	1.39E+04	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	1 1220 1540 2218 2546 2108	1.25E+00 1.53E+03 1.93E+03 2.77E+03 3.18E+03 2.64E+03	8.98E-05 1.10E-01 1.38E-01 1.99E-01 2.29E-01 1.89E-01	0.8
14-Dec-21	3	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 65 96 110 140 152	0.00E+00 6.50E+03 9.60E+03 1.10E+04 1.40E+04 1.52E+04	1.13E+04	0.60000 0.80000 0.80000 0.80000 0.80000 0.80000	0 0 0 0 2 0	0.00E+00 0.00E+00 0.00E+00 0.00E+00 2.50E+00 0.00E+00	0.00E+00 1.11E-04 1.11E-04 1.11E-04 2.22E-04 1.11E-04	3.9
14-Dec-21	3	Stable	0 30 45 60 75 90	0.02000 0.02000 0.02000 0.02000 0.02000 0.02000	0 102 332 296 233 160	0.00E+00 5.10E+03 1.66E+04 1.48E+04 1.17E+04 8.00E+03	1.12E+04	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 0 0 0 0 0	0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00 0.00E+00	0.00E+00 1.11E-04 1.11E-04 1.11E-04 1.11E-04 1.11E-04	4.0
14-Dec-21	2A	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 35 42 76 89 35	0.00E+00 3.50E+03 4.20E+03 7.60E+03 8.90E+03 3.50E+03	5.54E+03	0.60000 0.80000 0.80000 0.80000 0.80000 0.80000	0 0 15 0 0 4	0.00E+00 0.00E+00 1.88E+01 0.00E+00 0.00E+00 5.00E+00	0.00E+00 2.26E-04 3.38E-03 2.26E-04 2.26E-04 9.03E-04	3.0
14-Dec-21	4A	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 93 112 100 167 113	0.00E+00 9.30E+03 1.12E+04 1.00E+04 1.67E+04 1.13E+04	1.17E+04	0.40000 0.40000 0.40000 0.40000 0.40000 0.40000	0 0 0 0 1 2	0.00E+00 2.50E+00 2.50E+00 2.50E+00 2.50E+00 5.00E+00	2.14E-04 2.14E-04 2.14E-04 2.14E-04 2.14E-04 4.27E-04	3.6
14-Dec-21	4C	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 114 96 109 109 92	0.00E+00 5.70E+03 4.80E+03 5.45E+03 5.45E+03 4.60E+03	5.20E+03	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 0 2 5 13 6	0.00E+00 1.25E+00 2.50E+00 6.25E+00 1.63E+01 7.50E+00	2.40E-04 2.40E-04 4.81E-04 1.20E-03 3.13E-03 1.44E-03	2.9
15-Dec-21	3	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 22 46 69 40 85	0.00E+00 2.20E+03 4.60E+03 6.90E+03 4.00E+03 8.50E+03	5.24E+03	0.60000 0.80000 0.80000 0.80000 0.80000 0.80000	0 4 427 501 542 145	0.00E+00 5.00E+00 5.34E+02 6.26E+02 6.78E+02 1.81E+02	0.00E+00 9.54E-04 1.02E-01 1.20E-01 1.29E-01 3.46E-02	1.1
15-Dec-21	3	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 67 28 28 94 92	0.00E+00 6.70E+03 2.80E+03 2.80E+03 9.40E+03 9.20E+03	6.18E+03	0.60000 0.80000 0.80000 0.80000 0.80000 0.80000	0 2 4 1 366 506	0.00E+00 2.50E+00 5.00E+00 1.25E+00 4.58E+02 6.33E+02	0.00E+00 4.05E-04 8.09E-04 2.02E-04 7.40E-02 1.02E-01	1.4
15-Dec-21	2A	Stable	0 30 45 60 75 90	0.02000 0.02000 0.02000 0.02000 0.02000 0.02000	0 58 78 36 61 79	0.00E+00 2.90E+03 3.90E+03 1.80E+03 3.05E+03 3.95E+03	3.12E+03	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 1 284 329 364 93	0.00E+00 1.25E+00 3.55E+02 4.11E+02 4.55E+02 1.16E+02	0.00E+00 4.01E-04 1.14E-01 1.32E-01 1.46E-01 3.73E-02	1.1
15-Dec-21	4A	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	15 53 33 131 179 119	1.50E+03 5.30E+03 3.30E+03 1.31E+04 1.79E+04 1.19E+04	1.03E+04	0.40000 0.50000 0.40000 0.40000 0.40000 0.40000	0 152 185 52 193 136	0.00E+00 3.04E+02 4.63E+02 1.30E+02 4.83E+02 3.40E+02	2.43E-04 2.95E-02 4.49E-02 1.26E-02 4.68E-02 3.30E-02	1.5

15-Dec-21	4C	Stable	0	0.01000	15	1.50E+03	4.46E+03	0.40000	0	0.00E+00	5.61E-04	1.3
			30	0.01000	15	1.50E+03		0.50000	12	2.40E+01	5.38E-03	
			45	0.01000	7	7.00E+02		0.50000	184	3.68E+02	8.25E-02	
			60	0.01000	70	7.00E+03		0.40000	56	1.40E+02	3.14E-02	
			75	0.01000	33	3.30E+03		0.50000	152	3.04E+02	6.82E-02	
			90	0.01000	98	9.80E+03		0.40000	149	3.73E+02	8.35E-02	
16-Dec-21	3	Stable	0	0.01000	0	0.00E+00	7.82E+03	0.80000	0	0.00E+00	0.00E+00	2.6
			30	0.01000	38	3.80E+03		0.80000	25	3.13E+01	4.00E-03	
			45	0.01000	62	6.20E+03		0.80000	37	4.63E+01	5.91E-03	
			60	0.01000	49	4.90E+03		0.80000	15	1.88E+01	2.40E-03	
			75	0.01000	33	3.30E+03		0.80000	2	2.50E+00	3.20E-04	
			90	0.01000	209	2.09E+04		0.80000	5	6.25E+00	7.99E-04	
16-Dec-21	3	Stable	0	0.02000	0	0.00E+00	4.13E+03	0.80000	0	0.00E+00	0.00E+00	2.2
			30	0.02000	48	2.40E+03		0.80000	4	5.00E+00	1.21E-03	
			45	0.02000	96	4.80E+03		0.80000	28	3.50E+01	8.47E-03	
			60	0.02000	2	1.00E+02		0.80000	3	3.75E+00	9.08E-04	
			75	0.02000	78	3.90E+03		0.80000	59	7.38E+01	1.79E-02	
			90	0.02000	189	9.45E+03		0.80000	3	3.75E+00	9.08E-04	
16-Dec-21	2A	Stable	0	0.02000	0	0.00E+00	3.74E+03	0.80000	0	0.00E+00	0.00E+00	2.4
			30	0.02000	79	3.95E+03		0.80000	7	8.75E+00	2.34E-03	
			45	0.02000	61	3.05E+03		0.80000	2	2.50E+00	6.68E-04	
			60	0.02000	97	4.85E+03		0.80000	14	1.75E+01	4.68E-03	
			75	0.02000	69	3.45E+03		0.80000	38	4.75E+01	1.27E-02	
			90	0.02000	68	3.40E+03		0.80000	0	0.00E+00	3.34E-04	
16-Dec-21	4A	Stable	0	0.01000	6	6.00E+02	1.04E+04	0.40000	0	0.00E+00	2.40E-04	1.7
			30	0.01000	92	9.20E+03		0.40000	40	1.00E+02	9.62E-03	
			45	0.01000	56	5.60E+03		0.40000	10	2.50E+01	2.40E-03	
			60	0.01000	151	1.51E+04		0.40000	149	3.73E+02	3.58E-02	
			75	0.01000	179	1.79E+04		0.40000	94	2.35E+02	2.26E-02	
			90	0.01000	42	4.20E+03		0.40000	127	3.18E+02	3.05E-02	
16-Dec-21	4C	Stable	0	0.01000	6	6.00E+02	1.05E+04	0.40000	0	0.00E+00	2.38E-04	2.3
			30	0.01000	54	5.40E+03		0.40000	27	6.75E+01	6.42E-03	
			45	0.01000	112	1.12E+04		0.40000	0	0.00E+00	2.38E-04	
			60	0.01000	113	1.13E+04		0.40000	34	8.50E+01	8.08E-03	
			75	0.01000	118	1.18E+04		0.40000	32	8.00E+01	7.60E-03	
			90	0.01000	129	1.29E+04		0.40000	2	5.00E+00	4.75E-04	
16-Dec-21	3	Stable	0	0.01000	0	0.00E+00	9.64E+03	0.80000	0	0.00E+00	0.00E+00	3.4
			30	0.01000	70	7.00E+03		0.80000	5	6.25E+00	6.48E-04	
			45	0.01000	83	8.30E+03		0.80000	6	7.50E+00	7.78E-04	
			60	0.01000	132	1.32E+04		0.80000	3	3.75E+00	3.89E-04	
			75	0.01000	118	1.18E+04		0.80000	1	1.25E+00	1.30E-04	
			90	0.01000	79	7.90E+03		0.80000	0	0.00E+00	1.30E-04	
16-Dec-21	3	Stable	0	0.02000	0	0.00E+00	1.63E+03	0.80000	0	0.00E+00	0.00E+00	2.6
			30	0.02000	67	3.35E+03		0.80000	2	2.50E+00	1.53E-03	
			45	0.02000	12	6.00E+02		0.80000	0	0.00E+00	7.67E-04	
			60	0.02000	64	3.20E+03		0.80000	4	5.00E+00	3.07E-03	
			75	0.02000	3	1.50E+02		0.80000	3	3.75E+00	2.30E-03	
			90	0.02000	17	8.50E+02		0.80000	6	7.50E+00	4.60E-03	
16-Dec-21	2A	Stable	0	0.01000	0	0.00E+00	5.44E+03	0.80000	0	0.00E+00	0.00E+00	3.4
			30	0.01000	19	1.90E+03		0.80000	0	0.00E+00	2.30E-04	
			45	0.01000	128	1.28E+04		0.80000	4	5.00E+00	9.19E-04	
			60	0.01000	83	8.30E+03		0.80000	0	0.00E+00	2.30E-04	
			75	0.01000	26	2.60E+03		0.80000	0	0.00E+00	2.30E-04	
			90	0.01000	16	1.60E+03		0.80000	1	1.25E+00	2.30E-04	
16-Dec-21	4A	Stable	0	0.01000	14	1.40E+03	4.98E+03	0.40000	0	0.00E+00	5.02E-04	2.4
			30	0.01000	29	2.90E+03		0.40000	6	1.50E+01	3.01E-03	
			45	0.01000	95	9.50E+03		0.40000	7	1.75E+01	3.51E-03	
			60	0.01000	55	5.50E+03		0.40000	1	2.50E+00	5.02E-04	
			75	0.01000	23	2.30E+03		0.40000	18	4.50E+01	9.04E-03	
			90	0.01000	47	4.70E+03		0.40000	6	1.50E+01	3.01E-03	

16-Dec-21	4C	Stable	0	0.01000	14	1.40E+03	7.54E+03	0.40000	0	0.00E+00	3.32E-04	2.8
			30	0.01000	66	6.60E+03		0.40000	2	5.00E+00	6.63E-04	
			45	0.01000	56	5.60E+03		0.40000	7	1.75E+01	2.32E-03	
			60	0.01000	24	2.40E+03		0.40000	4	1.00E+01	1.33E-03	
			75	0.01000	122	1.22E+04		0.40000	6	1.50E+01	1.99E-03	
			90	0.01000	109	1.09E+04		0.40000	3	7.50E+00	9.95E-04	
04-Mar-22	3	Hydraulic surge	0	0.02000	2	1.00E+00	4.62E+03	0.80000	0	0.00E+00	0.00E+00	2.7
			30	0.02000	111	5.55E+03		0.80000	12	1.50E+01	3.25E-03	
			45	0.02000	156	7.80E+03		0.80000	3	3.75E+00	8.12E-04	
			60	0.02000	93	4.65E+03		0.80000	11	1.38E+01	2.98E-03	
			75	0.02000	59	2.95E+03		0.80000	0	0.00E+00	2.71E-04	
			90	0.02000	43	2.15E+03		0.80000	10	1.25E+01	2.71E-03	
04-Mar-22	3	Hydraulic surge	0	0.02000	2	1.00E+02	5.54E+03	0.80000	0	0.00E+00	0.00E+00	3.3
			30	0.02000	28	1.40E+03		0.80000	6	7.50E+00	1.35E-03	
			45	0.02000	107	5.35E+03		0.80000	2	2.50E+00	4.51E-04	
			60	0.02000	123	6.15E+03		0.80000	0	0.00E+00	2.26E-04	
			75	0.02000	152	7.60E+03		0.80000	2	2.50E+00	4.51E-04	
			90	0.02000	144	7.20E+03		0.80000	0	0.00E+00	2.26E-04	
12-Apr-22	3	Stable	0	0.10000	0	0.00E+00	1.06E+04	0.80000	0	0.00E+00	0.00E+00	3.5
			30	0.10000	717	7.17E+03		0.80000	4	5.00E+00	4.70E-04	
			45	0.10000	1107	1.11E+04		0.80000	0	0.00E+00	1.18E-04	
			60	0.10000	1210	1.21E+04		0.80000	3	3.75E+00	3.53E-04	
			75	0.10000	649	6.49E+03		0.80000	1	1.25E+00	1.18E-04	
			90	0.10000	1633	1.63E+04		0.80000	5	6.25E+00	5.88E-04	
12-Apr-22	3	Stable	0	0.10000	0	0.00E+00	4.38E+03	0.80000	0	0.00E+00	0.00E+00	3.1
			30	0.10000	130	1.30E+03		0.80000	3	3.75E+00	8.55E-04	
			45	0.10000	142	1.42E+03		0.80000	0	0.00E+00	2.85E-04	
			60	0.10000	328	3.28E+03		0.80000	5	6.25E+00	1.43E-03	
			75	0.10000	1354	1.35E+04		0.80000	1	1.25E+00	2.85E-04	
			90	0.10000	238	2.38E+03		0.80000	3	3.75E+00	8.55E-04	
12-Apr-22	2A	Stable	0	0.10000	0	0.00E+00	5.83E+03	0.80000	0	0.00E+00	0.00E+00	3.2
			30	0.10000	253	2.53E+03		0.80000	1	1.25E+00	2.14E-04	
			45	0.10000	199	1.99E+03		0.80000	1	1.25E+00	2.14E-04	
			60	0.10000	526	5.26E+03		0.80000	5	6.25E+00	1.07E-03	
			75	0.10000	1083	1.08E+04		0.80000	7	8.75E+00	1.50E-03	
			90	0.10000	856	8.56E+03		0.80000	2	2.50E+00	4.29E-04	

Appendix F

Raw data for Chapter 3

Table F.1. Raw water quality, pilot plant operational data, seed suspension data, and average *Cryptosporidium* oocyst removal for Chapter 3.

Date	Raw Water Quality				Pilot Plant Coagulation		Oocyst Seed Suspension Coagulation			Pilot Plant CAF		
	Temperature (°C)	Turbidity (NTU)	pH	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Coagulant Type	Dose (mg/L)	Final Zeta Potential (mV)	Filter Configuration	Filter Operational Condition	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
06-Sep-06	20.0	0.7	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	2B 4B	1.1 1.2
11-Sep-06	21.0	0.5	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	2B 4B	0.6 0.3
12-Sep-06	20.0	0.4	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	2B 4B	0.2 0.2
25-Sep-06	9.0	0.2	-	-	No Coagulant	0.0	No Coagulant	0.0	-	Stable	2B 4B	0.1 0.5
29-Jan-07	2.0	0.2	-	-	PACl	0.8	PACl	0.8	-	Stable	2B 4B	4.6 5.1
02-Apr-07	5.5	0.2	-	-	PACl	0.6	PACl	0.6	-	Stable	2B 4B	2.1 2.1
06-Apr-07	6.5	0.2	-	-	PACl	1.6	PACl	1.6	-	Stable	2B 4B	1.6 1.5
11-Apr-07	6.5	0.2	-	-	PACl	2.6	PACl	2.6	-	Stable	2B 4B	1.0 1.5
16-Apr-07	7.0	0.3	-	-	PACl	3.6	PACl	3.6	-	Stable	2B 4B	1.3 1.8
20-Apr-07	6.0	0.1	-	-	PACl	0.3	PACl	0.3	-8.8	Stable	2B 4B	0.9 1.3
20-Apr-07	6.0	0.1	-	-	PACl	0.3	PACl	0.3	-	Stable	2B 4B	1.1 1.2
24-Apr-07	7.0	0.2	-	-	PACl	0.3	PACl	1.3	-8.0	Stable	2B 4B	1.0 0.9
12-Sep-07	22.0	0.3	-	-	alum	5.0	alum	5.0	-	Stable	2B 4B	0.3 0.3
13-Sep-07	22.0	0.3	-	-	alum	3.7	alum	3.7	-	Stable	2B 4B	2.2 1.9
11-Dec-07	4.0	0.2	-	-	No Coagulant	0.0	No Coagulant	4.0	-	Stable	2B 4B	0.4 0.0
18-Sep-08	22.0	0.3	-	-	alum	5.0	alum	5.0	-	Stable	2B 4B	1.6 2.1

19-Sep-08	22.0	0.4	-	-	alum	5.0	alum	5.0	-	Stable	2B 4B	1.6 1.7
29-Sep-08	22.0	1.0	-	-	alum	5.0	alum	5.0	-	Stable	2B 4B	0.9 1.3
08-Jun-17	11.2	-	-	-	alum	-	alum	22.5	-9.5	Stable	1 2A	3.5 3.8
09-Jun-17	10.6	-	-	-	alum	-	alum	40	-5.2	Stable	1 2A	4.1 3.3
02-Aug-17	14.4	-	-	-	alum	-	alum	5	-15.6	Stable	1 2A	1.2 1.2
03-Aug-17	12.4	-	-	-	alum	-	alum	40	-7.1	Stable	1 2A	3.6 3.8
05-Oct-17	16.0	0.5	7.2	-	alum	5.5	alum	40.0	-	Stable	1 2A	3.8 4.0
23-Oct-17	9.7	0.2	7.0	-	alum	4.5	alum	40.0	-	Stable	1 2A	4.3 4.7
13-Nov-17	13.1	0.2	6.8	-	alum	4.8	alum	40.0	-	Hydraulic surge	1 2A	4.2 4.7
28-Nov-17	12.5	0.2	6.9	-	alum	6.0	alum	40.0	-	Hydraulic surge	1 2A	3.4 2.6
22-Jan-18	4.3	0.2	6.8	-	alum	4.3	alum	40.0	-	Hydraulic surge	1 2A	4.7 4.7
06-Feb-18	4.3	0.2	4.9	-	alum	4.5	alum	40.0	-	Hydraulic surge	1 2A	4.2 4.6
21-Feb-18	5.3	0.2	6.9	-	alum	4.0	alum	40.0	-	Hydraulic surge	1 2A	4.4 4.8
06-Mar-18	4.5	0.1	6.9	-	alum	4.5	alum	40.0	0.1	Stable	1 2A	4.8 4.7
19-Mar-18	4.6	0.2	6.9	-	alum	4.5	alum	40.0	2.0	Stable	1 2A	4.4 4.1
10-Apr-18	4.9	0.2	7.0	-	alum	4.3	alum	5.0	-10.0	Stable	1 2A	2.3 1.9
23-Apr-18	5.0	0.5	7.1	-	alum	5.0	alum	0.0	-7.4	Stable	1 2A	1.3 0.8
29-May-18	8.9	0.1	8.35	-	alum	5.0	alum	40.0	-2.3	End of the run	1 2A	3.1 3.3
									1.3	Rippening	1 2A	3.0 3.4
19-Jun-18	8.8	0.2	7.2	-	alum	4.5	alum	40.0	0.5	Hydraulic surge	1 2A	3.1 3.2
16-Oct-18	8.0	0.1	6.95	-	alum	5.0	alum	40.0	2.63	Stable	3	3.9
23-Oct-18	7.9	0.3	6.99	-	alum	4.5	alum	40.0	1.67	End of the run	3	4.3
06-Nov-18	11.4	0.3	7.12	-	alum	4.5	alum	40.0	1.71	Rippening	3	4.8
10-Dec-18	6.6	0.1	7.03	-	alum	4.0	alum	40.0	0.89	End of the run	3	4.1
20-Feb-19	3.9	0.3	7	-	alum	4.5	alum	40.0		Stable	3	3.5
	2.2	1.0	8.36	-	PACI	0.9	PACI	12.5	-8.88	Stable	4A	4.3

08-Mar-19	3.7	0.2	7	-	alum	4.0	alum	40.0	1.84	Stable	3 3	3.9 3.6
	2.1	1.0	8.33	-	PACI	0.9	PACI	12.5	-7.8	Stable	4A	4.2
26-Apr-19	6.3	0.4	7.06	-	alum	4.5	alum	40.0	0.6	Rippening	3 3	2.1 2.6
	6.0	0.2	8.44	-	PACI	0.9	PACI	12.5	-1.07	Rippening	4A	3.2
30-May-19	10.5	0.8	7.18	-	alum	4.0	alum	40.0	-3.4	End of the run	3 3	3.6 4.0
	7.7	0.3	8.5	-	PACI	0.9	PACI	12.5	-7.8		4A	4.7
02-Aug-19	10.2	0.5	8.68	-	alum	4.0	alum	0.0	-15.27	Stable	3 3	0.5 1.4
13-Oct-21	18.0	0.5	8.0	-9.7	alum	5.0	alum	5.0	-6.3	Stable	3 3 2A	1.1 0.9 0.8
					PACI	1.0	PACI	1.0	-7.3		4A	0.5
10-Nov-21	6.7	0.2	8.0	-7.7	alum	4.0	alum	6.0	-9.7	Stable	3 3 4A	3.6 2.7
					PACI	0.9	PACI	1.4	-12.2		4A	2.7
19-Nov-21	4.9	0.2	8.0	-6.0	alum	4.0	alum	10.0	-10.0	Stable	3 3 2A	3.1 3.5 3.1
					PACI	0.9	PACI	1.2	-13.3		4A 4C 4C 4C	1.0 0.9 0.8 0.9
14-Dec-21	4.8	0.4	8.0	-12.9	alum	4.0	alum	6.0	-8.3	Stable	3 3 2A	3.9 4.0 3.0
					PACI	0.9	PACI	2.4	-4.5		4A 4C	3.6 2.9
15-Dec-21	4.9	0.4	8.0	-11.1	alum	4.0	alum	6.0	-13.9	Stable	3 3 2A	1.1 1.4 1.1
					PACI	0.9	PACI	2.0	-11.1		4A 4C	1.5 1.3
16-Dec-21	4.7	1.8	8.0	-18.4	alum	4.0	alum	10.0	-12.7	Stable	3 3 2A	2.6 2.2 2.4
					PACI	0.9	PACI	2.4	-15.0		4A 4C	1.7 2.3
16-Dec-21	4.7	1.8	8.0	-18.4	alum	4.0	alum	10.0	-11.8	Stable	3 3 2A	3.4 2.6 3.4
					PACI	0.9	PACI	2.4	-16.5		4A 4C	2.4 2.8
04-Mar-22	2.0	0.4	7.9	-16.6	alum	5.0	alum	13.5	-0.8	Hydraulic surge	3 3	2.7 3.3
12-Apr-22	4.5	0.2	8.0	-6.2	alum	5.0	alum	25.5	-1.5	Stable	3 3 2A	3.5 3.1 3.2

Table F.2. Detailed *Cryptosporidium* oocyst removal data for Chapter 3. For any counts with a zero (ND) (except for T0) a count of one was assigned as a conservative adjustment. This change for NDs is reflected in the “Filter Effluent *Cryptosporidium* (oocysts/L)” column.

Date	Pilot Plant CAF											
	Filter Configuration	Filter Operational Condition	Sample Time (min)	Filter Influent Sample Volume (L)	Filter Influent <i>Cryptosporidium</i> (# oocysts)	Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Average Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Filter Effluent Sample Volume (L)	Filter Effluent <i>Cryptosporidium</i> (# oocysts)	Filter Effluent <i>Cryptosporidium</i> (oocysts/L)	<i>Cryptosporidium</i> Removal (%)	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
06-Sep-06	2B	Stable	20	0.005	124	2.48E+04	2.84E+04	0.05	21	4.20E+02	2.00E+01	1.2
			30	0.005	69	1.38E+04		0.05	43	8.60E+02	4.10E+01	
			40	0.01	214	2.14E+04		0.05	268	5.36E+03	2.55E+02	
			50	0.01	535	5.35E+04		0.05	101	2.02E+03	9.62E+01	
06-Sep-06	4B	Stable	20	0.005	192	3.84E+04	3.33E+04	0.05	59	1.18E+03	2.00E+01	1.2
			30	0.005	136	2.72E+04		0.05	21	4.20E+02	7.12E+00	
			40	0.01	356	3.56E+04		0.05	193	3.86E+03	6.54E+01	
			50	0.01	320	3.20E+04		0.05	182	3.64E+03	6.17E+01	
11-Sep-06	2B	Stable	20	0.02	1505	7.53E+04	3.49E+04	0.01	127	1.27E+04	1.00E+02	0.6
			30	0.002	43	2.15E+04		0.01	79	7.90E+03	6.22E+01	
			40	0.002	36	1.80E+04		0.02	35	1.75E+03	1.38E+01	
			50	0.002	50	2.50E+04		0.02	263	1.32E+04	1.04E+02	
11-Sep-06	4B	Stable	20	0.02	1469	7.35E+04	2.57E+04	0.1	1898	1.90E+04	1.00E+01	0.3
			30	0.002	34	1.70E+04		0.01	90	9.00E+03	4.74E+00	
			40	0.002	17	8.50E+03		0.014	130	9.29E+03	4.89E+00	
			50	0.002	8	4.00E+03		0.014	203	1.45E+04	7.64E+00	
12-Sep-06	2B	Stable	20	0.005	8	1.60E+03	1.20E+04	0.01	33	3.30E+03	1.00E+02	0.2
			30	0.005	69	1.38E+04		0.01	0	7.50E+03	2.27E+02	
			40	0.005	103	2.06E+04		0.01	64	6.40E+03	1.94E+02	
			50	0.005	0	1.20E+04		0.01	128	1.28E+04	3.88E+02	
12-Sep-06	4B	Stable	20	0.005	10	2.00E+03	7.05E+03	0.01	39	3.90E+03	1.00E+02	0.2
			30	0.005	46	9.20E+03		0.01	34	3.40E+03	8.72E+01	
			40	0.005	40	8.00E+03		0.01	45	4.50E+03	1.15E+02	
			50	0.005	45	9.00E+03		0.01	66	6.60E+03	1.69E+02	
25-Sep-06	2B	Stable	20	0.003	52	1.73E+04	2.18E+04	0.02	270	1.35E+04	4.09E+02	0.1
			30	0.003	65	2.17E+04		0.02	167	8.35E+03	2.53E+02	
			40	0.01	984	2.41E+04		0.02	716	3.58E+04	1.08E+03	
			50	0.01	1145	2.41E+04		0.02	334	1.67E+04	5.06E+02	
25-Sep-06	4B	Stable	20	0.003	85	2.83E+04	2.95E+04	0.014	96	6.86E+03	1.76E+02	0.5
			30	0.003	125	4.17E+04		0.02	154	7.70E+03	1.97E+02	
			40	0.01	1291	2.41E+04		0.014	24	1.71E+03	4.40E+01	
			50	0.01	904	2.41E+04		0.014	295	2.11E+04	5.40E+02	
29-Jan-07	2B	Stable	20	0.00015	46	3.07E+05	3.51E+05	0.823	16	1.94E+01	1.22E+00	4.6
			30	0.00015	70	4.67E+05		0.846	6	7.09E+00	4.43E-01	
			40	0.0001	21	2.10E+05		0.73	3	4.11E+00	2.57E-01	
			50	0.0001	42	4.20E+05		0.73	1	1.37E+00	8.56E-02	
29-Jan-07	4B	Stable	20	0.00015	80	5.33E+05	4.38E+05	0.79	1	1.27E+00	1.27E+00	5.2
			30	0.00015	111	7.40E+05		0.081	330	4.07E+03	4.07E+03	
			40	0.0001	37	3.70E+05		0.696	3	4.31E+00	4.31E+00	
			50	0.0001	11	1.10E+05		0.524	1	1.91E+00	1.91E+00	
02-Apr-07	2B	Stable	20	0.001	429	4.29E+05	5.33E+05	0.215	984	4.58E+03	4.65E+00	2.1
			30	0.001	767	7.67E+05		0.216	775	3.59E+03	3.65E+00	
			40	0.001	402	4.02E+05		0.211	907	4.30E+03	4.37E+00	
			50	0.001	533	5.33E+05		0.222	852	3.84E+03	3.90E+00	

02-Apr-07	4B	Stable	20	0.001	333	3.33E+05	5.33E+05	0.204	881	4.32E+03	4.90E+00	2.1
			30	0.001	753	7.53E+05		0.214	737	3.44E+03	3.91E+00	
			40	0.001	691	6.91E+05		0.213	778	3.65E+03	4.15E+00	
			50	0.001	354	3.54E+05		0.213	889	4.17E+03	4.74E+00	
06-Apr-07	2B	Stable	20	0.00125	579	4.63E+05	5.22E+05	0.02	161	8.05E+03	5.00E+01	1.6
			30	0.00125	481	3.85E+05		0.02	120	6.00E+03	3.73E+01	
			40	0.00125	838	6.70E+05		0.02	315	1.58E+04	9.78E+01	
			50	0.00125	712	5.70E+05		0.02	355	1.78E+04	1.10E+02	
06-Apr-07	4B	Stable	20	0.00125	336	2.69E+05	5.35E+05	0.02	80	4.00E+03	5.00E+01	1.5
			30	0.00125	851	6.81E+05		0.02	122	6.10E+03	7.63E+01	
			40	0.00125	784	6.27E+05		0.02	205	1.03E+04	1.28E+02	
			50	0.00125	702	5.62E+05		0.02	911	4.56E+04	5.69E+02	
11-Apr-07	2B	Stable	20	0.001	127	1.27E+05	9.98E+04	0.005	24	4.80E+03	2.00E+02	1.0
			30	0.001	51	5.10E+04		0.005	41	8.20E+03	3.42E+02	
			40	0.001	118	1.18E+05		0.005	94	1.88E+04	7.83E+02	
			50	0.001	103	1.03E+05		0.005	45	9.00E+03	3.75E+02	
11-Apr-07	4B	Stable	20	0.001	285	2.85E+05	2.16E+05	0.005	35	7.00E+03	2.00E+02	1.5
			30	0.001	145	1.45E+05		0.005	29	5.80E+03	1.66E+02	
			40	0.001	249	2.49E+05		0.005	54	1.08E+04	3.09E+02	
			50	0.001	186	1.86E+05		0.005	31	6.20E+03	1.77E+02	
16-Apr-07	2B	Stable	20	0.001	571	5.71E+05	3.67E+05	0.03	370	1.23E+04	3.33E+01	1.3
			30	0.001	389	3.89E+05		0.03	586	1.95E+04	5.28E+01	
			40	0.001	414	4.14E+05		0.03	937	3.12E+04	8.44E+01	
			50	0.004	373	9.33E+04		0.03	219	7.30E+03	1.97E+01	
16-Apr-07	4B	Stable	20	0.001	363	3.63E+05	5.01E+05	0.03	163	5.43E+03	3.33E+01	1.8
			30	0.001	233	2.33E+05		0.03	234	7.80E+03	4.79E+01	
			40	0.002	2611	1.31E+06		0.03	544	1.81E+04	1.11E+02	
			50	0.004	412	1.03E+05		0.03	128	4.27E+03	2.62E+01	
20-Apr-07	2B	Stable	20	0.00045	421	9.36E+05	8.06E+05	0.002	132	6.60E+04	5.00E+02	0.9
			30	0.00045	360	8.00E+05		0.002	205	1.03E+05	7.77E+02	
			40	0.0005	451	9.02E+05		0.002	247	1.24E+05	9.36E+02	
			50	0.0005	293	5.86E+05		0.002	253	1.27E+05	9.58E+02	
20-Apr-07	4B	Stable	20	0.00045	371	8.24E+05	9.06E+05	0.002	69	3.45E+04	5.00E+02	1.3
			30	0.00045	495	1.10E+06		0.002	85	4.25E+04	6.16E+02	
			40	0.0005	358	7.16E+05		0.002	112	5.60E+04	8.12E+02	
			50	0.0005	491	9.82E+05		0.002	97	4.85E+04	7.03E+02	
20-Apr-07	2B	Stable	20	0.00075	436	5.81E+05	6.52E+05	0.005	382	7.64E+04	2.00E+02	1.1
			30	0.00075	275	3.67E+05		0.005	240	4.80E+04	1.26E+02	
			40	0.00075	706	9.41E+05		0.004	37	9.25E+03	2.42E+01	
			50	0.00075	539	7.19E+05		0.004	342	8.55E+04	2.24E+02	
20-Apr-07	4B	Stable	20	0.00075	567	7.56E+05	6.39E+05	0.005	206	4.12E+04	2.00E+02	1.2
			30	0.00075	356	4.75E+05		0.005	169	3.38E+04	1.64E+02	
			40	0.00075	453	6.04E+05		0.004	135	3.38E+04	1.64E+02	
			50	0.00075	542	7.23E+05		0.004	264	6.60E+04	3.20E+02	
24-Apr-07	2B	Stable	20	0.0005	541	1.08E+06	8.92E+05	0.005	398	7.96E+04	2.00E+02	1.0
			30	0.0005	415	8.30E+05		0.005	517	1.03E+05	2.60E+02	
			40	0.0005	279	5.58E+05		0.005	634	1.27E+05	3.19E+02	
			50	0.0005	548	1.10E+06		0.005	380	7.60E+04	1.91E+02	
24-Apr-07	4B	Stable	20	0.0005	262	5.24E+05	7.19E+05	0.005	581	1.16E+05	2.00E+02	0.9
			30	0.0005	388	7.76E+05		0.005	309	6.18E+04	1.06E+02	
			40	0.0005	237	4.74E+05		0.005	608	1.22E+05	2.09E+02	
			50	0.0005	550	1.10E+06		0.005	357	7.14E+04	1.23E+02	

12-Sep-07	2B	Stable	20	0.00075	2302	3.07E+06	1.20E+06	0.001	1473	1.47E+06	1.00E+03	0.3
			30	0.00075	714	9.52E+05		0.02	1499	7.50E+04	5.09E+01	
			40	0.001	377	3.77E+05		0.001	590	5.90E+05	4.01E+02	
			50	0.001	408	4.08E+05		0.001	308	3.08E+05	2.09E+02	
12-Sep-07	4B	Stable	20	0.00075	1928	2.57E+06	9.30E+05	0.001	1157	1.16E+06	1.00E+03	0.3
			30	0.00075	385	5.13E+05		0.001	298	2.98E+05	2.58E+02	
			40	0.001	178	1.78E+05		0.001	241	2.41E+05	2.08E+02	
			50	0.001	457	4.57E+05		0.001	247	2.47E+05	2.13E+02	
13-Sep-07	2B	Stable	30	0.0004	257	6.43E+05	1.48E+06	0.05	700	1.40E+04	2.00E+01	2.2
			40	0.0004	596	1.49E+06		0.05	102	2.04E+03	2.91E+00	
			50	0.0004	503	1.26E+06		0.05	601	1.20E+04	1.72E+01	
			60	0.0004	1013	2.53E+06		0.05	308	6.16E+03	8.80E+00	
13-Sep-07	4B	Stable	30	0.0004	709	1.77E+06	1.76E+06	0.1	1800	1.80E+04	1.00E+01	1.9
			40	0.0004	758	1.90E+06		0.1	2735	2.74E+04	1.52E+01	
			50	0.0004	481	1.20E+06		0.1	2149	2.15E+04	1.19E+01	
			60	0.0004	861	2.15E+06		0.1	1469	1.47E+04	8.16E+00	
11-Dec-07	2B	Stable	20	0.061	89	1.46E+03	1.27E+03	0.207	164	7.92E+02	4.83E+00	0.0
			30	0.1	153	1.53E+03		0.27	197	7.30E+02	4.45E+00	
			40	0.05	56	1.12E+03		0.411	72	1.75E+02	1.07E+00	
			50	0.05	49	9.80E+02		0.304	73	2.40E+02	1.46E+00	
11-Dec-07	4B	Stable	20	0.077	59	7.66E+02	1.23E+03	0.21	112	5.33E+02	4.76E+00	0.4
			30	0.099	187	1.89E+03		0.21	950	4.52E+03	4.04E+01	
			40	0.005	56	1.12E+03		0.288	18	6.25E+01	5.58E-01	
			50	0.005	58	1.16E+03		0.185	23	1.24E+02	1.11E+00	
08-Jun-17	1	Stable	0	0.006	1	1.11E+02	2.21E+04	0.7	-	-	-	3.5
			15	0.006	20	3.33E+03		0.7	1	1.00E+00	4.53E-05	
			30	0.1	14	1.40E+04		0.7	3	4.00E+00	1.81E-04	
			45	0.0006	17	2.79E+04		0.7	3	4.00E+00	1.81E-04	
			60	0.0006	18	3.00E+04		0.7	13	1.90E+01	8.61E-04	
			75	0.0006	10	1.63E+04		0.7	0	1.00E+00	4.53E-05	
08-Jun-17	2A	Stable	0	0.0045	0	0.00E+00	5.04E+04	0.7	2	3.00E+00	5.95E-05	3.8
			15	0.0045	6	1.75E+03		0.7	0	1.00E+00	1.98E-05	
			30	0.0045	163	3.76E+04		0.7	3	4.00E+00	7.93E-05	
			45	0.0035	225	3.95E+04		0.4	1	5.50E+00	1.09E-04	
			60	0.0033	163	5.19E+04		0.4	4	1.85E+01	3.67E-04	
			75	0.0033	238	7.27E+04		0.7	0	1.00E+00	1.98E-05	
09-Jun-17	1	Stable	0	0.006	2	3.34E+02	3.38E+04	0.7	0	0.00E+00	0.00E+00	4.1
			15	0.006	21	3.50E+03		0.7	3	4.00E+00	1.19E-04	
			30	0.0035	25	3.17E+04		0.7	2	3.00E+00	8.89E-05	
			45	0.0006	15	2.50E+04		0.7	2	3.00E+00	8.89E-05	
			60	0.0006	26	4.25E+04		0.7	2	3.00E+00	8.89E-05	
			75	0.0006	22	3.58E+04		0.7	2	3.00E+00	8.89E-05	
09-Jun-17	2A	Stable	0	0.0045	0	0.00E+00	4.94E+04	0.7	1	1.00E+00	2.02E-05	3.4
			15	0.0045	9	2.21E+04		0.7	1	1.00E+00	2.02E-05	
			30	0.0045	151	3.97E+04		0.7	3	4.00E+00	8.09E-05	
			45	0.0033	216	6.05E+04		0.7	1	1.00E+00	2.02E-05	
			60	0.0033	201	4.54E+04		0.4	24	7.30E+01	1.48E-03	
			75	0.0033	47	5.21E+04		0.7	1	1.00E+00	2.02E-05	
02-Aug-17	1	Stable	0	0.0035	0	0.00E+00	3.11E+04	0.1	3	3.00E+01	9.65E-04	1.2
			15	0.005	11	2.44E+03		0.01	0	1.00E+00	3.22E-05	
			30	0.0045	87	2.37E+04		0.01	3	3.00E+02	9.65E-03	
			45	0.004	137	3.68E+04		0.01	9	9.00E+02	2.90E-02	
			60	0.001775	40	2.00E+04		0.055	256.5	3.83E+03	1.23E-01	
			75	0.004	176	4.39E+04		0.01	22.5	2.25E+03	7.24E-02	
02-Aug-17	2A	Stable	0	0.006	0	0.00E+00	4.14E+04	0.01	1	1.00E+02	2.42E-03	1.2
			15	0.006	6	1.00E+03		0.01	1	1.00E+02	2.42E-03	
			30	0.003	72	2.38E+04		0.01	5.5	5.50E+02	1.33E-02	
			45	0.003	110	3.67E+04		0.01	31.5	3.15E+03	7.61E-02	
			60	0.003	60	2.05E+04		0.01	27.5	2.75E+03	6.65E-02	
			75	0.003	254	8.45E+04		0.01	38.5	3.85E+03	9.31E-02	

03-Aug-17	1	Stable	0 15 30 45 60 75	0.006 0.006 0.0045 0.0045 0.0045 0.003	6 15 90 85 70 58	9.17E+02 2.42E+03 2.51E+04 2.55E+04 2.24E+04 1.93E+04	2.31E+04	0.7 0.7 0.7 0.355 0.4 0.7	1 1 5 2 3 1	1.00E+00 1.00E+00 7.00E+00 3.00E+00 1.30E+01 1.00E+00	4.33E-05 4.33E-05 3.03E-04 1.30E-04 5.63E-04 4.33E-05	3.6
03-Aug-17	2A	Stable	0 15 30 45 60 75	0.006 0.006 0.003 0.003 0.003 0.003	0 2 80 17 71 72	0.00E+00 3.34E+02 2.65E+04 5.67E+03 2.37E+04 2.40E+04	2.00E+04	0.7 0.7 0.7 0.7 0.4 0.7	0 1 2 2 2 0	0.00E+00 1.00E+00 3.00E+00 3.00E+00 5.00E+00 1.00E+00	0.00E+00 5.01E-05 1.50E-04 1.50E-04 2.51E-04 5.01E-05	3.8
05-Oct-17	1	Stable	0 15 30 45 60 75	0.006 0.006 0.003 0.003 0.003 0.003	0 0 116 159 325 171	0.00E+00 0.00E+00 3.87E+04 5.30E+04 1.08E+05 5.68E+04	6.42E+04	0.7 0.7 0.7 0.7 0.7 0.7	0 0 3 8 2 16	0.00E+00 1.00E+00 4.00E+00 1.10E+01 3.00E+00 2.30E+01	0.00E+00 1.56E-05 6.23E-05 1.71E-04 4.68E-05 3.59E-04	3.8
05-Oct-17	2A	Stable	0 15 30 45 60 75	0.006 0.006 0.003 0.003 0.003 0.003	0 0 94 207 121 147	0.00E+00 0.00E+00 3.13E+04 6.90E+04 4.03E+04 4.90E+04	4.74E+04	0.7 0.7 0.7 0.7 0.7 0.7	0 0 0 2 2 3	0.00E+00 1.00E+00 1.00E+00 1.14E+01 3.00E+00 4.00E+00	0.00E+00 2.11E-05 2.11E-05 2.41E-04 6.33E-05 8.44E-05	4.0
23-Oct-17	1	Stable	0 15 30 45 60 75 90 105	0.006 0.006 0.006 0.003 0.006 0.003 0.003 0.003	0 3 180 129 486 270 358 392	0.00E+00 5.00E+02 3.00E+04 3.38E+04 1.27E+05 8.98E+04 1.19E+05 1.31E+05	8.83E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 0 0 3 2 3 4 4	0.00E+00 1.00E+00 1.00E+00 4.30E+00 2.90E+00 4.30E+00 5.70E+00 5.70E+00	0.00E+00 1.13E-05 1.13E-05 4.87E-05 3.28E-05 4.87E-05 6.45E-05 6.45E-05	4.3
23-Oct-17	2A	Stable	0 15 30 45 60 75 90 105	0.006 0.006 0.006 0.003 0.006 0.003 0.003 0.003	0 2 84 337 627 138 334 278	0.00E+00 2.50E+02 1.40E+04 5.62E+04 1.46E+05 4.58E+04 1.11E+05 1.21E+05	8.23E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 1 0 0 2 2 1 1	0.00E+00 1.00E+00 1.00E+00 1.00E+00 2.90E+00 2.90E+00 1.00E+00 1.00E+00	0.00E+00 1.22E-05 1.22E-05 1.22E-05 3.53E-05 3.53E-05 1.22E-05 1.22E-05	4.7
13-Nov-17	1	Hydraulic Surge	0 50 55 61 66 71 80 100	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	4 67 55 68 94 86 61 54	5.84E+02 6.65E+04 5.50E+04 6.75E+04 9.40E+04 8.55E+04 6.10E+04 5.40E+04	6.91E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 6 1 1 8 6 0 1	0.00E+00 9.00E+00 1.40E+00 1.40E+00 1.10E+01 9.00E+00 1.00E+00 1.40E+00	0.00E+00 1.30E-04 2.03E-05 2.03E-05 1.59E-04 1.30E-04 1.45E-05 2.03E-05	4.2
13-Nov-17	2A	Hydraulic Surge	0 50 55 61 66 71 80 100	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	1 41 55 63 66 58 108 102	8.35E+01 4.10E+04 5.45E+04 6.30E+04 6.55E+04 5.70E+04 1.08E+05 1.02E+05	7.01E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 0 0 1 2 0 0 1	0.00E+00 1.00E+00 1.00E+00 1.43E+00 2.90E+00 1.00E+00 1.00E+00 1.40E+00	0.00E+00 1.43E-05 1.43E-05 2.04E-05 4.14E-05 1.43E-05 1.43E-05 2.00E-05	4.7

28-Nov-17	1	Hydraulic Surge	0	0.006	2	1.67E+02	8.61E+04	0.7	0	0.00E+00	0.00E+00	3.4
			50	0.001	74	7.40E+04		0.7	1	1.40E+00	1.63E-05	
			55	0.001	77	7.65E+04		0.7	3	4.30E+00	5.00E-05	
			61	0.001	72	7.15E+04		0.7	1	1.40E+00	1.63E-05	
			68	0.001	73	7.30E+04		0.7	3	4.30E+00	5.00E-05	
			73	0.001	94	9.40E+04		0.7	5	7.10E+00	8.25E-05	
			80	0.001	107	1.07E+05		0.7	160	2.29E+02	2.66E-03	
			100	0.001	107	1.07E+05		0.7	9	1.29E+01	1.50E-04	
28-Nov-17	2A	Hydraulic Surge	0	0.006	0	0.00E+00	8.58E+04	0.7	0	0.00E+00	0.00E+00	2.6
			50	0.001	59	5.90E+04		0.7	1	1.00E+00	1.17E-05	
			55	0.001	68	6.75E+04		0.7	0	1.00E+00	1.17E-05	
			61	0.001	61	6.10E+04		0.7	1500	1.50E+03	1.75E-02	
			68	0.001	80	8.00E+04		0.7	10	1.00E+01	1.17E-04	
			71	0.001	116	1.16E+05		0.7	1	1.40E+00	1.63E-05	
			80	0.001	118	1.18E+05		0.7	1	1.40E+00	1.63E-05	
			100	0.001	100	1.00E+05		0.7	1	1.40E+00	1.63E-05	
22-Jan-18	1	Hydraulic Surge	0	0.006	0	0.00E+00	8.20E+04	0.7	0	0.00E+00	0.00E+00	4.7
			50	0.001	49	4.90E+04		0.7	1	1.00E+00	1.22E-05	
			55	0.001	35	3.50E+04		0.7	2	3.00E+00	3.66E-05	
			61	0.001	56	5.55E+04		0.7	2	3.00E+00	3.66E-05	
			66	0.001	78	7.80E+04		0.7	1	1.40E+00	1.71E-05	
			73	0.001	87	8.70E+04		0.7	1	1.40E+00	1.71E-05	
			80	0.001	121	1.21E+05		0.7	1	1.40E+00	1.71E-05	
			100	0.001	149	1.49E+05		0.7	1	1.40E+00	1.71E-05	
22-Jan-18	2A	Hydraulic Surge	0	0.006	2	1.67E+02	1.09E+05	0.7	0	0.00E+00	0.00E+00	4.7
			50	0.001	59	5.90E+04		0.7	0	1.00E+00	9.20E-06	
			55	0.001	64	6.35E+04		0.7	1	1.43E+00	1.32E-05	
			61	0.001	79	7.85E+04		0.7	1	1.43E+00	1.32E-05	
			66	0.001	89	8.90E+04		0.7	2	2.86E+00	2.63E-05	
			71	0.001	104	1.04E+05		0.7	1	1.43E+00	1.32E-05	
			80	0.001	152	1.52E+05		0.7	2	2.86E+00	2.63E-05	
			100	0.001	215	2.15E+05		0.7	2	2.86E+00	2.63E-05	
06-Feb-18	1	Hydraulic Surge	0	0.006	0	0.00E+00	6.78E+04	0.7	0	0.00E+00	0.00E+00	4.2
			50	0.001	42	4.15E+04		0.7	2	2.86E+00	4.22E-05	
			55	0.001	45	4.50E+04		0.7	2	2.86E+00	4.22E-05	
			61	0.001	62	6.20E+04		0.7	3	4.29E+00	6.33E-05	
			66	0.001	81	8.05E+04		0.7	3	4.29E+00	6.33E-05	
			73	0.001	73	7.30E+04		0.7	3	4.29E+00	6.33E-05	
			80	0.001	84	8.35E+04		0.7	4	5.71E+00	8.43E-05	
			100	0.001	89	8.90E+04		0.7	5	7.14E+00	1.05E-04	
06-Feb-18	2A	Hydraulic Surge	0	0.006	0	0.00E+00	8.56E+04	0.7	0	0.00E+00	0.00E+00	4.6
			50	0.001	26	2.60E+04		0.7	1	1.43E+00	1.67E-05	
			55	0.001	35	3.50E+04		0.7	1	1.43E+00	1.67E-05	
			61	0.001	102	1.02E+05		0.7	1	1.43E+00	1.67E-05	
			66	0.001	57	5.70E+04		0.7	2	2.86E+00	3.34E-05	
			71	0.001	102	1.02E+05		0.7	1	1.43E+00	1.67E-05	
			80	0.001	119	1.19E+05		0.7	2	2.86E+00	3.34E-05	
			100	0.001	159	1.59E+05		0.7	3	4.29E+00	5.01E-05	
21-Feb-18	1	Hydraulic Surge	0	0.006	0	0.00E+00	1.01E+05	0.7	0	0.00E+00	0.00E+00	4.4
			50	0.001	60	6.00E+04		0.7	9	1.29E+01	1.28E-04	
			55	0.001	41	4.05E+04		0.7	1	1.43E+00	1.42E-05	
			61	0.001	136	1.36E+05		0.7	2	2.86E+00	2.84E-05	
			66	0.001	147	1.47E+05		0.7	2	2.86E+00	2.84E-05	
			73	0.001	111	1.11E+05		0.7	2	2.86E+00	2.84E-05	
			80	0.001	119	1.19E+05		0.7	4	5.71E+00	5.68E-05	
			100	0.001	92	9.15E+04		0.7	2	2.86E+00	2.84E-05	

21-Feb-18	2A	Hydraulic Surge	0	0.006	0	0.00E+00	1.12E+05	0.7	0	0.00E+00	0.00E+00	4.8
			50	0.001	73	7.25E+04		0.7	0	1.00E+00	8.96E-06	
			55	0.001	84	8.40E+04		0.7	1	1.40E+00	1.25E-05	
			61	0.001	124	1.24E+05		0.7	1	1.40E+00	1.25E-05	
			66	0.001	122	1.22E+05		0.7	2	3.00E+00	2.69E-05	
			71	0.001	122	1.22E+05		0.7	2	3.00E+00	2.69E-05	
			80	0.001	126	1.26E+05		0.7	1	1.43E+00	1.28E-05	
			100	0.001	131	1.31E+05		0.7	1	1.43E+00	1.28E-05	
06-Mar-18	1	Stable	0	0.006	0	0.00E+00	6.70E+04	0.7	0	0.00E+00	0.00E+00	4.8
			15	0.001	1	5.00E+02		0.7	0	1.00E+00	1.49E-05	
			30	0.001	16	1.60E+04		0.7	1	1.43E+00	2.13E-05	
			45	0.001	48	4.80E+04		0.7	1	1.43E+00	2.13E-05	
			60	0.001	63	6.25E+04		0.7	0	1.00E+00	1.49E-05	
			75	0.001	87	8.70E+04		0.7	0	1.00E+00	1.49E-05	
			90	0.001	89	8.85E+04		0.7	0	1.00E+00	1.49E-05	
			105	0.001	100	1.00E+05		0.7	0	1.00E+00	1.49E-05	
06-Mar-18	2A	Stable	0	0.006	0	0.00E+00	6.09E+04	0.7	0	0.00E+00	0.00E+00	4.7
			15	0.001	2	2.00E+03		0.7	1	1.43E+00	2.35E-05	
			30	0.001	29	2.85E+04		0.7	1	1.43E+00	2.35E-05	
			45	0.001	34	3.35E+04		0.7	0	1.00E+00	1.64E-05	
			60	0.001	48	4.80E+04		0.7	0	1.00E+00	1.64E-05	
			75	0.001	60	6.00E+04		0.7	0	1.00E+00	1.64E-05	
			90	0.001	92	9.15E+04		0.7	1	1.43E+00	2.35E-05	
			105	0.001	104	1.04E+05		0.7	0	1.00E+00	1.64E-05	
19-Mar-18	1	Stable	0	0.006	0	0.00E+00	5.23E+04	0.7	0	0.00E+00	0.00E+00	4.4
			15	0.001	3	3.00E+03		0.7	1	1.43E+00	2.74E-05	
			30	0.001	12	1.15E+04		0.7	3	4.29E+00	8.21E-05	
			45	0.001	31	3.05E+04		0.7	2	2.86E+00	5.47E-05	
			60	0.001	49	4.85E+04		0.7	0	1.00E+00	1.91E-05	
			75	0.001	62	6.20E+04		0.7	1	1.43E+00	2.74E-05	
			90	0.001	78	7.75E+04		0.7	1	1.43E+00	2.74E-05	
			105	0.001	84	8.35E+04		0.7	0	1.00E+00	1.91E-05	
19-Mar-18	2A	Stable	0	0.006	0	0.00E+00	2.81E+04	0.7	0	0.00E+00	0.00E+00	4.1
			15	0.001	1	5.00E+02		0.7	1	1.00E+00	3.56E-05	
			30	0.001	9	9.00E+03		0.7	2	2.86E+00	1.02E-04	
			45	0.001	6	6.00E+03		0.7	1	1.43E+00	5.09E-05	
			60	0.001	22	2.20E+04		0.7	3	4.29E+00	1.53E-04	
			75	0.001	40	3.95E+04		0.7	-	-	-	
			90	0.001	42	4.20E+04		0.7	1	1.43E+00	5.09E-05	
			105	0.001	50	5.00E+04		0.7	1	1.43E+00	5.09E-05	
10-Apr-18	1	Stable	0	0.006	0	0.00E+00	6.30E+04	0.03	0	0.00E+00	0.00E+00	2.3
			15	0.001	17	1.65E+04		0.03	6	2.00E+02	3.17E-03	
			30	0.001	31	3.05E+04		0.03	8	2.67E+02	4.23E-03	
			45	0.001	45	4.50E+04		0.03	4	1.33E+02	2.12E-03	
			60	0.001	61	6.05E+04		0.03	15	5.00E+02	7.94E-03	
			75	0.001	63	6.25E+04		0.03	10	3.33E+02	5.29E-03	
			90	0.001	84	8.35E+04		0.03	4	1.33E+02	2.12E-03	
			105	0.001	96	9.60E+04		0.03	12	4.00E+02	6.35E-03	
10-Apr-18	2A	Stable	0	0.006	0	0.00E+00	6.28E+04	0.03	8	2.67E+02	4.25E-03	1.9
			15	0.001	10	9.50E+03		0.03	1	3.33E+01	5.31E-04	
			30	0.001	19	1.85E+04		0.03	2	6.67E+01	1.06E-03	
			45	0.001	36	3.60E+04		0.03	2	5.00E+01	7.97E-04	
			60	0.001	43	4.30E+04		0.03	1	3.33E+01	5.31E-04	
			75	0.001	75	7.45E+04		0.03	32	1.07E+03	1.70E-02	
			90	0.001	96	9.55E+04		0.03	47	1.57E+03	2.50E-02	
			105	0.001	109	1.09E+05		0.03	66	2.20E+03	3.51E-02	

23-Apr-18	1	Stable	0	0.006	17	1.42E+03	7.80E+04	0.03	4	1.33E+02	1.71E-03	1.3
			15	0.001	0	0.00E+00		0.03	48	1.60E+03	2.05E-02	
			30	0.001	18	1.75E+04		0.03	57	1.90E+03	2.44E-02	
			45	0.001	35	3.50E+04		0.03	59	1.83E+03	2.35E-02	
			60	0.001	61	6.05E+04		0.03	175	5.83E+03	7.48E-02	
			75	0.001	89	8.90E+04		0.03	153	5.10E+03	6.54E-02	
			90	0.001	117	1.17E+05		0.03	187	6.23E+03	7.99E-02	
			105	0.001	150	1.50E+05		0.03	87	2.90E+03	3.72E-02	
23-Apr-18	2A	Stable	0	0.006	2	1.67E+02	6.28E+04	0.03	118	3.93E+03	6.26E-02	0.8
			15	0.001	11	5.50E+03		0.03	79	2.63E+03	4.19E-02	
			30	0.001	14	1.35E+04		0.03	151	5.03E+03	8.01E-02	
			45	0.001	32	3.20E+04		0.03	45	1.50E+03	2.39E-02	
			60	0.001	84	8.35E+04		0.03	303	1.01E+04	1.61E-01	
			75	0.001	72	7.20E+04		0.03	382	1.27E+04	2.03E-01	
			90	0.001	85	8.45E+04		0.03	373	1.24E+04	1.98E-01	
			105	0.001	92	9.15E+04		0.03	381	1.27E+04	2.02E-01	
29-May-18	1	End of the run	0	0.006	11	9.17E+02	3.24E+04	0.4	38	9.50E+01	2.93E-03	3.1
			15	0.001	2	1.00E+03		0.7	29	4.14E+01	1.28E-03	
			30	0.001	6	6.00E+03		0.7	6	8.57E+00	2.64E-04	
			45	0.001	18	1.75E+04		0.7	1	1.00E+00	3.08E-05	
			60	0.001	48	4.80E+04		0.7	5	7.14E+00	2.20E-04	
			75	0.001	25	2.50E+04		0.7	23	3.29E+01	1.01E-03	
			90	0.001	46	4.55E+04		0.7	23	3.29E+01	1.01E-03	
			105	0.001	53	5.25E+04		0.7	41	5.86E+01	1.81E-03	
29-May-18	2A	End of the run	0	0.006	3	5.00E+02	4.36E+04	0.7	0	0.00E+00	0.00E+00	3.0
			15	0.001	1	5.00E+02		0.7	23	3.29E+01	7.53E-04	
			30	0.001	17	1.70E+04		0.7	28	4.00E+01	9.17E-04	
			45	0.001	15	1.50E+04		0.7	7	1.00E+01	2.29E-04	
			60	0.001	46	4.60E+04		0.7	28	4.00E+01	9.17E-04	
			75	0.001	36	3.58E+04		0.7	10	1.43E+01	3.27E-04	
			90	0.001	67	6.70E+04		0.7	8	1.14E+01	2.62E-04	
			105	0.001	81	8.10E+04		0.7	10	1.43E+01	3.27E-04	
29-May-18	1	Ripening	0	0.008	64	5.33E+03	5.08E+04	0.7	25	3.57E+01	7.03E-04	3.0
			5	0.0015	0	0.00E+00		0.689	1	1.45E+00	2.86E-05	
			10	0.0015	41	2.85E+04		0.7	37	5.29E+01	1.04E-03	
			15	0.0015	79	5.60E+04		0.7	33	4.71E+01	9.28E-04	
			20	0.0015	103	7.23E+04		0.7	21	3.00E+01	5.91E-04	
			25	0.0015	90	6.03E+04		0.7	60	8.57E+01	1.69E-03	
			30	0.0015	65	3.70E+04		0.7	18	2.57E+01	5.06E-04	
29-May-18	2A	Ripening	0	0.008	0	0.00E+00	7.91E+04	0.7	9	1.29E+01	1.63E-04	3.4
			15	0.0015	51	3.18E+04		0.7	13	1.86E+01	2.35E-04	
			30	0.0015	53	3.53E+04		0.7	11	1.57E+01	1.99E-04	
			45	0.0015	250	1.65E+05		0.7	62	8.86E+01	1.12E-03	
			60	0.0015	150	9.50E+04		0.7	20	2.86E+01	3.61E-04	
			75	0.0015	120	7.95E+04		0.7	22	3.14E+01	3.98E-04	
			90	0.0015	27	2.03E+04		0.7	8	1.14E+01	1.45E-04	
19-Jun-18	1	Hydraulic surge	0	0.006	6	5.00E+02	5.06E+04	0.7	4	5.71E+00	1.13E-04	3.1
			50	0.001	31	3.10E+04		0.7	27	3.86E+01	7.63E-04	
			55	0.001	33	3.25E+04		0.7	17	2.43E+01	4.80E-04	
			67	0.001	56	5.60E+04		0.7	9	1.29E+01	2.54E-04	
			72	0.001	53	5.30E+04		0.7	27	3.86E+01	7.63E-04	
			77	0.001	58	5.75E+04		0.7	51	7.29E+01	1.44E-03	
			86	0.001	50	5.00E+04		0.7	26	3.71E+01	7.34E-04	
			106	0.001	74	7.40E+04		0.7	20	2.86E+01	5.65E-04	

29-May-18	2A	Hydraulic surge	0	0.006	0	0.00E+00	5.11E+04	0.7	134	1.91E+02	3.75E-03	3.2
			50	0.001	31	3.05E+04		0.7	12	1.71E+01	3.36E-04	
			55	0.001	40	3.95E+04		0.7	11	1.57E+01	3.08E-04	
			67	0.001	32	3.20E+04		0.7	6	8.57E+00	1.68E-04	
			72	0.001	41	4.10E+04		0.7	92	1.31E+02	2.57E-03	
			77	0.001	53	5.30E+04		0.7	5	7.14E+00	1.40E-04	
			86	0.001	77	7.65E+04		0.7	14	2.00E+01	3.92E-04	
			106	0.001	85	8.50E+04		0.7	10	1.43E+01	2.80E-04	
16-Oct-18	3	Stable	0	0.006	2	3.33E+02	2.26E+04	0.7	0	0.00E+00	0.00E+00	3.9
			15	0.001	9	9.00E+03		0.8	2	2.50E+00	1.10E-04	
			30	0.001	21	2.05E+04		0.8	5	6.25E+00	2.76E-04	
			45	0.001	24	2.35E+04		0.7	2	2.86E+00	1.26E-04	
			75	0.001	24	2.35E+04	2.26E+04	0.7	0	1.00E+00	4.42E-05	
			105	0.001	23	2.30E+04		0.8	1	1.25E+00	5.52E-05	
			0	0.005	5	1.00E+03		0.7	0	0.00E+00	0.00E+00	
			15	0.005	18	3.60E+03		0.8	2	2.50E+00	1.10E-04	
			30	0.005	71	1.42E+04		0.8	5	6.25E+00	2.76E-04	
			45	0.005	83	1.66E+04		0.7	2	2.86E+00	1.26E-04	
			75	0.005	116	2.31E+04		0.7	0	1.00E+00	4.42E-05	
			105	0.005	183	3.66E+04		0.8	1	1.25E+00	5.52E-05	
23-Oct-18	3	End of the run	0	0.006	0	0.00E+00	2.19E+04	0.8	0	0.00E+00	0.00E+00	4.3
			5	0.005	4	8.00E+02		0.8	0	1.00E+00	4.57E-05	
			87	0.005	64	1.27E+04		0.8	0	1.00E+00	4.57E-05	
			83	0.003	91	3.03E+04		0.8	0	1.00E+00	4.57E-05	
			64	0.003	114	3.80E+04		0.8	0	1.00E+00	4.57E-05	
			67	0.003	101	3.37E+04		0.8	0	1.00E+00	4.57E-05	
06-Nov-18	3	Ripening	0	0.005	0	0.00E+00	1.25E+05	0.8	0	0.00E+00	0.00E+00	4.8
			5	0.005	349	6.98E+04		0.8	4	5.00E+00	4.00E-05	
			10	0.005	185	3.69E+04		0.8	0	1.00E+00	8.00E-06	
			20	0.005	872	1.74E+05		0.8	0	1.00E+00	8.00E-06	
			30	0.005	830	1.66E+05		0.8	3	3.75E+00	3.00E-05	
10-Dec-18	3	End of the run	0	0.006	0	0.00E+00	2.61E+04	0.8	0	1.00E+00	0.00E+00	4.1
			15	0.004	4	1.00E+03		0.8	0	1.00E+00	3.84E-05	
			30	0.006	117	2.12E+04		0.8	0	1.00E+00	3.84E-05	
			45	0.006	705	1.28E+05		0.8	0	1.00E+00	3.84E-05	
			75	0.006	150	2.73E+04		0.8	-	-	-	
			105	0.006	125	2.27E+04		0.8	3	3.75E+00	1.44E-04	
20-Feb-19	3	Stable	0	0.005	6	1.10E+03	3.80E+04	0.8	0	0.00E+00	0.00E+00	3.5
			15	0.005	0	0.00E+00		0.8	0	1.00E+00	2.63E-05	
			30	0.005	46	9.10E+03		0.8	0	1.00E+00	2.63E-05	
			45	0.005	107	2.14E+04		0.8	0	1.00E+00	2.63E-05	
			60	0.005	184	3.67E+04		0.8	56	7.00E+01	1.84E-03	
			75	0.005	297	5.93E+04		0.8	0	1.00E+00	2.63E-05	
			90	0.005	289	5.78E+04		0.8	0	1.00E+00	2.63E-05	
			105	0.005	220	4.39E+04		0.8	0	1.00E+00	2.63E-05	
20-Feb-19	4A	Stable	0	0.005	41	8.20E+03	1.98E+04	0.8	0	0.00E+00	0.00E+00	4.3
			15	0.005	31	6.10E+03		0.8	0	1.00E+00	5.04E-05	
			30	0.005	104	2.07E+04		0.8	0	1.00E+00	5.04E-05	
			45	0.005	57	1.13E+04		0.8	0	1.00E+00	5.04E-05	
			60	0.005	103	2.05E+04		0.8	0	1.00E+00	5.04E-05	
			75	0.005	100	2.00E+04		0.8	0	1.00E+00	5.04E-05	
			90	0.005	114	2.28E+04		0.8	0	1.00E+00	5.04E-05	
			105	0.005	119	2.37E+04		0.8	1	1.25E+00	6.30E-05	

08-Mar-19	3	Stable	0	0.005	177	3.53E+04	5.87E+04	0.8	0	0.00E+00	0.00E+00	3.9
			15	0.005	0	0.00E+00		0.8	0	1.00E+00	1.70E-05	
			30	0.005	8	1.50E+03		0.8	0	1.00E+00	1.70E-05	
			45	0.005	311	6.21E+04		0.8	12	1.50E+01	2.55E-04	
			60	0.005	342	6.84E+04		0.8	2	2.50E+00	4.26E-05	
			75	0.005	334	6.68E+04		0.8	18	2.25E+01	3.83E-04	
			90	0.005	382	7.63E+04		0.8	5	6.25E+00	1.06E-04	
			105	0.005	386	7.72E+04		0.8	0	1.00E+00	1.70E-05	
			0	0.005	377	7.53E+04	6.36E+04	0.8	1	1.25E+00	1.97E-05	3.6
			15	0.005	240	4.80E+04		0.8	0	1.00E+00	1.57E-05	
			30	0.005	253	5.06E+04		0.8	3	3.75E+00	5.90E-05	
			45	0.005	467	9.34E+04		0.8	33	4.13E+01	6.49E-04	
			60	0.005	303	6.06E+04		0.8	3	3.75E+00	5.90E-05	
			75	0.005	474	9.48E+04		0.8	28	3.50E+01	5.51E-04	
			90	0.005	395	7.89E+04		0.8	2	2.50E+00	3.93E-05	
			105	0.005	400	8.00E+04		0.8	0	1.00E+00	1.57E-05	
08-Mar-19	4A	Stable	0	0.005	42	8.40E+03	2.47E+04	0.8	0	0.00E+00	0.00E+00	4.2
			15	0.005	4	8.00E+02		0.8	0	1.00E+00	4.04E-05	
			30	0.005	43	8.50E+03		0.8	2	2.50E+00	1.01E-04	
			45	0.005	132	2.64E+04		0.8	2	2.50E+00	1.01E-04	
			60	0.005	208	4.15E+04		0.8	0	1.00E+00	4.04E-05	
			75	0.005	162	3.24E+04		0.8	0	1.00E+00	4.04E-05	
			90	0.005	-	-		0.8	0	1.00E+00	4.04E-05	
			105	0.005	75	1.49E+04		0.8	0	1.00E+00	4.04E-05	
26-Apr-19	3	Ripening	0	0.005	27	5.40E+03	4.33E+03	0.8	401	5.01E+02	1.16E-01	2.1
			5	0.005	90	1.79E+04		0.8	77	9.63E+01	2.22E-02	
			10	0.005	39	7.70E+03		0.8	32	4.00E+01	9.23E-03	
			15	0.005	5	1.00E+03		0.8	23	2.88E+01	6.63E-03	
			20	0.005	30	5.90E+03		0.8	83	1.04E+02	2.39E-02	
			25	0.005	26	5.10E+03		0.8	4	5.00E+00	1.15E-03	
			30	0.005	3	6.00E+02		0.8	0	1.00E+00	2.31E-04	
			0	0.005	7	1.40E+03	6.14E+03	0.8	52	6.50E+01	1.06E-02	2.6
			5	0.005	8	1.50E+03		0.8	2072	2.59E+03	4.22E-01	
			10	0.005	15	2.90E+03		0.8	18	2.25E+01	3.66E-03	
			15	0.005	43	8.60E+03		0.8	2	2.50E+00	4.07E-04	
			20	0.005	49	9.80E+03		0.8	2	2.50E+00	4.07E-04	
			25	0.005	24	4.80E+03		0.8	18	2.25E+01	3.66E-03	
			30	0.005	23	4.60E+03		0.8	15	1.88E+01	3.05E-03	
26-Mar-19	4A	Stable	0	0.005	665	1.33E+05	1.05E+04	0.8	0	0.00E+00	0.00E+00	3.2
			5	0.005	359	7.17E+04		0.8	0	1.00E+00	9.54E-05	
			10	0.005	39	7.70E+03		0.8	-	-	-	
			15	0.005	109	2.17E+04		0.8	1	1.25E+00	1.19E-04	
			20	0.005	37	7.40E+03		0.8	1	1.25E+00	1.19E-04	
			25	0.005	41	8.10E+03		0.8	3	3.75E+00	3.58E-04	
			30	0.005	38	7.50E+03		0.8	14	1.75E+01	1.67E-03	

30-May-19	3	End of run	0	0.005	481	9.62E+04	1.15E+05	0.8	1	1.25E+00	1.09E-05	3.6
			15	0.005	452	9.03E+04		0.8	2	2.50E+00	2.17E-05	
			30	0.005	525	1.05E+05		0.8	76	9.50E+01	8.25E-04	
			45	0.005	689	1.38E+05		0.8	2	2.50E+00	2.17E-05	
			60	0.005	435	8.69E+04		0.8	22	2.75E+01	2.39E-04	
			75	0.005	446	8.92E+04		0.8	11	1.38E+01	1.19E-04	
			90	0.005	649	1.30E+05		0.8	5	6.25E+00	5.43E-05	
			105	0.005	712	1.42E+05		0.8	9	1.13E+01	9.77E-05	
			0	0.005	220	4.40E+04	7.59E+04	0.8	0	0.00E+00	0.00E+00	4.0
			15	0.005	120	2.40E+04		0.8	0	1.00E+00	1.32E-05	
			30	0.005	256	5.12E+04		0.8	1	1.25E+00	1.65E-05	
			45	0.005	313	6.26E+04		0.8	7	8.75E+00	1.15E-04	
			60	0.005	462	9.24E+04		0.8	1	1.25E+00	1.65E-05	
			75	0.005	472	9.43E+04		0.8	10	1.25E+01	1.65E-04	
			90	0.005	465	9.29E+04		0.8	5	6.25E+00	8.23E-05	
			105	0.005	310	6.20E+04		0.8	9	1.13E+01	1.48E-04	
30-May-19	4A	Stable	0	0.005	600	1.20E+05	1.66E+05	0.8	-	-	-	4.7
			15	0.005	393	7.86E+04		0.8	2	2.50E+00	1.50E-05	
			30	0.005	514	1.03E+05		0.8	1	1.25E+00	7.52E-06	
			45	0.005	538	1.08E+05		0.8	6	7.50E+00	4.51E-05	
			60	0.005	856	1.71E+05		0.8	2	2.50E+00	1.50E-05	
			75	0.005	1452	2.90E+05		0.8	0	1.00E+00	6.02E-06	
			90	0.005	650	1.30E+05		0.8	-	-	-	
			105	0.005	979	1.96E+05		0.8	5	6.25E+00	3.76E-05	
02-Aug-19	3	Stable	0	0.005	19	3.80E+03	3.27E+03	0.8	13	1.63E+01	4.97E-03	0.5
			15	0.005	7	1.30E+03		0.8	2	2.50E+00	7.65E-04	
			30	0.005	7	1.30E+03		0.8	-	-	-	
			45	0.005	5	9.00E+02		0.8	460	5.75E+02	1.76E-01	
			60	0.005	7	1.30E+03		0.8	650	8.13E+02	2.49E-01	
			75	0.005	34	6.70E+03		0.8	1127	1.41E+03	4.31E-01	
			90	0.005	26	5.10E+03		0.8	536	6.70E+02	2.05E-01	
			105	0.005	22	4.30E+03		0.8	1470	1.84E+03	5.63E-01	
			0	0.005	3	6.00E+02	1.40E+04	0.8	2	2.50E+00	1.78E-04	1.4
			15	0.005	84	1.68E+04		0.8	14	1.75E+01	1.25E-03	
			30	0.005	39	7.80E+03		0.8	-	-	-	
			45	0.005	131	2.62E+04		0.8	131	1.64E+02	1.17E-02	
			60	0.005	72	1.44E+04		0.8	1846	2.31E+03	1.64E-01	
			75	0.005	30	5.90E+03		0.8	26	3.25E+01	2.32E-03	
			90	0.005	63	1.26E+04		0.8	68	8.50E+01	6.06E-03	
			105	0.005	87	1.73E+04		0.8	3	3.75E+00	2.67E-04	
13-Oct-21	3	Stable	0	0.00500	0	0.00E+00	1.85E+04	0.80000	0	0.00E+00	0.00E+00	1.10
			30	0.00500	36	7.20E+03		0.80000	31	3.88E+01	2.10E-03	
			45	0.00500	89	1.78E+04		0.80000	997	1.25E+03	6.74E-02	
			60	0.00500	72	1.44E+04		0.80000	2156	2.70E+03	1.46E-01	
			75	0.00500	166	3.32E+04		0.80000	2200	2.75E+03	1.49E-01	
			90	0.00500	99	1.98E+04		0.80000	515	6.44E+02	3.48E-02	
13-Oct-21	3	Stable	0	0.00500	0	0.00E+00	1.16E+04	0.50000	2	4.00E+00	3.46E-04	0.90
			30	0.00500	56	1.12E+04		0.50000	114	2.28E+02	1.97E-02	
			45	0.00500	52	1.04E+04		0.50000	748	1.50E+03	1.29E-01	
			60	0.00500	72	1.44E+04		0.30000	665	2.22E+03	1.92E-01	
			75	0.00500	55	1.10E+04		0.30000	652	2.17E+03	1.88E-01	
			90	0.00500	54	1.08E+04		0.30000	326	1.09E+03	9.40E-02	
13-Oct-21	2A	Stable	0	0.00500	0	0.00E+00	1.23E+04	0.50000	0	0.00E+00	0.00E+00	0.8
			30	0.00500	29	5.80E+03		0.50000	288	5.76E+02	4.69E-02	
			45	0.00500	65	1.30E+04		0.50000	553	1.11E+03	9.01E-02	
			60	0.00500	70	1.40E+04		0.30000	911	3.04E+03	2.47E-01	
			75	0.00500	64	1.28E+04		0.30000	684	2.28E+03	1.86E-01	
			90	0.00500	79	1.58E+04		0.30000	775	2.58E+03	2.10E-01	

13-Oct-21	4A	Stable	0	0.00500	0	0.00E+00	8.20E+03	0.80000	0	0.00E+00	1.52E-04	0.5
			30	0.00500	24	4.80E+03		0.80000	762	9.53E+02	1.16E-01	
			45	0.00500	73	1.46E+04		0.70000	2294	3.28E+03	4.00E-01	
			60	0.00500	21	4.20E+03		0.80000	1408	1.76E+03	2.15E-01	
			75	0.00500	35	7.00E+03		0.80000	2155	2.69E+03	3.29E-01	
			90	0.00500	52	1.04E+04		0.80000	3056	3.82E+03	4.66E-01	
10-Nov-21	3	Stable	0	0.01000	0	0.00E+00	6.22E+03	0.80000	0	1.25E+00	0.00E+00	3.6
			30	0.01000	38	3.80E+03		0.80000	1	1.25E+00	2.01E-04	
			45	0.01000	5	5.00E+02		0.80000	2	2.50E+00	4.02E-04	
			60	0.01000	78	7.80E+03		0.80000	0	1.25E+00	2.01E-04	
			75	0.01000	101	1.01E+04		0.80000	1	1.25E+00	2.01E-04	
			90	0.01000	89	8.90E+03		0.80000	0	1.25E+00	2.01E-04	
10-Nov-21	4A	Stable	0	0.01000	0	0.00E+00	2.00E+03	0.80000	0	0.00E+00	6.25E-04	2.7
			30	0.01000	12	1.20E+03		0.80000	5	6.25E+00	3.13E-03	
			45	0.01000	15	1.50E+03		0.80000	7	8.75E+00	4.38E-03	
			60	0.01000	19	1.90E+03		0.80000	0	1.25E+00	6.25E-04	
			75	0.01000	23	2.30E+03		0.80000	1	1.25E+00	6.25E-04	
			90	0.01000	31	3.10E+03		0.80000	1	1.25E+00	6.25E-04	
19-Nov-21	3	Stable	0	0.00500	0	0.00E+00	8.44E+03	0.80000	0	0.00E+00	0.00E+00	3.1
			30	0.00500	19	3.80E+03		0.80000	0	0.00E+00	1.48E-04	
			45	0.00500	43	8.60E+03		0.80000	0	0.00E+00	1.48E-04	
			60	0.00500	49	9.80E+03		0.80000	19	2.38E+01	2.81E-03	
			75	0.00500	58	1.16E+04		0.80000	1	1.25E+00	1.48E-04	
			90	0.00500	42	8.40E+03		0.80000	4	5.00E+00	5.92E-04	
19-Nov-21	3	Stable	0	0.00500	0	0.00E+00	8.00E+03	0.80000	0	0.00E+00	0.00E+00	3.5
			30	0.00500	40	8.00E+03		0.80000	6	7.50E+00	9.38E-04	
			45	0.00500	21	4.20E+03		0.80000	2	2.50E+00	3.13E-04	
			60	0.00500	47	9.40E+03		0.80000	1	1.25E+00	1.56E-04	
			75	0.00500	37	7.40E+03		0.80000	1	1.25E+00	1.56E-04	
			90	0.00500	55	1.10E+04		0.80000	1	1.25E+00	1.56E-04	
19-Nov-21	2A	Stable	0	0.00500	0	0.00E+00	7.36E+03	0.80000	0	0.00E+00	0.00E+00	3.1
			30	0.00500	22	4.40E+03		0.80000	1	1.25E+00	1.70E-04	
			45	0.00500	33	6.60E+03		0.80000	2	2.50E+00	3.40E-04	
			60	0.00500	32	6.40E+03		0.80000	5	6.25E+00	8.49E-04	
			75	0.00500	30	6.00E+03		0.80000	7	8.75E+00	1.19E-03	
			90	0.00500	67	1.34E+04		0.80000	8	1.00E+01	1.36E-03	
19-Nov-21	4A	Stable	0	0.00500	0	0.00E+00	1.26E+04	0.80000	0	0.00E+00	9.95E-05	1.0
			30	0.00500	42	8.40E+03		0.80000	546	6.83E+02	5.43E-02	
			45	0.00500	71	1.42E+04		0.80000	1106	1.38E+03	1.10E-01	
			60	0.00500	62	1.24E+04		0.80000	260	3.25E+02	2.59E-02	
			75	0.00500	50	1.00E+04		0.80000	1475	1.84E+03	1.47E-01	
			90	0.00500	89	1.78E+04		0.80000	1421	1.78E+03	1.41E-01	
19-Nov-21	4C	Stable	0	0.00500	0	0.00E+00	1.85E+04	0.80000	1	1.25E+00	6.76E-05	0.9
			30	0.00500	72	1.44E+04		0.80000	1313	1.64E+03	8.88E-02	
			45	0.00500	69	1.38E+04		0.80000	1954	2.44E+03	1.32E-01	
			60	0.00500	111	2.22E+04		0.80000	1916	2.40E+03	1.30E-01	
			75	0.00500	81	1.62E+04		0.80000	2847	3.56E+03	1.93E-01	
			90	0.00500	129	2.58E+04		0.80000	1938	2.42E+03	1.31E-01	
19-Nov-21	4C	Stable	0	0.00500	0	0.00E+00	1.75E+04	0.80000	1	1.25E+00	7.15E-05	0.9
			30	0.00500	88	1.76E+04		0.80000	1220	1.53E+03	8.72E-02	
			45	0.00500	33	6.60E+03		0.80000	1540	1.93E+03	1.10E-01	
			60	0.00500	97	1.94E+04		0.80000	2218	2.77E+03	1.59E-01	
			75	0.00500	108	2.16E+04		0.80000	2546	3.18E+03	1.82E-01	
			90	0.00500	111	2.22E+04		0.80000	2108	2.64E+03	1.51E-01	

19-Nov-21	4C	Stable	0	0.00500	0	0.00E+00	1.39E+04	0.80000	1	1.25E+00	8.98E-05	0.8
			30	0.00500	68	1.36E+04		0.80000	1220	1.53E+03	1.10E-01	
			45	0.00500	137	2.74E+04		0.80000	1540	1.93E+03	1.38E-01	
			60	0.00500	47	9.40E+03		0.80000	2218	2.77E+03	1.99E-01	
			75	0.00500	7	1.40E+03		0.80000	2546	3.18E+03	2.29E-01	
			90	0.00500	89	1.78E+04		0.80000	2108	2.64E+03	1.89E-01	
14-Dec-21	3	Stable	0	0.01000	0	0.00E+00	1.13E+04	0.60000	0	0.00E+00	0.00E+00	3.9
			30	0.01000	65	6.50E+03		0.80000	0	0.00E+00	1.11E-04	
			45	0.01000	96	9.60E+03		0.80000	0	0.00E+00	1.11E-04	
			60	0.01000	110	1.10E+04		0.80000	0	0.00E+00	1.11E-04	
			75	0.01000	140	1.40E+04		0.80000	2	2.50E+00	2.22E-04	
			90	0.01000	152	1.52E+04		0.80000	0	0.00E+00	1.11E-04	
14-Dec-21	3	Stable	0	0.02000	0	0.00E+00	1.12E+04	0.80000	0	0.00E+00	0.00E+00	4.0
			30	0.02000	102	5.10E+03		0.80000	0	0.00E+00	1.11E-04	
			45	0.02000	332	1.66E+04		0.80000	0	0.00E+00	1.11E-04	
			60	0.02000	296	1.48E+04		0.80000	0	0.00E+00	1.11E-04	
			75	0.02000	233	1.17E+04		0.80000	0	0.00E+00	1.11E-04	
			90	0.02000	160	8.00E+03		0.80000	0	0.00E+00	1.11E-04	
14-Dec-21	2A	Stable	0	0.01000	0	0.00E+00	5.54E+03	0.60000	0	0.00E+00	0.00E+00	3.0
			30	0.01000	35	3.50E+03		0.80000	0	0.00E+00	2.26E-04	
			45	0.01000	42	4.20E+03		0.80000	15	1.88E+01	3.38E-03	
			60	0.01000	76	7.60E+03		0.80000	0	0.00E+00	2.26E-04	
			75	0.01000	89	8.90E+03		0.80000	0	0.00E+00	2.26E-04	
			90	0.01000	35	3.50E+03		0.80000	4	5.00E+00	9.03E-04	
14-Dec-21	4A	Stable	0	0.01000	0	0.00E+00	1.17E+04	0.40000	0	0.00E+00	2.14E-04	3.6
			30	0.01000	93	9.30E+03		0.40000	0	2.50E+00	2.14E-04	
			45	0.01000	112	1.12E+04		0.40000	0	2.50E+00	2.14E-04	
			60	0.01000	100	1.00E+04		0.40000	0	2.50E+00	2.14E-04	
			75	0.01000	167	1.67E+04		0.40000	1	2.50E+00	2.14E-04	
			90	0.01000	113	1.13E+04		0.40000	2	5.00E+00	4.27E-04	
14-Dec-21	4C	Stable	0	0.01000	0	0.00E+00	5.20E+03	0.80000	0	0.00E+00	2.40E-04	2.9
			30	0.01000	114	5.70E+03		0.80000	0	1.25E+00	2.40E-04	
			45	0.01000	96	4.80E+03		0.80000	2	2.50E+00	4.81E-04	
			60	0.01000	109	5.45E+03		0.80000	5	6.25E+00	1.20E-03	
			75	0.01000	109	5.45E+03		0.80000	13	1.63E+01	3.13E-03	
			90	0.01000	92	4.60E+03		0.80000	6	7.50E+00	1.44E-03	
15-Dec-21	3	Stable	0	0.01000	0	0.00E+00	5.24E+03	0.60000	0	0.00E+00	0.00E+00	1.1
			30	0.01000	22	2.20E+03		0.80000	4	5.00E+00	9.54E-04	
			45	0.01000	46	4.60E+03		0.80000	427	5.34E+02	1.02E-01	
			60	0.01000	69	6.90E+03		0.80000	501	6.26E+02	1.20E-01	
			75	0.01000	40	4.00E+03		0.80000	542	6.78E+02	1.29E-01	
			90	0.01000	85	8.50E+03		0.80000	145	1.81E+02	3.46E-02	
15-Dec-21	3	Stable	0	0.01000	0	0.00E+00	6.18E+03	0.60000	0	0.00E+00	0.00E+00	1.4
			30	0.01000	67	6.70E+03		0.80000	2	2.50E+00	4.05E-04	
			45	0.01000	28	2.80E+03		0.80000	4	5.00E+00	8.09E-04	
			60	0.01000	28	2.80E+03		0.80000	1	1.25E+00	2.02E-04	
			75	0.01000	94	9.40E+03		0.80000	366	4.58E+02	7.40E-02	
			90	0.01000	92	9.20E+03		0.80000	506	6.33E+02	1.02E-01	
15-Dec-21	2A	Stable	0	0.02000	0	0.00E+00	3.12E+03	0.80000	0	0.00E+00	0.00E+00	1.1
			30	0.02000	58	2.90E+03		0.80000	1	1.25E+00	4.01E-04	
			45	0.02000	78	3.90E+03		0.80000	284	3.55E+02	1.14E-01	
			60	0.02000	36	1.80E+03		0.80000	329	4.11E+02	1.32E-01	
			75	0.02000	61	3.05E+03		0.80000	364	4.55E+02	1.46E-01	
			90	0.02000	79	3.95E+03		0.80000	93	1.16E+02	3.73E-02	

15-Dec-21	4A	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	15 53 33 131 179 119	1.50E+03 5.30E+03 3.30E+03 1.31E+04 1.79E+04 1.19E+04	1.03E+04	0.40000 0.50000 0.40000 0.40000 0.40000 0.40000	0 152 185 52 193 136	0.00E+00 3.04E+02 4.63E+02 1.30E+02 4.83E+02 3.40E+02	2.43E-04 2.95E-02 4.49E-02 1.26E-02 4.68E-02 3.30E-02	1.5
15-Dec-21	4C	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	15 15 7 70 33 98	1.50E+03 1.50E+03 7.00E+02 7.00E+03 3.30E+03 9.80E+03	4.46E+03	0.40000 0.50000 0.50000 0.40000 0.50000 0.40000	0 12 184 56 152 149	0.00E+00 2.40E+01 3.68E+02 1.40E+02 3.04E+02 3.73E+02	5.61E-04 5.38E-03 8.25E-02 3.14E-02 6.82E-02 8.35E-02	1.3
16-Dec-21	3	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 38 62 49 33 209	0.00E+00 3.80E+03 6.20E+03 4.90E+03 3.30E+03 2.09E+04	7.82E+03	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 25 37 15 2 5	0.00E+00 3.13E+01 4.63E+01 1.88E+01 2.50E+00 6.25E+00	0.00E+00 4.00E-03 5.91E-03 2.40E-03 3.20E-04 7.99E-04	2.6
16-Dec-21	3	Stable	0 30 45 60 75 90	0.02000 0.02000 0.02000 0.02000 0.02000 0.02000	0 48 96 2 78 189	0.00E+00 2.40E+03 4.80E+03 1.00E+02 3.90E+03 9.45E+03	4.13E+03	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 4 28 3 59 3	0.00E+00 5.00E+00 3.50E+01 3.75E+00 7.38E+01 3.75E+00	0.00E+00 1.21E-03 8.47E-03 9.08E-04 1.79E-02 9.08E-04	2.2
16-Dec-21	2A	Stable	0 30 45 60 75 90	0.02000 0.02000 0.02000 0.02000 0.02000 0.02000	0 79 61 97 69 68	0.00E+00 3.95E+03 3.05E+03 4.85E+03 3.45E+03 3.40E+03	3.74E+03	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 7 2 14 38 0	0.00E+00 8.75E+00 2.50E+00 1.75E+01 4.75E+01 0.00E+00	0.00E+00 2.34E-03 6.68E-04 4.68E-03 1.27E-02 3.34E-04	2.4
16-Dec-21	4A	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	6 92 56 151 179 42	6.00E+02 9.20E+03 5.60E+03 1.51E+04 1.79E+04 4.20E+03	1.04E+04	0.40000 0.40000 0.40000 0.40000 0.40000 0.40000	0 40 10 149 94 127	0.00E+00 1.00E+02 2.50E+01 3.73E+02 2.35E+02 3.18E+02	2.40E-04 9.62E-03 2.40E-03 3.58E-02 2.26E-02 3.05E-02	1.7
16-Dec-21	4C	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	6 54 112 113 118 129	6.00E+02 5.40E+03 1.12E+04 1.13E+04 1.18E+04 1.29E+04	1.05E+04	0.40000 0.40000 0.40000 0.40000 0.40000 0.40000	0 27 0 34 32 2	0.00E+00 6.75E+01 0.00E+00 8.50E+01 8.00E+01 5.00E+00	2.38E-04 6.42E-03 2.38E-04 8.08E-03 7.60E-03 4.75E-04	2.3
16-Dec-21	3	Stable	0 30 45 60 75 90	0.01000 0.01000 0.01000 0.01000 0.01000 0.01000	0 70 83 132 118 79	0.00E+00 7.00E+03 8.30E+03 1.32E+04 1.18E+04 7.90E+03	9.64E+03	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 5 6 3 1 0	0.00E+00 6.25E+00 7.50E+00 3.75E+00 1.25E+00 0.00E+00	0.00E+00 6.48E-04 7.78E-04 3.89E-04 1.30E-04 1.30E-04	3.4
16-Dec-21	3	Stable	0 30 45 60 75 90	0.02000 0.02000 0.02000 0.02000 0.02000 0.02000	0 67 12 64 3 17	0.00E+00 3.35E+03 6.00E+02 3.20E+03 1.50E+02 8.50E+02	1.63E+03	0.80000 0.80000 0.80000 0.80000 0.80000 0.80000	0 2 0 4 3 6	0.00E+00 2.50E+00 0.00E+00 5.00E+00 3.75E+00 7.50E+00	0.00E+00 1.53E-03 7.67E-04 3.07E-03 2.30E-03 4.60E-03	2.6

16-Dec-21	2A	Stable	0	0.01000	0	0.00E+00	5.44E+03	0.80000	0	0.00E+00	0.00E+00	3.4
			30	0.01000	19	1.90E+03		0.80000	0	0.00E+00	2.30E-04	
			45	0.01000	128	1.28E+04		0.80000	4	5.00E+00	9.19E-04	
			60	0.01000	83	8.30E+03		0.80000	0	0.00E+00	2.30E-04	
			75	0.01000	26	2.60E+03		0.80000	0	0.00E+00	2.30E-04	
			90	0.01000	16	1.60E+03		0.80000	1	1.25E+00	2.30E-04	
16-Dec-21	4A	Stable	0	0.01000	14	1.40E+03	4.98E+03	0.40000	0	0.00E+00	5.02E-04	2.4
			30	0.01000	29	2.90E+03		0.40000	6	1.50E+01	3.01E-03	
			45	0.01000	95	9.50E+03		0.40000	7	1.75E+01	3.51E-03	
			60	0.01000	55	5.50E+03		0.40000	1	2.50E+00	5.02E-04	
			75	0.01000	23	2.30E+03		0.40000	18	4.50E+01	9.04E-03	
			90	0.01000	47	4.70E+03		0.40000	6	1.50E+01	3.01E-03	
16-Dec-21	4C	Stable	0	0.01000	14	1.40E+03	7.54E+03	0.40000	0	0.00E+00	3.32E-04	2.8
			30	0.01000	66	6.60E+03		0.40000	2	5.00E+00	6.63E-04	
			45	0.01000	56	5.60E+03		0.40000	7	1.75E+01	2.32E-03	
			60	0.01000	24	2.40E+03		0.40000	4	1.00E+01	1.33E-03	
			75	0.01000	122	1.22E+04		0.40000	6	1.50E+01	1.99E-03	
			90	0.01000	109	1.09E+04		0.40000	3	7.50E+00	9.95E-04	
04-Mar-22	3	Hydraulic surge	0	0.02000	2	1.00E+00	4.62E+03	0.80000	0	0.00E+00	0.00E+00	2.7
			30	0.02000	111	5.55E+03		0.80000	12	1.50E+01	3.25E-03	
			45	0.02000	156	7.80E+03		0.80000	3	3.75E+00	8.12E-04	
			60	0.02000	93	4.65E+03		0.80000	11	1.38E+01	2.98E-03	
			75	0.02000	59	2.95E+03		0.80000	0	0.00E+00	2.71E-04	
			90	0.02000	43	2.15E+03		0.80000	10	1.25E+01	2.71E-03	
04-Mar-22	3	Hydraulic surge	0	0.02000	2	1.00E+02	5.54E+03	0.80000	0	0.00E+00	0.00E+00	3.3
			30	0.02000	28	1.40E+03		0.80000	6	7.50E+00	1.35E-03	
			45	0.02000	107	5.35E+03		0.80000	2	2.50E+00	4.51E-04	
			60	0.02000	123	6.15E+03		0.80000	0	0.00E+00	2.26E-04	
			75	0.02000	152	7.60E+03		0.80000	2	2.50E+00	4.51E-04	
			90	0.02000	144	7.20E+03		0.80000	0	0.00E+00	2.26E-04	
12-Apr-22	3	Stable	0	0.10000	0	0.00E+00	1.06E+04	0.80000	0	0.00E+00	0.00E+00	3.5
			30	0.10000	717	7.17E+03		0.80000	4	5.00E+00	4.70E-04	
			45	0.10000	1107	1.11E+04		0.80000	0	0.00E+00	1.18E-04	
			60	0.10000	1210	1.21E+04		0.80000	3	3.75E+00	3.53E-04	
			75	0.10000	649	6.49E+03		0.80000	1	1.25E+00	1.18E-04	
			90	0.10000	1633	1.63E+04		0.80000	5	6.25E+00	5.88E-04	
12-Apr-22	3	Stable	0	0.10000	0	0.00E+00	4.38E+03	0.80000	0	0.00E+00	0.00E+00	3.1
			30	0.10000	130	1.30E+03		0.80000	3	3.75E+00	8.55E-04	
			45	0.10000	142	1.42E+03		0.80000	0	0.00E+00	2.85E-04	
			60	0.10000	328	3.28E+03		0.80000	5	6.25E+00	1.43E-03	
			75	0.10000	1354	1.35E+04		0.80000	1	1.25E+00	2.85E-04	
			90	0.10000	238	2.38E+03		0.80000	3	3.75E+00	8.55E-04	
12-Apr-22	2A	Stable	0	0.10000	0	0.00E+00	5.83E+03	0.80000	0	0.00E+00	0.00E+00	3.2
			30	0.10000	253	2.53E+03		0.80000	1	1.25E+00	2.14E-04	
			45	0.10000	199	1.99E+03		0.80000	1	1.25E+00	2.14E-04	
			60	0.10000	526	5.26E+03		0.80000	5	6.25E+00	1.07E-03	
			75	0.10000	1083	1.08E+04		0.80000	7	8.75E+00	1.50E-03	
			90	0.10000	856	8.56E+03		0.80000	2	2.50E+00	4.29E-04	

Appendix G

Bench-scale investigations on zeta potential

A bench-scale experiment was conducted as part of this study to investigate potential variations in zeta potential during the drinking water treatment process. In full-scale systems, coagulated water may require several hours to travel from the sedimentation basin to the filter media, during which water quality and coagulant speciation can evolve significantly. To evaluate this, varying doses of alum coagulant (0, 25, and 40 mg/L) were added to raw water collected from the pilot plant and stirred continuously in a jar test apparatus. Zeta potential measurements were taken at 30-minute intervals over a five-hour period, following the procedures described in Section 2.4 of this paper, to assess changes in particle destabilization over time after coagulant addition. The raw data collected from this bench-scale experiment are presented in Table F.1, and the results were used to generate Figure 4.5 in the main body of the paper.

Table G.1. Zeta potential variations over time for different alum doses.

Time (min)	0 mg/L	25 mg/L	40 mg/L
	Zeta potential (mV)		
0	-15.13	-2.15	1.52
30	-16.17	-3.59	-1.33
60	-15.43	-4.68	-3.92
120	-14.77	-5.99	-4.83
180	-15.43	-6.28	-5.12
240	-14.90	-7.25	-7.15
300	-16.53	-6.71	-6.36

Appendix H

Effective log removal values for direct in-line CAF experiments in Figure 4.2

Figure 4.2 in the main body of the thesis illustrates the removal of *Cryptosporidium* oocysts by pilot-scale direct in-line CAF. Because of the amount of data presented, the effective log reduction values were not shown directly on the figure. Table G.1 in this appendix summarizes the corresponding log removal values for all boxplots in Figure 4.2, from the lowest zeta potential (farthest from 0 mV) to the highest zeta potential (closest to 0 mV), which matches the left-to-right arrangement of the boxplots.

Table H.1. Effective log removals calculated for only data represented in Figure 4.2 in Chapter 3.

Particle destabilization condition	Filter configuration	Zeta potential (mV)	Effective log removal (log)
Sub-optimal	3-1	-15.8	2.8
	3-2		2.8
	2A		2.7
Sub-optimal	3-1	-11.4	3.8
	2A		4
Sub-optimal	3-1	-11.3	2.7
	3-2		3.1
	2A		2.8
Sub-optimal	3-1	-9.4	4.6
	3-2		4.6
	2A		4.2
Sub-optimal	3-1	-8.9	3.9
	3-2		3.6
	2A		3.6
Optimal	3-1	-4.9	4.8
	3-2		4.5
Optimal	3-1	-4.6	5.2
	3-2		5.2
	2A		4.8
Optimal	2A	-4.6	5.1
Optimal	3-1	-2.3	4.3
	3-2		4.9
	2A		4.6

Appendix I

Individual CAF removal results for Figure 4.3 and Figure 4.4

The following plots illustrate the removal observed for each individual filter (i.e., Filters 3-1, 3-2, and 2A). Figures 4.3 and 4.4 in the main body of the paper present the combined removal results for Filters 3-1 and 3-2. In the figures below, this information is reproduced to show the performance of Filters 3-1 and 3-2 separately. This was done to demonstrate that the removal observed for the two filters was similar, with no significant variations, confirming that inter-column variability was minimal. Any differences observed were within 1-log, which is consistent with the variability typically observed in experiments of this type (as explained in Chapter 4 section 4.3.2)

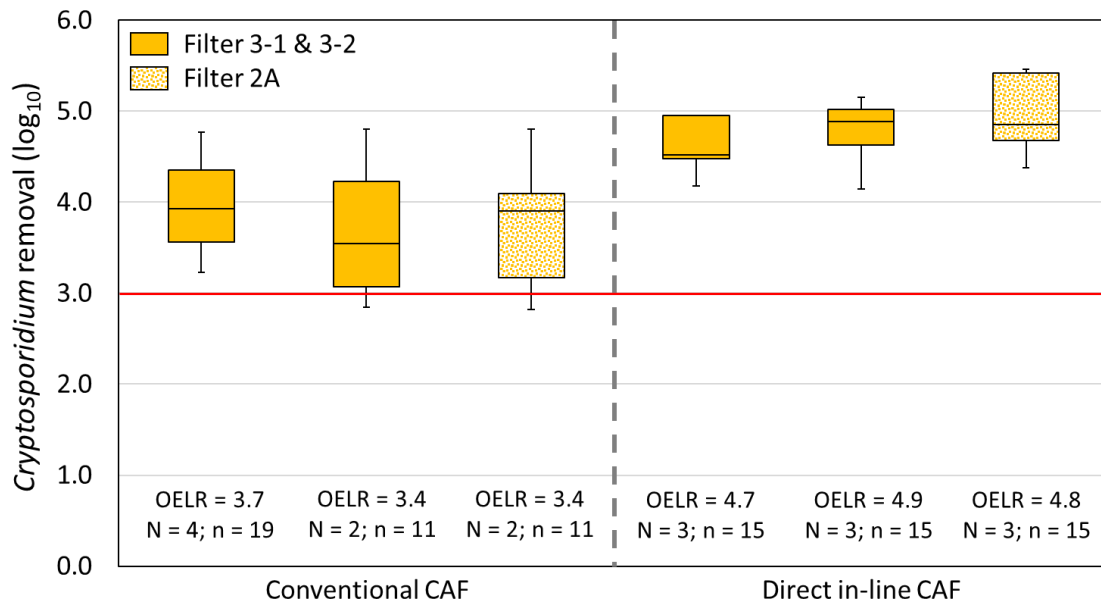


Figure I.1. Comparison of *Cryptosporidium* oocyst removal by pilot-scale conventional and direct in-line CAF with high concentrations of optimally destabilized oocysts added to filter influent streams to show removal achieved by each of the three filters. Each box plot summarizes data from multiple experiments, where N signifies the count of individual filter runs/experiments, and n denotes the number of filter effluent samples considered. The effective log reduction, a logarithmically expressed average of reduction or passage rates, is additionally indicated for each box plot as overall effective log reduction (OELR; Schmidt et al., 2020). The pattern-filled box plots indicated Filter 2A and solid-filled boxplots indicate duplicate Filters 3-1 and 3-2.

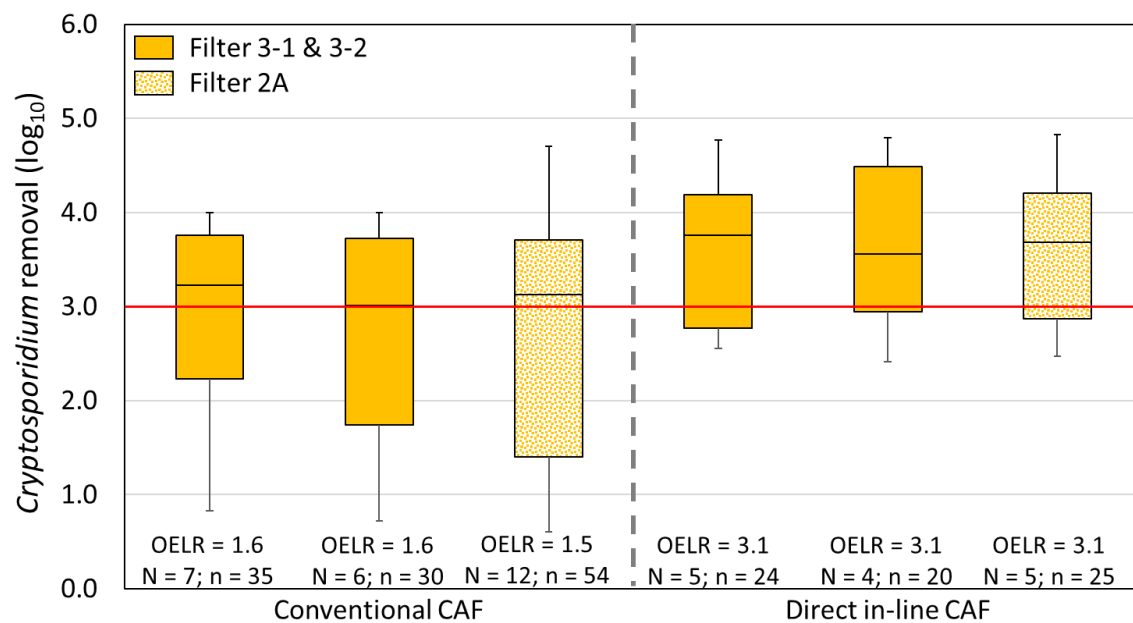


Figure I.2. Comparison of *Cryptosporidium* oocyst removal by pilot-scale conventional and direct in-line CAF with high concentrations of sub-optimally destabilized oocysts added to filter influent streams to show removal achieved by each of the three filters. Each box plot summarizes data from multiple experiments, where N signifies the count of individual filter runs/experiments, and n denotes the number of filter effluent samples considered. The effective log reduction, a logarithmically expressed average of reduction or passage rates, is additionally indicated for each box plot as overall effective log reduction (OEHR; Schmidt et al., 2020). The pattern-filled box plots indicated Filter 2A and solid-filled boxplots indicate duplicate Filters 3-1 and 3-2.

Appendix J

Raw data for Chapter 4

Table J.1. Raw water quality, pilot plant operational data, seed suspension data, and average *Cryptosporidium* oocyst removal for Chapter 4.

Date	Raw Water Quality				Pilot Plant Coagulation			Oocyst Seed Suspension Coagulation			Pilot Plant CAF	
	Temperature (°C)	Turbidity (NTU)	pH	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Zeta Potential (mV)	Filter Configuration	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
13-Sep-22	21.5	0.6	8.4	-14.0	alum	9.0	-8.9	alum	10.0	-11.4	3-1 2A	3.8 4.0
12-Oct-22	6.4	0.2	7.8	-4.5	alum	9.0	-11.3	alum	10.0	-9.4	3-1 3-2 2A	4.6 4.6 4.2
25-Oct-22	6.4	0.2	8.0	-9.2	alum	4.0	-15.3	alum	41.0	-4.5	3-1 3-2 2A	5.2 5.1 4.8
25-Oct-22	6.4	0.2	8.0	-8.9	alum	4.0	-15.5	alum	10.0	-15.9	3-1 3-2 2A	2.8 2.8 2.7
22-Nov-22	5.4	0.5	7.9	-8.3	alum	4.0	-13.9	alum	6.0	-11.3	3-1 3-2 2A	2.7 3.1 2.8
29-Nov-22	4.6	0.2	8.0	-5.9	alum	5.0	-12.0	alum	5.0	-8.9	3-1 3-2 2A	3.9 3.6 3.6
07-Feb-23	3.1	0.2	8.1	-10.7	alum	4.0	-17.2	alum	42.5	-4.6	2A	5.2
18-Apr-23	4.3	0.2	8.2	-10.8	alum	4.0	-14.0	alum	45.0	-5.0	3-1 3-2	4.8 4.5
03-May-23	5.1	0.1	8.2	-9.6	alum	40.0	-1.9	alum	4.0	-15.1	3-1 3-2 2A	5.0 4.9 4.7
24-May-23	6.1	0.2	8.2	-11.4	alum	40.0	-2.7	alum	45.0	-4.9	3-1 3-2 2A	4.6 4.9 5.0
23-Jul-24	11.5	0.4	8.0	-16.6	alum	5.0	-14.8	alum	57.5	-2.3	3-1 3-2 2A	4.3 4.9 4.6
30-Jul-24	17.1	0.7	8.4	-8.5	alum	40.0	-3.4	alum	62.5	-3.6	3-1 3-2 2A	4.6 5.0 4.8

31-Jul-24	17.2	0.5	8.4	-10.5	alum	40.0	-1.7	alum	5.0	-13.0	3-1 3-2 2A	4.9 4.9 4.9
20-Aug-24	18.9	0.8	8.4	-16.2	alum	40.0	-3.1	alum	62.5	-3.5	3-1 3-2 2A	5.1 5.3 5.2
21-Aug-24	19.2	0.6	8.5	-18.5	alum	40.0	-3.3	alum	5.0	-16.8	3-1 3-2 2A	4.2 4.2 4.2
11-Feb-25	2.8	0.2	8.1	-7.4	No coagulant	0.0	-9.5	alum	40.0	-5.0	3-1 3-2 2A	4.2 4.3 4.1
12-Feb-25	2.7	0.2	8.1	-8.0	alum	43.0	-1.6	No coagulant	0.0	-8.7	3-1 3-2 2A	4.8 5.2 5.0
12-Mar-25	2.5	0.2	8.1	-10.2	No coagulant	0.0	-10.7	alum	40.0	-4.7	3-1 3-2 2A	4.2 4.3 4.1
18-Mar-25	3.2	0.2	8.2	-8.5	alum	43.0	-3.7	alum	0.0	-10.4	3-1 3-2 2A	4.8 5.0 4.8
02-Apr-25	3.2	0.2	8.2	-9.5	alum	43.0	0.0	No coagulant	0.0	-11.3	3-1 3-2 2A	4.4 4.1 3.8
08-Apr-25	3.5	0.3	8.2	-11.8	No coagulant	0.0	-12.1	alum	40.0	-4.7	3-1 3-2 2A	4.2 4.3 4.4
09-Apr-25	3.3	0.2	8.2	-9.5	No coagulant	0.0	-9.7	No coagulant	0.0	-10.8	3-1 3-2 2A	-0.3 -0.3 -0.3

Table J.2. Detailed *Cryptosporidium* oocyst removal data for Chapter 4. For any counts with a zero (ND) (except for T0) a count of one was assigned as a conservative adjustment. This change for NDs is reflected in the “Filter Effluent *Cryptosporidium* (oocysts/L)” column. All experiments were conducted during stable operation.

Date	Pilot Plant CAF										
	Filter Configuration	Sample Time (min)	Filter Influent Sample Volume (L)	Filter Influent <i>Cryptosporidium</i> (# oocysts)	Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Average Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Filter Effluent Sample Volume (L)	Filter Effluent <i>Cryptosporidium</i> (# oocysts)	Filter Effluent <i>Cryptosporidium</i> (oocysts/L)	<i>Cryptosporidium</i> Removal (%)	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
13-Sep-22	3-1	0	0.005	1	2.00E+02	4.62E+04	0.54	0	0.00E+00	0.00E+00	3.8
		15	0.005	62	1.24E+04		0.54	5	9.26E+00	2.00E-04	
		30	0.005	265	5.30E+04		0.54	3	5.56E+00	1.20E-04	
		45	0.005	178	3.56E+04		0.54	-	-	-	
		60	0.005	311	6.22E+04		0.54	4	7.41E+00	1.60E-04	
		75	0.005	250	5.00E+04		0.54	3	5.56E+00	1.20E-04	
		90	0.005	266	5.32E+04		0.54	3	5.56E+00	1.20E-04	
		105	0.005	147	2.94E+04		0.54	0	1.85E+00	4.01E-05	
13-Sep-22	2A	0	0.01	0	0.00E+00	5.36E+04	0.54	0	0.00E+00	0.00E+00	4.0
		15	0.01	249	2.49E+04		0.54	1	1.85E+00	3.12E-05	
		30	0.01	481	4.81E+04		0.54	6	1.11E+01	1.87E-04	
		45	0.01	558	5.58E+04		0.54	6	1.11E+01	1.87E-04	
		60	0.01	834	8.34E+04		0.54	2	3.70E+00	6.24E-05	
		75	0.01	540	5.40E+04		0.54	2	3.70E+00	6.24E-05	
		90	0.01	553	5.53E+04		0.54	1	1.85E+00	3.12E-05	
12-Oct-22	3-1	0	0.003	0	0.00E+00	1.08E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.003	173	5.77E+04		0.54	1	1.85E+00	1.70E-05	
		25	0.003	249	8.30E+04		0.54	0	1.85E+00	1.70E-05	
		35	0.003	338	1.13E+05		0.54	0	1.85E+00	1.70E-05	
		45	0.003	343	1.14E+05		0.54	1	1.85E+00	1.70E-05	
		55	0.003	358	1.19E+05		0.54	2	3.70E+00	3.41E-05	
		65	0.003	339	1.13E+05		0.54	1	1.85E+00	1.70E-05	
		75	0.003	192	6.40E+04		0.54	1	1.85E+00	1.70E-05	
12-Oct-22	3-2	0	0.003	0	0.00E+00	1.15E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.003	141	4.70E+04		0.54	0	1.85E+00	1.61E-05	
		25	0.003	260	8.67E+04		0.54	1	1.85E+00	1.61E-05	
		35	0.003	325	1.08E+05		0.54	2	3.70E+00	3.23E-05	
		45	0.003	332	1.11E+05		0.54	1	1.85E+00	1.61E-05	
		55	0.003	458	1.53E+05		0.54	2	3.70E+00	3.23E-05	
		65	0.003	3	1.00E+03		0.54	0	1.85E+00	1.61E-05	
		75	0.003	0	0.00E+00		0.54	1	1.85E+00	1.61E-05	
12-Oct-22	2A	0	0.003	0	0.00E+00	1.08E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.003	130	4.33E+04		0.54	1	1.85E+00	1.70E-05	
		25	0.003	190	6.33E+04		0.54	3	5.56E+00	5.12E-05	
		35	0.003	357	1.19E+05		0.54	4	7.41E+00	6.83E-05	
		45	0.003	347	1.16E+05		0.54	5	9.26E+00	8.54E-05	
		55	0.003	350	1.17E+05		0.54	4	7.41E+00	6.83E-05	
		65	0.003	381	1.27E+05		0.54	2	3.70E+00	3.41E-05	
		75	0.003	191	6.37E+04		0.54	2	3.70E+00	3.41E-05	

25-Oct-22	3-1	0	0.003	0	0.00E+00	1.93E+05	0.714	0	0.00E+00	0.000E+00	5.1
		15	0.003	330	1.10E+05		0.714	0	1.40E+00	1.707E-05	
		25	0.003	505	1.68E+05		1.1904	0	8.40E-01	1.707E-05	
		35	0.003	530	1.77E+05		1.1904	1	8.40E-01	1.707E-05	
		45	0.003	705	2.35E+05		0.714	0	1.40E+00	1.707E-05	
		55	0.003	757	2.52E+05		0.714	0	1.40E+00	3.415E-05	
		65	0.003	401	1.34E+05		0.714	2	2.80E+00	1.707E-05	
		75	0.003	286	9.53E+04		0.714	2	2.80E+00	1.707E-05	
25-Oct-22	3-2	0	0.003	0	0.00E+00	2.05E+05	0.714	0	0.00E+00	0.000E+00	5.1
		15	0.003	305	1.02E+05		0.714	0	1.40E+00	1.616E-05	
		25	0.003	511	1.70E+05		1.1904	1	8.40E-01	1.616E-05	
		35	0.003	818	2.73E+05		1.1904	1	8.40E-01	3.232E-05	
		45	0.003	542	1.81E+05		0.714	2	2.80E+00	1.616E-05	
		55	0.003	664	2.21E+05		0.714	1	1.40E+00	3.232E-05	
		65	0.003	540	1.80E+05		0.714	2	2.80E+00	1.616E-05	
		75	0.003	172	5.73E+04		0.714	0	1.40E+00	1.616E-05	
25-Oct-22	2A	0	0.003	0	0.00E+00	1.98E+05	0.714	0	0.00E+00	0.000E+00	4.9
		15	0.003	194	6.47E+04		0.714	2	2.80E+00	1.709E-05	
		25	0.003	540	1.80E+05		1.1904	1	8.40E-01	5.128E-05	
		35	0.003	823	2.74E+05		1.1904	5	4.20E+00	6.838E-05	
		45	0.003	381	1.27E+05		0.714	3	4.20E+00	8.547E-05	
		55	0.003	581	1.94E+05		0.714	0	1.40E+00	6.838E-05	
		65	0.003	4	1.33E+03		0.714	4	5.60E+00	3.419E-05	
		75	0.003	2	6.67E+02		0.714	2	2.80E+00	3.419E-05	
25-Oct-22	3-1	0	0.003	0	0.00E+00	7.88E+04	0.714	0	0.00E+00	0.000E+00	2.7
		15	0.003	200	6.67E+04		0.714	16	2.24E+01	2.844E-04	
		25	0.004	387	9.68E+04		1.1904	116	9.74E+01	1.237E-03	
		35	0.004	138	3.45E+04		1.1904	167	1.40E+02	1.781E-03	
		45	0.003	320	1.07E+05		0.714	158	2.21E+02	2.809E-03	
		55	0.003	333	1.11E+05		0.714	121	1.69E+02	2.151E-03	
		65	0.003	135	4.50E+04		0.714	99	1.39E+02	1.760E-03	
		75	0.003	80	2.67E+04		0.714	46	6.44E+01	8.178E-04	
25-Oct-22	3-2	0	0.003	0	0.00E+00	5.91E+04	0.714	0	0.00E+00	0.000E+00	2.6
		15	0.003	240	8.00E+04		0.714	10	1.40E+01	2.370E-04	
		25	0.004	272	6.80E+04		1.1904	88	7.39E+01	1.251E-03	
		35	0.004	215	5.38E+04		1.1904	92	7.73E+01	1.308E-03	
		45	0.003	292	9.73E+04		0.714	164	2.30E+02	3.888E-03	
		55	0.003	151	5.03E+04		0.714	154	2.16E+02	3.651E-03	
		65	0.003	78	2.60E+04		0.714	66	9.24E+01	1.565E-03	
		75	0.003	65	2.17E+04		0.714	3	4.20E+00	7.111E-05	
25-Oct-22	2A	0	0.003	0	0.00E+00	7.90E+04	0.714	0	0.00E+00	0.000E+00	2.7
		15	0.003	140	4.67E+04		0.714	44	6.16E+01	7.804E-04	
		25	0.004	181	4.53E+04		1.1904	140	1.18E+02	1.489E-03	
		35	0.004	309	7.73E+04		1.1904	264	2.22E+02	2.808E-03	
		45	0.003	347	1.16E+05		0.714	191	2.68E+02	3.388E-03	
		55	0.003	350	1.17E+05		0.714	141	1.97E+02	2.501E-03	
		65	0.003	120	4.00E+04		0.714	17	2.38E+01	3.015E-04	
		75	0.003	44	1.47E+04		0.714	21	2.94E+01	3.725E-04	

22-Nov-22	3-1	0	0.003	0	0.00E+00	7.45E+04	0.54	0	0.00E+00	0.000E+00	2.7
		15	0.003	122	4.07E+04		0.54	38	7.04E+01	9.441E-04	
		25	0.003	139	4.63E+04		1.08	183	1.69E+02	2.273E-03	
		35	0.003	201	6.70E+04		1.08	122	1.13E+02	1.516E-03	
		45	0.003	190	6.33E+04		0.54	65	1.20E+02	1.615E-03	
		55	0.003	243	8.10E+04		0.54	68	1.26E+02	1.690E-03	
		65	0.003	345	1.15E+05		0.54	75	1.39E+02	1.863E-03	
		75	0.003	87	2.90E+04		0.54	40	7.41E+01	9.938E-04	
22-Nov-22	3-2	0	0.003	0	0.00E+00	8.73E+04	0.54	0	0.00E+00	0.000E+00	3.1
		15	0.003	118	3.93E+04		0.54	29	5.37E+01	6.155E-04	
		25	0.003	178	5.93E+04		1.08	105	9.72E+01	1.114E-03	
		35	0.003	216	7.20E+04		1.08	87	8.06E+01	9.233E-04	
		45	0.003	300	1.00E+05		0.54	39	7.22E+01	8.278E-04	
		55	0.003	353	1.18E+05		0.54	21	3.89E+01	4.457E-04	
		65	0.003	354	1.18E+05		0.54		1.85E+00	2.122E-05	
		75	0.003	125	4.17E+04		0.54		1.85E+00	2.122E-05	
22-Nov-22	2A	0	0.003	0	0.00E+00	1.25E+05	0.54	0	0.00E+00	0.000E+00	2.8
		15	0.003	134	4.47E+04		0.54	58	1.07E+02	8.570E-04	
		25	0.003	352	1.17E+05		1.08	195	1.81E+02	1.441E-03	
		35	0.003	326	1.09E+05		1.08	167	1.55E+02	1.234E-03	
		45	0.003	446	1.49E+05		0.54	92	1.70E+02	1.359E-03	
		55	0.003	380	1.27E+05		0.54	126	2.33E+02	1.862E-03	
		65	0.003	188	6.27E+04		0.54		1.85E+00	1.478E-05	
		75	0.003	156	5.20E+04		0.54	46	8.52E+01	6.797E-04	
29-Nov-22	3-1	0	0.004	0	0.00E+00	7.72E+04	0.54	0	0.00E+00	0.000E+00	3.9
		15	0.004	420	1.05E+05		0.54	2	3.70E+00	4.799E-05	
		25	0.004	234	5.85E+04		1.08	18	1.67E+01	2.159E-04	
		35	0.004	340	8.50E+04		1.08	16	1.48E+01	1.919E-04	
		45	0.004	357	8.93E+04		0.54	5	9.26E+00	1.200E-04	
		55	0.004	366	9.15E+04		0.54	3	5.56E+00	7.198E-05	
		65	0.003	185	6.17E+04		0.54	2	3.70E+00	4.799E-05	
		75	0.003	63	2.10E+04		0.54	0	1.85E+00	2.399E-05	
29-Nov-22	3-2	0	0.004	0	0.00E+00	9.98E+04	0.54	0	0.00E+00	0.000E+00	3.7
		15	0.004	263	6.58E+04		0.54	8	1.48E+01	1.485E-04	
		25	0.004	187	4.68E+04		1.08	22	2.04E+01	2.042E-04	
		35	0.004	434	1.09E+05		1.08	28	2.59E+01	2.599E-04	
		45	0.004	563	1.41E+05		0.54	8	1.48E+01	1.485E-04	
		55	0.004	438	1.10E+05		0.54	16	2.96E+01	2.970E-04	
		65	0.003	280	9.33E+04		0.54	3	5.56E+00	5.569E-05	
		75	0.003	55	1.83E+04		0.54	10	1.85E+01	1.856E-04	
29-Nov-22	2A	0	0.004	0	0.00E+00	6.19E+04	0.54	0	0.00E+00	0.000E+00	3.6
		15	0.004	145	3.63E+04		0.54	0	1.85E+00	2.992E-05	
		25	0.004	195	4.88E+04		1.08	22	2.04E+01	3.291E-04	
		35	0.004	239	5.98E+04		1.08	27	2.50E+01	4.039E-04	
		45	0.004	360	9.00E+04		0.54	8	1.48E+01	2.393E-04	
		55	0.004	321	8.03E+04		0.54	7	1.30E+01	2.094E-04	
		65	0.004	123	3.08E+04		0.54	2	3.70E+00	5.983E-05	
		75	0.004	105	2.63E+04		0.54		1.85E+00	2.992E-05	

07-Feb-23	2A	0	0.003	0	0.00E+00	5.37E+05	0.54	0	0.00E+00	0.000E+00	5.4
		15	0.003	231	7.70E+04		0.54	2	3.70E+00	6.899E-06	
		25	0.003	361	1.20E+05		0.54	1	1.85E+00	3.450E-06	
		35	0.003	2361	7.87E+05		0.54	0	1.85E+00	3.450E-06	
		45	0.003	1400	4.67E+05		0.54	2	3.70E+00	6.899E-06	
		55	0.003	2320	7.73E+05		0.54	1	1.85E+00	3.450E-06	
		65	0.003	-	-		0.54	-	-	-	
18-Apr-23	3-1	0	0.005	0	0.00E+00	1.67E+05	0.54	0	0.00E+00	0.000E+00	5.0
		15	0.003	352	1.17E+05		0.54	3	5.56E+00	3.327E-05	
		25	0.003	430	1.43E+05		0.54	0	1.85E+00	1.109E-05	
		35	0.003	496	1.65E+05		0.54	1	1.85E+00	1.109E-05	
		45	0.003	397	1.32E+05		0.54	0	1.85E+00	1.109E-05	
		55	0.003	681	2.27E+05		0.54	0	1.85E+00	1.109E-05	
		65	0.003	89	2.97E+04		0.54	0	1.85E+00	1.109E-05	
18-Apr-23	3-2	0	0.005	0	0.00E+00	2.61E+05	0.54	0	0.00E+00	0.000E+00	4.6
		15	0.005	578	1.16E+05		0.54	8	1.48E+01	5.680E-05	
		25	0.005	1030	2.06E+05		0.54	1	1.85E+00	7.100E-06	
		35	0.003	1180	3.93E+05		0.54	10	1.85E+01	7.100E-05	
		45	0.003	514	1.71E+05		0.54	1	1.85E+00	7.100E-06	
		55	0.003	818	2.73E+05		0.54	0	1.85E+00	7.100E-06	
		65	0.003	208	6.93E+04		0.54	0	1.85E+00	7.100E-06	
03-May-23	3-1	0	0.003	0	0.00E+00	2.24E+05	0.54	0	0.00E+00	0.000E+00	5.1
		15	0.002	274	1.37E+05		0.54	0	1.85E+00	8.276E-06	
		25	0.002	462	2.31E+05		0.54	1	1.85E+00	8.276E-06	
		35	0.002	524	2.62E+05		0.54	0	1.85E+00	8.276E-06	
		45	0.002	407	2.04E+05		0.54	1	1.85E+00	8.276E-06	
		55	0.002	397	1.99E+05		0.54	0	1.85E+00	8.276E-06	
		65	0.002	50	2.50E+04		0.54	0	1.85E+00	8.276E-06	
03-May-23	3-2	0	0.003	0	0.00E+00	2.17E+05	0.54	0	0.00E+00	0.000E+00	4.9
		15	0.002	272	1.36E+05		0.54	0	1.85E+00	8.526E-06	
		25	0.003	541	1.80E+05		0.54	1	1.85E+00	8.526E-06	
		35	0.002	471	2.36E+05		0.54	1	1.85E+00	8.526E-06	
		45	0.001	226	2.26E+05		0.54	0	1.85E+00	8.526E-06	
		55	0.002	454	2.27E+05		0.54	3	5.56E+00	2.558E-05	
		65	0.003	43	1.43E+04		0.54	3	5.56E+00	2.558E-05	
03-May-23	2A	0	0.005	0	0.00E+00	1.22E+05	0.54	0	0.00E+00	0.000E+00	4.8
		15	0.005	160	3.20E+04		0.54	0	1.85E+00	1.517E-05	
		25	0.005	407	8.14E+04		0.54	0	1.85E+00	1.517E-05	
		35	0.003	355	1.18E+05		0.54	0	1.85E+00	1.517E-05	
		45	0.003	400	1.33E+05		0.54	0	1.85E+00	1.517E-05	
		55	0.003	466	1.55E+05		0.54	0	1.85E+00	1.517E-05	
		65	0.003	40	1.33E+04		0.54	0	1.85E+00	1.517E-05	
24-May-23	3-1	0	0.003	0	0.00E+00	1.35E+05	0.714	0	0.00E+00	0.000E+00	4.8
		15	0.003	461	9.22E+04		0.714	5	7.00E+00	5.182E-05	
		25	0.003	623	1.25E+05		0.714	1	1.40E+00	1.036E-05	
		35	0.002	425	8.50E+04		0.714	2	2.80E+00	2.073E-05	
		45	0.003	748	1.50E+05		0.714	2	2.80E+00	2.073E-05	
		55	0.002	480	9.60E+04		0.714	1	1.40E+00	1.036E-05	
		65	0.002	441	2.21E+05		0.714	0	1.40E+00	1.036E-05	

24-May-23	3-2	0	0.003	0	0.00E+00	2.55E+05	0.714	0	0.00E+00	0.000E+00	4.9
		15	0.003	650	2.17E+05		0.714	1	1.40E+00	5.497E-06	
		25	0.003	476	1.59E+05		0.714	4	5.60E+00	2.199E-05	
		35	0.003	849	2.83E+05		0.714	3	4.20E+00	1.649E-05	
		45	0.003	835	2.78E+05		0.714	1	1.40E+00	5.497E-06	
		55	0.002	598	2.99E+05		0.714	3	4.20E+00	1.649E-05	
		65	0.002	510	2.55E+05		0.714	1	1.40E+00	5.497E-06	
24-May-23	2A	0	0.003	0	0.00E+00	2.21E+05	0.714	0	0.00E+00	0.000E+00	5.0
		15	0.003	343	1.14E+05		0.714	1	1.40E+00	6.336E-06	
		25	0.003	447	1.49E+05		0.714	0	1.40E+00	6.336E-06	
		35	0.002	579	2.90E+05		0.714	2	2.80E+00	1.267E-05	
		45	0.003	848	2.83E+05		0.714	2	2.80E+00	1.267E-05	
		55	0.002	331	1.66E+05		0.714	1	1.40E+00	6.336E-06	
		65	0.002	437	2.19E+05		0.714	2	2.80E+00	1.267E-05	
23-Jul-24	3-1	0	0.003	0	0.00E+00	4.68E+04	0.54	0	0.00E+00	0.000E+00	4.3
		15	0.003	275	9.17E+04		0.54	1	1.85E+00	3.961E-05	
		25	0.003	78	2.60E+04		0.54	0	1.85E+00	3.961E-05	
		35	0.003	205	6.83E+04		0.54	0	1.85E+00	3.961E-05	
		45	0.003	135	4.50E+04		0.54	1	1.85E+00	3.961E-05	
		55	0.003	143	4.77E+04		0.54	2	3.70E+00	7.922E-05	
		65	0.003	-	-		0.54	0	1.85E+00	3.961E-05	
23-Jul-24	3-2	0	0.003	0	0.00E+00	1.41E+05	0.54	0	0.00E+00	0.000E+00	4.9
		15	0.003	267	8.90E+04		0.54	0	1.85E+00	1.310E-05	
		25	0.003	488	1.63E+05		0.54	0	1.85E+00	1.310E-05	
		35	0.003	351	1.17E+05		0.54	1	1.85E+00	1.310E-05	
		45	0.003	403	1.34E+05		0.54	1	1.85E+00	1.310E-05	
		55	0.002	303	1.52E+05		0.54	0	1.85E+00	1.310E-05	
		65	0.002	-	-		0.54	0	1.85E+00	1.310E-05	
23-Jul-24	2A	0	0.003	0	0.00E+00	1.32E+05	0.54	0	0.00E+00	0.000E+00	4.6
		15	0.003	43	1.43E+04		0.54	2	3.70E+00	2.800E+00	
		25	0.003	100	3.33E+04		0.54	0	1.85E+00	1.401E-05	
		35	0.003	445	1.48E+05		0.54	2	3.70E+00	2.802E-05	
		45	0.002	431	2.16E+05		0.54	3	5.56E+00	4.202E-05	
		55	0.002	367	1.84E+05		0.54	1	1.85E+00	1.401E-05	
		65	0.003	241	8.03E+04		0.54	0	1.85E+00	1.401E-05	
30-Jul-24	3-1	0	0.003	0	0.00E+00	2.72E+05	0.54	0	0.00E+00	0.00E+00	4.6
		15	0.002	314	1.57E+05		0.54	5	9.26E+00	3.40E-05	
		25	0.002	446	2.23E+05		0.54	3	5.56E+00	2.04E-05	
		35	0.002	559	2.80E+05		0.54	11	2.04E+01	7.49E-05	
		45	0.002	551	2.76E+05		0.54	2	3.70E+00	1.36E-05	
		55	0.002	660	3.30E+05		0.54	0	1.85E+00	6.81E-06	
		65	0.002	504	2.52E+05		0.54	1	1.85E+00	6.81E-06	
30-Jul-24	3-2	0	0.003	0	0.00E+00	3.24E+05	0.54	0	0.00E+00	0.00E+00	5.0
		15	0.002	285	1.43E+05		0.54	0	1.85E+00	5.72E-06	
		25	0.002	532	2.66E+05		0.54	1	1.85E+00	5.72E-06	
		35	0.002	613	3.07E+05		0.54	4	7.41E+00	2.29E-05	
		45	0.002	702	3.51E+05		0.54	1	1.85E+00	5.72E-06	
		55	0.002	730	3.65E+05		0.54	0	1.85E+00	5.72E-06	
		65	0.002	660	3.30E+05		0.54	0	1.85E+00	5.72E-06	

30-Jul-24	2A	0	0.003	0	0.00E+00	3.07E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.002	275	1.38E+05		0.54	2	3.70E+00	1.21E-05	
		25	0.002	662	3.31E+05		0.54	1	1.85E+00	6.03E-06	
		35	0.002	541	2.71E+05		0.54	9	1.67E+01	5.43E-05	
		45	0.002	578	2.89E+05		0.54	1	1.85E+00	6.03E-06	
		55	0.002	698	3.49E+05		0.54	0	1.85E+00	6.03E-06	
		65	0.002	590	2.95E+05		0.54	0	1.85E+00	6.03E-06	
31-Jul-24	3-1	0	0.003	0	0.00E+00	1.97E+05	0.54	0	0.00E+00	0.00E+00	4.9
		15	0.002	200	1.00E+05		0.54	2	1.85E+00	9.39E-06	
		25	0.002	348	1.74E+05		0.54	1	5.56E+00	2.82E-05	
		35	0.002	371	1.86E+05		0.54	9	1.85E+00	9.39E-06	
		45	0.002	434	2.17E+05		0.54	1	1.85E+00	9.39E-06	
		55	0.002	442	2.21E+05		0.54	0	1.85E+00	9.39E-06	
		65	0.002	378	1.89E+05		0.54	0	1.85E+00	9.39E-06	
31-Jul-24	3-2	0	0.003	0	0.00E+00	1.62E+05	0.54	0	0.00E+00	0.00E+00	4.9
		15	0.002	202	1.01E+05		0.54	1	1.85E+00	1.14E-05	
		25	0.002	228	1.14E+05		0.54	3	1.85E+00	1.14E-05	
		35	0.002	300	1.50E+05		0.54	1	1.85E+00	1.14E-05	
		45	0.002	342	1.71E+05		0.54	1	1.85E+00	1.14E-05	
		55	0.002	350	1.75E+05		0.54	0	1.85E+00	1.14E-05	
		65	0.002	399	2.00E+05		0.54	0	1.85E+00	1.14E-05	
31-Jul-24	2A	0	0.003	0	0.00E+00	1.63E+05	0.54	0	0.00E+00	0.00E+00	4.9
		15	0.002	125	6.25E+04		0.54	0	3.70E+00	2.28E-05	
		25	0.002	246	1.23E+05		0.54	1	3.70E+00	2.28E-05	
		35	0.002	321	1.61E+05		0.54	0	1.85E+00	1.14E-05	
		45	0.002	332	1.66E+05		0.54	0	1.85E+00	1.14E-05	
		55	0.002	420	2.10E+05		0.54	0	1.85E+00	1.14E-05	
		65	0.002	308	1.54E+05		0.54	0	1.85E+00	1.14E-05	
20-Aug-24	3-1	0	0.006	0	0.00E+00	2.30E+05	0.71	0	0.00E+00	0.00E+00	5.1
		15	0.006	633	1.06E+05		0.71	3	4.20E+00	1.83E-05	
		25	0.006	1313	2.19E+05		0.71	1	1.40E+00	6.10E-06	
		35	0.005	1019	2.04E+05		0.71	0	1.40E+00	6.10E-06	
		45	0.004	1059	2.65E+05		0.71	2	2.80E+00	1.22E-05	
		55	0.005	978	1.96E+05		0.71	0	1.40E+00	6.10E-06	
		65	0.005	1325	2.65E+05		0.71	0	1.40E+00	6.10E-06	
20-Aug-24	3-2	0	0.006	0	0.00E+00	2.78E+05	0.71	0	0.00E+00	0.00E+00	5.3
		15	0.003	476	1.59E+05		0.71	1	1.40E+00	5.03E-06	
		25	0.006	1345	2.24E+05		0.71	0	1.40E+00	5.03E-06	
		35	0.005	1359	2.72E+05		0.71	0	1.40E+00	5.03E-06	
		45	0.004	1255	3.14E+05		0.71	1	1.40E+00	5.03E-06	
		55	0.005	1458	2.92E+05		0.71	1	1.40E+00	5.03E-06	
		65	0.005	1451	2.90E+05		0.71	0	1.40E+00	5.03E-06	
20-Aug-24	2A	0	0.006	0	0.00E+00	2.12E+05	0.71	0	0.00E+00	0.00E+00	5.2
		15	0.003	251	8.37E+04		0.71	0	1.40E+00	6.61E-06	
		25	0.006	1031	1.72E+05		0.71	1	1.40E+00	6.61E-06	
		35	0.005	963	1.93E+05		0.71	0	1.40E+00	6.61E-06	
		45	0.004	921	2.30E+05		0.71	0	1.40E+00	6.61E-06	
		55	0.005	1125	2.25E+05		0.71	0	1.40E+00	6.61E-06	
		65	0.005	1195	2.39E+05		0.71	0	1.40E+00	6.61E-06	

21-Aug-24	3-1	0	0.004	0	0.00E+00	1.38E+05	0.71	0	0.00E+00	0.00E+00	4.2
		15	0.004	302	7.55E+04		0.71	3	4.20E+00	3.05E-05	
		25	0.004	500	1.25E+05		0.71	18	2.52E+01	1.83E-04	
		35	0.004	547	1.37E+05		0.71	8	1.12E+01	8.13E-05	
		45	0.004	420	1.05E+05		0.71	2	2.80E+00	2.03E-05	
		55	0.004	359	8.98E+04		0.71	3	4.20E+00	3.05E-05	
		65	0.002	466	2.33E+05		0.71	0	1.40E+00	1.02E-05	
21-Aug-24	3-2	0	0.003	0	0.00E+00	1.50E+05	0.71	0	0.00E+00	0.00E+00	4.2
		15	0.004	441	1.10E+05		0.71	15	2.10E+01	1.40E-04	
		25	0.004	593	1.48E+05		0.71	15	2.10E+01	1.40E-04	
		35	0.006	879	1.47E+05		0.71	10	1.40E+01	9.33E-05	
		45	0.004	608	1.52E+05		0.71	2	2.80E+00	1.87E-05	
		55	0.004	610	1.53E+05		0.71	5	7.00E+00	4.67E-05	
		65	0.004	605	1.51E+05		0.71	1	1.40E+00	9.33E-06	
21-Aug-24	2A	0	0.003	0	0.00E+00	1.25E+05	0.71	0	0.00E+00	0.00E+00	4.2
		15	0.004	321	8.03E+04		0.71	6	8.40E+00	6.70E-05	
		25	0.004	340	8.50E+04		0.71	9	1.26E+01	1.01E-04	
		35	0.004	537	1.34E+05		0.71	11	1.54E+01	1.23E-04	
		45	0.004	497	1.24E+05		0.71	5	7.00E+00	5.58E-05	
		55	0.004	419	1.05E+05		0.71	1	1.40E+00	1.12E-05	
		65	0.004	715	1.79E+05		0.71	0	1.40E+00	1.12E-05	
11-Feb-25	3-1	0	0.004	0	0.00E+00	1.30E+05	0.71	0	0.00E+00	0.00E+00	4.2
		15	0.004	281	7.03E+04		0.71	3	4.20E+00	3.24E-05	
		25	0.004	535	1.34E+05		0.71	5	7.00E+00	5.41E-05	
		35	0.004	540	1.35E+05		0.71	7	9.80E+00	7.57E-05	
		45	0.004	498	1.25E+05		0.71	6	8.40E+00	6.49E-05	
		55	0.004	489	1.22E+05		0.71	7	9.80E+00	7.57E-05	
		65	0.004	529	1.32E+05		0.71	4	5.60E+00	4.32E-05	
11-Feb-25	3-2	0	0.004	0	0.00E+00	1.18E+05	0.71	0	0.00E+00	0.00E+00	4.3
		15	0.004	298	7.45E+04		0.71	4	5.60E+00	4.74E-05	
		25	0.004	357	8.93E+04		0.71	3	4.20E+00	3.56E-05	
		35	0.004	333	8.33E+04		0.71	4	5.60E+00	4.74E-05	
		45	0.004	611	1.53E+05		0.71	3	4.20E+00	3.56E-05	
		55	0.004	566	1.42E+05		0.71	4	5.60E+00	4.74E-05	
		65	0.004	496	1.24E+05		0.71	5	7.00E+00	5.93E-05	
11-Feb-25	2A	0	0.004	0	0.00E+00	1.25E+05	0.71	0	0.00E+00	0.00E+00	4.1
		15	0.004	359	8.98E+04		0.71	4	5.60E+00	4.48E-05	
		25	0.004	360	9.00E+04		0.71	5	7.00E+00	5.60E-05	
		35	0.004	541	1.35E+05		0.71	7	9.80E+00	7.84E-05	
		45	0.004	612	1.53E+05		0.71	11	1.54E+01	1.23E-04	
		55	0.004	464	1.16E+05		0.71	3	4.20E+00	3.36E-05	
		65	0.004	524	1.31E+05		0.71	8	1.12E+01	8.96E-05	
12-Feb-25	3-1	0	0.015	0	0.00E+00	1.57E+05	0.71	0	0.00E+00	0.00E+00	4.8
		15	0.004	608	1.52E+05		0.71	0	1.40E+00	8.94E-06	
		25	0.004	489	1.22E+05		0.71	2	2.80E+00	1.79E-05	
		35	0.004	525	1.31E+05		0.71	1	1.40E+00	8.94E-06	
		45	0.004	511	1.28E+05		0.71	2	2.80E+00	1.79E-05	
		55	0.004	757	1.89E+05		0.71	0	1.40E+00	8.94E-06	
		65	0.004	850	2.13E+05		0.71	2	2.80E+00	1.79E-05	

12-Feb-25	3-2	0	0.015	0	0.00E+00	2.99E+05	0.71	0	0.00E+00	0.00E+00	5.2
		15	0.004	486	1.22E+05		0.71	0	1.40E+00	4.69E-06	
		25	0.004	641	1.60E+05		0.71	0	1.40E+00	4.69E-06	
		35	0.004	881	2.20E+05		0.71	0	1.40E+00	4.69E-06	
		45	0.004	1280	3.20E+05		0.71	1	1.40E+00	4.69E-06	
		55	0.003	1241	4.14E+05		0.71	2	2.80E+00	9.38E-06	
		65	0.004	1518	3.80E+05		0.71	1	1.40E+00	4.69E-06	
12-Feb-25	2A	0	0.015	0	0.00E+00	1.62E+05	0.71	0	0.00E+00	0.00E+00	5.0
		15	0.004	245	6.13E+04		0.71	1	1.40E+00	8.62E-06	
		25	0.004	415	1.04E+05		0.71	0	1.40E+00	8.62E-06	
		35	0.003	498	1.66E+05		0.71	0	1.40E+00	8.62E-06	
		45	0.004	590	1.48E+05		0.71	0	1.40E+00	8.62E-06	
		55	0.004	706	1.77E+05		0.71	2	2.80E+00	1.72E-05	
		65	0.003	656	2.19E+05		0.71	0	1.40E+00	8.62E-06	
12-Mar-25	3-1	0	0.004	0	0.00E+00	1.54E+05	0.54	0	0.00E+00	0.00E+00	4.2
		15	0.004	267	6.68E+04		0.54	1	1.85E+00	1.21E-05	
		25	0.004	543	1.36E+05		0.54	3	5.56E+00	3.62E-05	
		35	0.004	798	2.00E+05		0.54	6	1.11E+01	7.23E-05	
		45	0.004	515	1.29E+05		0.54	4	7.41E+00	4.82E-05	
		55	0.004	801	2.00E+05		0.54	8	1.48E+01	9.64E-05	
		65	0.004	416	1.04E+05		0.54	7	1.30E+01	8.44E-05	
12-Mar-25	3-2	0	0.004	0	0.00E+00	1.67E+05	0.54	0	0.00E+00	0.00E+00	4.3
		15	0.004	661	1.65E+05		0.54	0	1.85E+00	1.11E-05	
		25	0.004	720	1.80E+05		0.54	5	9.26E+00	5.55E-05	
		35	0.004	603	1.51E+05		0.54	5	9.26E+00	5.55E-05	
		45	0.004	286	7.15E+04		0.54	4	7.41E+00	4.44E-05	
		55	0.004	515	1.29E+05		0.54	3	5.56E+00	3.33E-05	
		65	0.004	1215	3.04E+05		0.54	5	9.26E+00	5.55E-05	
12-Mar-25	2A	0	0.004	0	0.00E+00	1.44E+05	0.54	0	0.00E+00	0.00E+00	4.1
		15	0.004	405	1.01E+05		0.54	2	3.70E+00	2.57E-05	
		25	0.004	401	1.00E+05		0.54	4	7.41E+00	5.15E-05	
		35	0.004	389	9.73E+04		0.54	5	9.26E+00	6.43E-05	
		45	0.004	921	2.30E+05		0.54	3	5.56E+00	3.86E-05	
		55	0.004	420	1.05E+05		0.54	4	7.41E+00	5.15E-05	
		65	0.004	748	1.87E+05		0.54	13	2.41E+01	1.67E-04	
18-Mar-25	3-1	0	0.01	0	0.00E+00	3.39E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.004	265	6.63E+04		0.54	0	1.85E+00	5.47E-06	
		25	0.004	1068	2.67E+05		0.54	2	3.70E+00	1.09E-05	
		35	0.003	818	2.73E+05		0.54	6	1.11E+01	3.28E-05	
		45	0.003	1121	3.74E+05		0.54	2	3.70E+00	1.09E-05	
		55	0.003	1201	4.00E+05		0.54	3	5.56E+00	1.64E-05	
		65	0.003	1139	3.80E+05		0.54	0	1.85E+00	5.47E-06	
18-Mar-25	3-2	0	0.01	0	0.00E+00	3.98E+05	0.54	0	0.00E+00	0.00E+00	5.0
		15	0.004	268	6.70E+04		0.54	2	3.70E+00	9.30E-06	
		25	0.004	1492	3.73E+05		0.54	4	7.41E+00	1.86E-05	
		35	0.003	1044	3.48E+05		0.54	3	5.56E+00	1.39E-05	
		45	0.003	1282	4.27E+05		0.54	0	1.85E+00	4.65E-06	
		55	0.003	1396	4.65E+05		0.54	1	1.85E+00	4.65E-06	
		65	0.003	1134	3.78E+05		0.54	0	1.85E+00	4.65E-06	

18-Mar-25	2A	0	0.01	0	0.00E+00	3.06E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.004	261	6.53E+04		0.54	1	1.85E+00	6.06E-06	
		25	0.004	812	2.03E+05		0.54	7	1.30E+01	4.24E-05	
		35	0.003	990	3.30E+05		0.54	1	1.85E+00	6.06E-06	
		45	0.003	888	2.96E+05		0.54	2	3.70E+00	1.21E-05	
		55	0.003	1095	3.65E+05		0.54	2	3.70E+00	1.21E-05	
		65	0.003	1003	3.34E+05		0.54	1	1.85E+00	6.06E-06	
02-Apr-25	3-1	0	0.01	0	0.00E+00	4.33E+05	0.54	0	0.00E+00	0.00E+00	4.4
		15	0.001	108	1.08E+05		0.54	0	1.85E+00	4.28E-06	
		25	0.004	1489	3.72E+05		0.54	1	1.85E+00	4.28E-06	
		35	0.003	1284	4.28E+05		0.54	0	1.85E+00	4.28E-06	
		45	0.004	1866	4.67E+05		0.54	7	1.30E+01	3.00E-05	
		55	0.004	1857	4.64E+05		0.54	25	4.63E+01	1.07E-04	
		65	0.002	1179	5.90E+05		0.54	-	-	-	
02-Apr-25	3-2	0	0.01	0	0.00E+00	5.51E+05	0.54	0	0.00E+00	0.00E+00	4.1
		15	0.001	72	7.20E+04		0.54	0	1.85E+00	3.36E-06	
		25	0.004	1921	4.80E+05		0.54	3	5.56E+00	1.01E-05	
		35	0.003	1430	4.77E+05		0.54	2	3.70E+00	6.72E-06	
		45	0.004	2226	5.57E+05		0.54	93	1.72E+02	3.12E-04	
		55	0.004	2411	6.03E+05		0.54	16	2.96E+01	5.37E-05	
		65	0.002	1281	6.41E+05		0.54	2	3.70E+00	6.72E-06	
02-Apr-25	2A	0	0.01	0	0.00E+00	3.56E+05	0.54	0	0.00E+00	0.00E+00	3.8
		15	0.001	89	8.90E+04		0.54	2	3.70E+00	1.04E-05	
		25	0.004	955	2.39E+05		0.54	57	1.06E+02	2.97E-04	
		35	0.003	1267	4.22E+05		0.54	-	5.80E+02	1.63E-03	
		45	0.004	1655	4.14E+05		0.54	2	3.70E+00	1.04E-05	
		55	0.004	1476	3.69E+05		0.54	10	1.85E+01	5.21E-05	
		65	0.002	801	4.01E+05		0.54	42	7.78E+01	2.19E-04	
08-Apr-25	3-1	0	0.01	0	0.00E+00	2.18E+05	0.71	0	0.00E+00	0.00E+00	4.2
		15	0.006	665	1.11E+05		0.71	8	1.12E+01	5.13E-05	
		25	0.004	521	1.30E+05		0.71	13	1.82E+01	8.34E-05	
		35	0.006	1415	2.36E+05		0.71	10	1.40E+01	6.42E-05	
		45	0.006	1315	2.19E+05		0.71	7	9.80E+00	4.49E-05	
		55	0.006	1481	2.47E+05		0.71	12	1.68E+01	7.70E-05	
		65	0.004	1036	2.59E+05		0.71	5	7.00E+00	3.21E-05	
08-Apr-25	3-2	0	0.01	0	0.00E+00	1.95E+05	0.71	0	0.00E+00	0.00E+00	4.3
		15	0.006	721	1.20E+05		0.71	3	4.20E+00	2.16E-05	
		25	0.004	558	1.40E+05		0.71	8	1.12E+01	5.75E-05	
		35	0.006	1050	1.75E+05		0.71	12	1.68E+01	8.63E-05	
		45	0.006	1325	2.21E+05		0.71	6	8.40E+00	4.31E-05	
		55	0.006	1126	1.88E+05		0.71	5	7.00E+00	3.60E-05	
		65	0.004	1003	2.51E+05		0.71	8	1.12E+01	5.75E-05	
08-Apr-25	2A	0	0	0	0.00E+00	1.81E+05	0.71	0	0.00E+00	0.00E+00	4.4
		15	0.006	878	1.46E+05		0.71	4	5.60E+00	3.09E-05	
		25	0.004	391	9.78E+04		0.71	4	5.60E+00	3.09E-05	
		35	0.004	441	1.10E+05		0.71	6	8.40E+00	4.64E-05	
		45	0.006	1370	2.28E+05		0.71	1	1.40E+00	7.73E-06	
		55	0.006	1444	2.41E+05		0.71	4	5.60E+00	3.09E-05	
		65	0.004	914	2.29E+05		0.71	8	1.12E+01	6.19E-05	

09-Apr-25	3-1	0	0.01	0	0.00E+00	9.11E+03	0.71	0	0.00E+00	0.00E+00	-0.3
		15	0.015	44	2.93E+03		0.71	46	6.44E+01	7.07E-03	
		25	0.015	108	7.20E+03		0.71	3456	4.84E+03	5.32E-01	
		35	0.015	141	9.40E+03		0.15	5680	3.79E+04	4.16E+00	
		45	0.015	126	8.40E+03		0.20	4172	2.09E+04	2.29E+00	
		55	0.015	173	1.15E+04		0.15	3745	2.50E+04	2.74E+00	
		65	0.015	135	9.00E+03		0.15	3985	2.66E+04	2.92E+00	
09-Apr-25	3-2	0	0.01	0	0.00E+00	9.75E+03	0.71	0	0.00E+00	0.00E+00	-0.3
		15	0.015	112	7.47E+03		0.71	53	7.42E+01	7.62E-03	
		25	0.015	98	6.53E+03		0.71	8721	1.22E+04	1.25E+00	
		35	0.015	111	7.40E+03		0.15	2388	1.59E+04	1.63E+00	
		45	0.015	182	1.21E+04		0.20	3644	1.82E+04	1.87E+00	
		55	0.015	181	1.21E+04		0.15	4838	3.23E+04	3.31E+00	
		65	0.015	159	1.06E+04		0.15	4245	2.83E+04	2.90E+00	
09-Apr-25	2A	0	0.01	0	0.00E+00	7.61E+03	0.71	0	0.00E+00	0.00E+00	-0.3
		15	0.015	91	6.07E+03		0.71	54	7.56E+01	9.93E-03	
		25	0.015	65	4.33E+03		0.71	4474	6.27E+03	8.23E-01	
		35	0.015	147	9.80E+03		0.15	3267	2.18E+04	2.86E+00	
		45	0.015	123	8.20E+03		0.71	2237	3.13E+03	4.12E-01	
		55	0.015	133	8.87E+03		0.15	3657	2.44E+04	3.20E+00	
		65	0.015	103	6.87E+03		0.15	3500	2.33E+04	3.06E+00	

Appendix K

Raw data for Chapter 5

Table K.1. Raw water quality, pilot plant operational data, seed suspension data, and average *Cryptosporidium* oocyst, Pristine microplastic (MP), and Weathered MP removal for Chapter 5.

Date	Raw Water Quality				Pilot Plant Coagulation			Oocyst Seed Suspension Coagulation			Pilot Plant CAF			
	Temperature (°C)	Turbidity (NTU)	pH	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Zeta Potential (mV)	Filter Configuration	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)	Pristine MP Removal as OELR (log ₁₀)	Weathered MP Removal as OELR (log ₁₀)
09-Sep-25	7.67	0.16	5.63	-8.74	alum	5.0	-17.5	alum	5.0	-13.7	3-1 2A	4.3 4.3	1.9 1.7	3.8 3.6
11-Sep-25	13.01	0.37	7.90	-13.83	alum	5.0	-17.2	alum	5.0	-15.3	3-1 2A	3.9 3.9	1.2 0.9	3.1 3.0
16-Sep-25	17.90	0.54	8.20	-15.40	alum	5.0	-18.2	alum	9.0	-12.4	3-1 2A	4.5 4.5	1.2 1.1	1.0 1.0
18-Sep-25	18.75	1.01	8.28	-15.98	alum	5.0	-18.2	alum	93.0	-0.5	3-1 2A	5.2 5.1	3.6 3.5	3.3 3.2
23-Sep-25	18.75	0.72	8.20	-11.26	alum	5.0	-12.3	alum	90.0	-3.2	3-1 2A	5.2 4.5	3.7 3.5	4.3 4.1
25-Sep-25	19.20	0.88	8.09	-13.11	alum	5.0	-12.7	alum	127.5	-4.0	3-1 2A	4.3 4.8	4.1 3.8	5.2 5.2

Table K.2. Detailed *Cryptosporidium* oocyst removal data for Chapter 5. For any counts with a zero (ND) (except for T0) a count of one was assigned as a conservative adjustment. This change for NDs is reflected in the “Filter Effluent *Cryptosporidium* (oocysts/L)” column. All experiments were conducted during stable operation.

Date	Filter Configuration	Sample Time (min)	Pilot Plant CAF								
			Filter Influent Sample Volume (L)	Filter Influent <i>Cryptosporidium</i> (# oocysts)	Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Average Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Filter Effluent Sample Volume (L)	Filter Effluent <i>Cryptosporidium</i> (# oocysts)	Filter Effluent <i>Cryptosporidium</i> (oocysts/L)	<i>Cryptosporidium</i> Removal (%)	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
09-Sep-25	3-1	0	0.015	0	0.00E+00	1.33E+05	0.714	0	0.00E+00	0.00E+00	4.3
		15	0.003	128	4.27E+04		0.714	5	7.00E+00	5.27E-05	
		25	0.003	303	1.01E+05		0.714	8	1.12E+01	8.42E-05	
		35	0.003	483	1.61E+05		0.714	3	4.20E+00	3.16E-05	
		45	0.003	523	1.74E+05		0.714	7	9.80E+00	7.37E-05	
		55	0.003	397	1.32E+05		0.714	5	7.00E+00	5.27E-05	
		65	0.003	289	9.63E+04		0.714	2	2.80E+00	2.11E-05	
09-Sep-25	2A	0	0.015	0	0.00E+00	1.16E+05	0.714	0	0.00E+00	0.00E+00	4.3
		15	0.003	98	3.27E+04		0.714	3	4.20E+00	3.63E-05	
		25	0.003	209	6.97E+04		0.714	3	4.20E+00	3.63E-05	
		35	0.003	399	1.33E+05		0.714	6	8.40E+00	7.26E-05	
		45	0.003	342	1.14E+05		0.714	3	4.20E+00	3.63E-05	
		55	0.003	418	1.39E+05		0.714	4	5.60E+00	4.84E-05	
		65	0.003	369	1.23E+05		0.714	3	4.20E+00	3.63E-05	
11-Sep-25	3-1	0	0.015	0	0.00E+00	1.22E+05	0.714	0	0.00E+00	0.00E+00	3.8
		15	0.003	181	6.03E+04		0.714	8	1.12E+01	9.19E-05	
		25	0.003	423	1.41E+05		0.714	11	1.54E+01	1.26E-04	
		35	0.003	412	1.37E+05		0.714	16	2.24E+01	1.84E-04	
		45	0.003	386	1.29E+05		0.714	9	1.26E+01	1.03E-04	
		55	0.003	377	1.26E+05		0.714	12	1.68E+01	1.38E-04	
		65	0.003	230	7.67E+04		0.714	15	2.10E+01	1.72E-04	
11-Sep-25	2A	0	0.015	0	0.00E+00	1.26E+05	0.714	0	0.00E+00	1.12E-05	3.8
		15	0.003	116	3.87E+04		0.714	10	1.40E+01	1.12E-04	
		25	0.003	319	1.06E+05		0.714	8	1.12E+01	8.92E-05	
		35	0.003	302	1.01E+05		0.714	15	2.10E+01	1.67E-04	
		45	0.003	389	1.30E+05		0.714	12	1.68E+01	1.34E-04	
		55	0.003	450	1.50E+05		0.714	13	1.82E+01	1.45E-04	
		65	0.003	424	1.41E+05		0.714	17	2.38E+01	1.90E-04	
16-Sep-25	3-1	0	0.015	0	0.00E+00	8.11E+04	0.714	0	0.00E+00	0.00E+00	4.5
		15	0.003	118	3.93E+04		0.714	2	2.80E+00	3.46E-05	
		25	0.003	234	7.80E+04		0.714	2	2.80E+00	3.46E-05	
		35	0.003	315	1.05E+05		0.714	1	1.40E+00	1.73E-05	
		45	0.003	243	8.10E+04		0.714	0	1.40E+00	1.73E-05	
		55	0.003	220	7.33E+04		0.714	4	5.60E+00	6.91E-05	
		65	0.003	204	6.80E+04		0.714	1	1.40E+00	1.73E-05	
16-Sep-25	2A	0	0.015	0	0.00E+00	8.37E+04	0.714	0	0.00E+00	0.00E+00	4.5
		15	0.003	98	3.27E+04		0.714	1	1.40E+00	1.67E-05	
		25	0.003	213	7.10E+04		0.714	1	1.40E+00	1.67E-05	
		35	0.003	378	1.26E+05		0.714	3	4.20E+00	5.02E-05	
		45	0.003	204	6.80E+04		0.714	2	2.80E+00	3.35E-05	
		55	0.003	275	9.17E+04		0.714	-	-	-	
		65	0.003	209	6.97E+04		0.714	2	2.80E+00	3.35E-05	

18-Sep-25	3-1	0	0.015	0	0.00E+00	4.34E+05	0.714	0	0.00E+00	0.00E+00	5.2
		15	0.003	516	1.72E+05		0.714	0	1.40E+00	3.23E-06	
		25	0.003	1380	4.60E+05		0.714	0	1.40E+00	3.23E-06	
		35	0.003	1608	5.36E+05		0.714	3	4.20E+00	9.68E-06	
		45	0.003	1355	4.52E+05		0.714	3	4.20E+00	9.68E-06	
		55	0.003	1105	3.68E+05		0.714	1	1.40E+00	3.23E-06	
		65	0.003	1061	3.54E+05		0.714	1	1.40E+00	3.23E-06	
18-Sep-25	2A	0	0.015	0	0.00E+00	4.45E+05	0.714	0	0.00E+00	0.00E+00	5.1
		15	0.003	434	1.45E+05		0.714	0	1.40E+00	3.15E-06	
		25	0.003	1048	3.49E+05		0.714	1	1.40E+00	3.15E-06	
		35	0.003	1107	3.69E+05		0.714	2	2.80E+00	6.29E-06	
		45	0.003	1541	5.14E+05		0.714	7	9.80E+00	2.20E-05	
		55	0.003	1405	4.68E+05		0.714	0	1.40E+00	3.15E-06	
		65	0.003	1574	5.25E+05		0.714	2	2.80E+00	6.29E-06	
23-Sep-25	3-1	0	0.015	0	0.00E+00	3.41E+05	0.714	0	0.00E+00	0.00E+00	5.2
		15	0.003	192	6.40E+04		0.714	1	1.40E+00	4.10E-06	
		25	0.003	1057	3.52E+05		0.714	1	1.40E+00	4.10E-06	
		35	0.001	192	1.92E+05		0.714	3	4.20E+00	1.23E-05	
		45	0.001	369	3.69E+05		0.714	0	1.40E+00	4.10E-06	
		55	0.001	424	4.24E+05		0.714	1	1.40E+00	4.10E-06	
		65	0.001	370	3.70E+05		0.714	2	2.80E+00	8.20E-06	
23-Sep-25	2A	0	0.015	0	0.00E+00	2.69E+05	0.714	0	0.00E+00	0.00E+00	4.5
		15	0.003	130	4.33E+04		0.714	1	1.40E+00	5.20E-06	
		25	0.003	851	2.84E+05		0.714	2	2.80E+00	1.04E-05	
		35	0.003	990	3.30E+05		0.714	3	4.20E+00	1.56E-05	
		45	0.001	201	2.01E+05		0.714	2	2.80E+00	1.04E-05	
		55	0.001	263	2.63E+05		0.714	19	2.66E+01	9.88E-05	
		65	0.001	341	3.41E+05		0.714	190	2.66E+02	9.88E-04	
25-Sep-25	3-1	0	0.015	0	0.00E+00	3.66E+05	0.714	0	0.00E+00	0.00E+00	4.3
		15	0.003	163	5.43E+04		0.714	0	1.40E+00	3.82E-06	
		25	0.001	376	3.76E+05		0.714	2	2.80E+00	7.64E-06	
		35	0.001	423	4.23E+05		0.714	3	4.20E+00	1.15E-05	
		45	0.001	297	2.97E+05		0.714	11	1.54E+01	4.20E-05	
		55	0.001	445	4.45E+05		0.714	36	5.04E+01	1.38E-04	
		65	0.001	291	2.91E+05		0.714	7	9.80E+00	2.68E-05	
25-Sep-25	2A	0	0.015	0	0.00E+00	3.71E+05	0.714	0	0.00E+00	0.00E+00	4.8
		15	0.003	142	4.73E+04		0.714	1	1.40E+00	3.77E-06	
		25	0.001	411	4.11E+05		0.714	4	5.60E+00	1.51E-05	
		35	0.001	379	3.79E+05		0.714	4	5.60E+00	1.51E-05	
		45	0.001	358	3.58E+05		0.714	2	2.80E+00	7.55E-06	
		55	0.001	382	3.82E+05		0.714	6	8.40E+00	2.26E-05	
		65	0.001	326	3.26E+05		0.714	5	7.00E+00	1.89E-05	

Table K.3. Detailed Pristine MPs removal data for Chapter 5. For any counts with a zero (ND) (except for T0) a count of one was assigned as a conservative adjustment. This change for NDs is reflected in the “Filter Effluent Pristine MP (MPs/L)” column. All experiments were conducted during stable operation.

Date	Pilot Plant CAF										
	Filter Configuration	Sample Time (min)	Filter Influent Sample Volume (L)	Filter Influent Pristine MP (# MPs)	Filter Influent Pristine MP (MPs/L)	Average Filter Influent Pristine MP (MPs/L)	Filter Effluent Sample Volume (L)	Filter Effluent Pristine MP (# MPs)	Filter Effluent Pristine MP (MPs/L)	Pristine MP Removal (%)	Pristine MP Removal as OELR (log ₁₀)
09-Sep-25	3-1	0	0.015	0	0.00E+00	9.87E+04	0.714	0	0.00E+00	0.00E+00	1.9
		15	0.003	107	3.57E+04		0.714	54	7.56E+01	7.67E-04	
		25	0.003	261	8.70E+04		0.714	468	6.55E+02	6.64E-03	
		35	0.003	377	1.26E+05		0.714	898	1.26E+03	1.27E-02	
		45	0.003	255	8.50E+04		0.714	778	1.09E+03	1.10E-02	
		55	0.003	312	1.04E+05		0.714	1140	1.60E+03	1.62E-02	
		65	0.003	275	9.17E+04		0.714	735	1.03E+03	1.04E-02	
09-Sep-25	2A	0	0.015	0	0.00E+00	8.53E+04	0.714	0	0.00E+00	0.00E+00	1.7
		15	0.003	81	2.70E+04		0.714	71	9.94E+01	1.17E-03	
		25	0.003	145	4.83E+04		0.714	475	6.65E+02	7.80E-03	
		35	0.003	285	9.50E+04		0.714	1168	1.64E+03	1.92E-02	
		45	0.003	345	1.15E+05		0.714	1137	1.59E+03	1.87E-02	
		55	0.003	324	1.08E+05		0.714	1929	2.70E+03	3.17E-02	
		65	0.003	180	6.00E+04		0.714	1628	2.28E+03	2.67E-02	
11-Sep-25	3-1	0	0.015	0	0.00E+00	1.13E+05	0.714	0	0.00E+00	0.00E+00	1.2
		15	0.003	189	6.30E+04		0.714	717	1.00E+03	8.89E-03	
		25	0.003	291	9.70E+04		0.714	4358	6.10E+03	5.40E-02	
		35	0.003	372	1.24E+05		0.714	8595	1.20E+04	1.07E-01	
		45	0.003	398	1.33E+05		0.714	425	5.95E+02	5.27E-03	
		55	0.003	366	1.22E+05		0.714	4888	6.85E+03	6.06E-02	
		65	0.003	267	8.90E+04		0.714	7967	1.12E+04	9.88E-02	
11-Sep-25	2A	0	0.015	0	0.00E+00	8.80E+04	0.714	0	0.00E+00	0.00E+00	0.9
		15	0.003	91	3.03E+04		0.714	381	5.34E+02	6.06E-03	
		25	0.003	227	7.57E+04		0.714	5517	7.73E+03	8.78E-02	
		35	0.003	256	8.53E+04		0.714	8947	1.25E+04	1.42E-01	
		45	0.003	246	8.20E+04		0.714	821	1.15E+03	1.31E-02	
		55	0.003	311	1.04E+05		0.714	11976	1.68E+04	1.91E-01	
		65	0.003	280	9.33E+04		0.714	10304	1.44E+04	1.64E-01	
16-Sep-25	3-1	0	0.015	0	0.00E+00	1.84E+04	0.714	0	0.00E+00	0.00E+00	1.2
		15	0.003	21	7.00E+03		0.714	45	6.30E+01	3.43E-03	
		25	0.003	44	1.47E+04		0.714	379	5.31E+02	2.88E-02	
		35	0.003	40	1.33E+04		0.714	828	1.16E+03	6.30E-02	
		45	0.003	115	3.83E+04		0.714	980	1.37E+03	7.46E-02	
		55	0.003	42	1.40E+04		0.714	727	1.02E+03	5.53E-02	
		65	0.003	35	1.17E+04		0.714	1127	1.58E+03	8.58E-02	
16-Sep-25	2A	0	0.015	0	0.00E+00	1.33E+04	0.714	0	0.00E+00	0.00E+00	1.1
		15	0.003	34	1.13E+04		0.714	26	3.64E+01	2.75E-03	
		25	0.003	36	1.20E+04		0.714	484	6.78E+02	5.12E-02	
		35	0.003	43	1.43E+04		0.714	334	4.68E+02	3.53E-02	
		45	0.003	38	1.27E+04		0.714	1269	1.78E+03	1.34E-01	
		55	0.003	57	1.90E+04		0.714	-	-	-	
		65	0.003	42	1.40E+04		0.714	1030	1.44E+03	1.09E-01	

18-Sep-25	3-1	0	0.015	0	0.00E+00	4.57E+04	0.714	0	0.00E+00	0.00E+00	3.6
		15	0.003	50	1.67E+04		0.714	5	7.00E+00	1.53E-04	
		25	0.003	115	3.83E+04		0.714	8	1.12E+01	2.45E-04	
		35	0.003	165	5.50E+04		0.714	13	1.82E+01	3.99E-04	
		45	0.003	133	4.43E+04		0.714	7	9.80E+00	2.15E-04	
		55	0.003	144	4.80E+04		0.714	11	1.54E+01	3.37E-04	
		65	0.003	128	4.27E+04		0.714	6	8.40E+00	1.84E-04	
18-Sep-25	2A	0	0.015	0	0.00E+00	4.49E+04	0.714	0	0.00E+00	0.00E+00	3.5
		15	0.003	72	2.40E+04		0.714	7	9.80E+00	2.18E-04	
		25	0.003	120	4.00E+04		0.714	12	1.68E+01	3.74E-04	
		35	0.003	147	4.90E+04		0.714	3	4.20E+00	9.35E-05	
		45	0.003	138	4.60E+04		0.714	10	1.40E+01	3.12E-04	
		55	0.003	131	4.37E+04		0.714	6	8.40E+00	1.87E-04	
		65	0.003	138	4.60E+04		0.714	17	2.38E+01	5.30E-04	
23-Sep-25	3-1	0	0.015	0	0.00E+00	4.35E+04	0.714	0	0.00E+00	0.00E+00	3.7
		15	0.003	19	6.33E+03		0.714	0	1.40E+00	3.22E-05	
		25	0.003	89	2.97E+04		0.714	2	2.80E+00	6.43E-05	
		35	0.001	37	3.70E+04		0.714	7	9.80E+00	2.25E-04	
		45	0.001	54	5.40E+04		0.714	6	8.40E+00	1.93E-04	
		55	0.001	48	4.80E+04		0.714	11	1.54E+01	3.54E-04	
		65	0.001	49	4.90E+04		0.714	8	1.12E+01	2.57E-04	
23-Sep-25	2A	0	0.015	0	0.00E+00	4.47E+04	0.714	0	0.00E+00	0.00E+00	3.5
		15	0.003	22	7.33E+03		0.714	1	1.40E+00	3.14E-05	
		25	0.003	121	4.03E+04		0.714	4	5.60E+00	1.25E-04	
		35	0.003	91	3.03E+04		0.714	12	1.68E+01	3.76E-04	
		45	0.001	44	4.40E+04		0.714	6	8.40E+00	1.88E-04	
		55	0.001	64	6.40E+04		0.714	18	2.52E+01	5.64E-04	
		65	0.001	67	6.70E+04		0.714	40	5.60E+01	1.25E-03	
25-Sep-25	3-1	0	0.015	0	0.00E+00	8.92E+04	0.714	0	0.00E+00	0.00E+00	4.1
		15	0.003	23	7.67E+03		0.714	0	1.40E+00	1.57E-05	
		25	0.001	86	8.60E+04		0.714	2	2.80E+00	3.14E-05	
		35	0.001	52	5.20E+04		0.714	6	8.40E+00	9.42E-05	
		45	0.001	73	7.30E+04		0.714	3	4.20E+00	4.71E-05	
		55	0.001	106	1.06E+05		0.714	11	1.54E+01	1.73E-04	
		65	0.001	129	1.29E+05		0.714	5	7.00E+00	7.85E-05	
25-Sep-25	2A	0	0.015	0	0.00E+00	9.66E+04	0.714	0	0.00E+00	0.00E+00	3.8
		15	0.003	17	5.67E+03		0.714	0	1.40E+00	1.45E-05	
		25	0.001	74	7.40E+04		0.714	5	7.00E+00	7.25E-05	
		35	0.001	105	1.05E+05		0.714	5	7.00E+00	7.25E-05	
		45	0.001	110	1.10E+05		0.714	17	2.38E+01	2.46E-04	
		55	0.001	108	1.08E+05		0.714	16	2.24E+01	2.32E-04	
		65	0.001	86	8.60E+04		0.714	12	1.68E+01	1.74E-04	

Table K.4. Detailed Weathered MPs removal data for Chapter 5. For any counts with a zero (ND) (except for T0) a count of one was assigned as a conservative adjustment. This change for NDs is reflected in the “Filter Effluent Weathered MP (MPs/L)” column. All experiments were conducted during stable operation.

Date	Filter Configuration	Sample Time (min)	Pilot Plant CAF								
			Filter Influent Sample Volume (L)	Filter Influent Weathered MP (# MPs)	Filter Influent Weathered MP (MPs/L)	Average Filter Influent Weathered MP (MPs/L)	Filter Effluent Sample Volume (L)	Filter Effluent Weathered MP (# MPs)	Filter Effluent Weathered MP (MPs/L)	Weathered MP Removal (%)	Weathered MP Removal as OELR (log ₁₀)
09-Sep-25	3-1	0	0.015	0	0.00E+00	3.46E+05	0.714	0	0.00E+00	0.00E+00	3.8
		15	0.003	736	2.45E+05		0.714	7	9.80E+00	4.55E+00	
		25	0.003	989	3.30E+05		0.714	24	3.36E+01	4.01E+00	
		35	0.003	1063	3.54E+05		0.714	35	4.90E+01	3.85E+00	
		45	0.003	1295	4.32E+05		0.714	32	4.48E+01	3.89E+00	
		55	0.003	1008	3.36E+05		0.714	58	8.12E+01	3.63E+00	
		65	0.003	829	2.76E+05		0.714	36	5.04E+01	3.84E+00	
09-Sep-25	2A	0	0.015	0	0.00E+00	3.09E+05	0.714	0	0.00E+00	0.00E+00	3.6
		15	0.003	365	1.22E+05		0.714	7	9.80E+00	4.50E+00	
		25	0.003	447	1.49E+05		0.714	14	1.96E+01	4.20E+00	
		35	0.003	958	3.19E+05		0.714	32	4.48E+01	3.84E+00	
		45	0.003	1152	3.84E+05		0.714	54	7.56E+01	3.61E+00	
		55	0.003	1089	3.63E+05		0.714	63	8.82E+01	3.54E+00	
		65	0.003	989	3.30E+05		0.714	84	1.18E+02	3.42E+00	
11-Sep-25	3-1	0	0.015	0	0.00E+00	3.25E+05	0.714	0	0.00E+00	0.00E+00	3.1
		15	0.003	473	1.58E+05		0.714	29	4.06E+01	3.90E+00	
		25	0.003	892	2.97E+05		0.714	133	1.86E+02	3.24E+00	
		35	0.003	1025	3.42E+05		0.714	209	2.93E+02	3.05E+00	
		45	0.003	1172	3.91E+05		0.714	193	2.70E+02	3.08E+00	
		55	0.003	977	3.26E+05		0.714	256	3.59E+02	2.96E+00	
		65	0.003	805	2.68E+05		0.714	312	4.37E+02	2.87E+00	
11-Sep-25	2A	0	0.015	0	0.00E+00	2.90E+05	0.714	0	0.00E+00	0.00E+00	3.0
		15	0.003	284	9.47E+04		0.714	22	3.08E+01	3.97E+00	
		25	0.003	629	2.10E+05		0.714	134	1.88E+02	3.19E+00	
		35	0.003	872	2.91E+05		0.714	206	2.89E+02	3.00E+00	
		45	0.003	765	2.55E+05		0.714	255	3.57E+02	2.91E+00	
		55	0.003	1121	3.74E+05		0.714	301	4.22E+02	2.84E+00	
		65	0.003	960	3.20E+05		0.714	374	5.24E+02	2.74E+00	
16-Sep-25	3-1	0	0.015	0	0.00E+00	9.03E+04	0.714	0	0.00E+00	0.00E+00	1.0
		15	0.003	117	3.90E+04		0.714	1167	1.63E+03	1.74E+00	
		25	0.003	271	9.03E+04		0.714	5215	7.30E+03	1.09E+00	
		35	0.003	310	1.03E+05		0.714	7980	1.12E+04	9.07E-01	
		45	0.003	316	1.05E+05		0.714	8042	1.13E+04	9.04E-01	
		55	0.003	252	8.40E+04		0.714	6648	9.31E+03	9.87E-01	
		65	0.003	205	6.83E+04		0.714	7841	1.10E+04	9.15E-01	
16-Sep-25	2A	0	0.015	0	0.00E+00	9.34E+04	0.714	0	0.00E+00	0.00E+00	1.0
		15	0.003	126	4.20E+04		0.714	1059	1.48E+03	1.80E+00	
		25	0.003	214	7.13E+04		0.714	5693	7.97E+03	1.07E+00	
		35	0.003	299	9.97E+04		0.714	5052	7.08E+03	1.12E+00	
		45	0.003	267	8.90E+04		0.714	9752	1.37E+04	8.35E-01	
		55	0.003	363	1.21E+05		0.714	-	-	-	
		65	0.003	341	1.14E+05		0.714	6710	9.40E+03	9.97E-01	

18-Sep-25	3-1	0	0.015	0	0.00E+00	3.12E+05	0.714	0	0.00E+00	0.00E+00	3.3
		15	0.003	413	1.38E+05		0.714	7	9.80E+00	4.50E+00	
		25	0.003	832	2.77E+05		0.714	31	4.34E+01	3.86E+00	
		35	0.003	1075	3.58E+05		0.714	84	1.18E+02	3.42E+00	
		45	0.003	942	3.14E+05		0.714	146	2.04E+02	3.18E+00	
		55	0.003	1047	3.49E+05		0.714	90	1.26E+02	3.39E+00	
		65	0.003	789	2.63E+05		0.714	162	2.27E+02	3.14E+00	
18-Sep-25	2A	0	0.015	0	0.00E+00	3.20E+05	0.714	0	0.00E+00	0.00E+00	3.2
		15	0.003	417	1.39E+05		0.714	15	2.10E+01	4.18E+00	
		25	0.003	796	2.65E+05		0.714	38	5.32E+01	3.78E+00	
		35	0.003	924	3.08E+05		0.714	50	7.00E+01	3.66E+00	
		45	0.003	944	3.15E+05		0.714	160	2.24E+02	3.15E+00	
		55	0.003	1087	3.62E+05		0.714	151	2.11E+02	3.18E+00	
		65	0.003	1052	3.51E+05		0.714	251	3.52E+02	2.96E+00	
23-Sep-25	3-1	0	0.015	0	0.00E+00	1.07E+06	0.714	0	0.00E+00	0.00E+00	4.3
		15	0.003	631	2.10E+05		0.714	18	2.52E+01	4.63E+00	
		25	0.003	2802	9.34E+05		0.714	31	4.34E+01	4.39E+00	
		35	0.001	901	9.01E+05		0.714	43	6.02E+01	4.25E+00	
		45	0.001	1145	1.15E+06		0.714	51	7.14E+01	4.17E+00	
		55	0.001	1290	1.29E+06		0.714	46	6.44E+01	4.22E+00	
		65	0.001	1070	1.07E+06		0.714	32	4.48E+01	4.38E+00	
23-Sep-25	2A	0	0.015	0	0.00E+00	9.63E+05	0.714	0	0.00E+00	0.00E+00	4.1
		15	0.003	553	1.84E+05		0.714	41	5.74E+01	4.22E+00	
		25	0.003	2640	8.80E+05		0.714	24	3.36E+01	4.46E+00	
		35	0.003	2548	8.49E+05		0.714	67	9.38E+01	4.01E+00	
		45	0.001	879	8.79E+05		0.714	75	1.05E+02	3.96E+00	
		55	0.001	1242	1.24E+06		0.714	70	9.80E+01	3.99E+00	
		65	0.001	1162	1.16E+06		0.714	115	1.61E+02	3.78E+00	
25-Sep-25	3-1	0	0.015	0	0.00E+00	2.06E+06	0.714	0	0.00E+00	0.00E+00	5.2
		15	0.003	710	2.37E+05		0.714	7	9.80E+00	5.32E+00	
		25	0.001	1512	1.51E+06		0.714	8	1.12E+01	5.26E+00	
		35	0.001	1748	1.75E+06		0.714	12	1.68E+01	5.09E+00	
		45	0.001	2321	2.32E+06		0.714	4	5.60E+00	5.56E+00	
		55	0.001	2240	2.24E+06		0.714	7	9.80E+00	5.32E+00	
		65	0.001	2466	2.47E+06		0.714	13	1.82E+01	5.05E+00	
25-Sep-25	2A	0	0.015	0	0.00E+00	1.95E+06	0.714	0	0.00E+00	0.00E+00	5.2
		15	0.003	625	2.08E+05		0.714	1	1.40E+00	6.14E+00	
		25	0.001	1506	1.51E+06		0.714	10	1.40E+01	5.14E+00	
		35	0.001	1681	1.68E+06		0.714	16	2.24E+01	4.94E+00	
		45	0.001	2220	2.22E+06		0.714	8	1.12E+01	5.24E+00	
		55	0.001	2050	2.05E+06		0.714	9	1.26E+01	5.19E+00	
		65	0.001	2290	2.29E+06		0.714	4	5.60E+00	5.54E+00	

Appendix L

Raw data for Chapter 6

Table L.1. Raw water quality, pilot plant operational data, seed suspension data, and average *Cryptosporidium* oocyst removal for direct in-line CAF experiments in Chapter 6, where oocysts were introduced into the raw-water stream at high concentrations and samples were collected by grab sampling for membrane filtration analysis.

Date	Raw Water Quality				Pilot Plant Coagulation			Oocyst seed suspension	Pilot Plant CAF	
	Temperature (°C)	Turbidity (NTU)	pH	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Zeta Potential (mV)	Zeta Potential (mV)	Filter Configuration	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
25-May-23	8.7	0.4	0.3	-11.6	alum	40.0	-0.8	-7.0	3-1 3-2 2A	4.4 4.6 3.3
10-Sep-24	5.5	0.3	8.0	-11.9	alum	40.0	-1.0	-8.6	3-1 3-2 2A	4.7 4.7 4.9
11-Sep-24	5.6	0.3	8.0	-9.1	alum	40.0	-0.6	-6.5	3-1 3-2 2A	4.8 4.7 5.2
01-Oct-24	20.2	0.8	8.5	-17.5	alum	5.0	-17.6	-8.0	3-1 3-2 2A	1.5 1.4 1.5
02-Oct-24	19.6	0.7	8.4	-17.3	alum	5.0	-19.1	-9.3	3-1 3-2 2A	1.1 1.1 1.1
29-Oct-24	9.2	1.6	8.1	-15.3	alum	25.0	-6.5	-9.4	3-1 3-2 2A	5.0 5.1 4.7

03-Dec-24	4.8	0.2	8.0	-8.4	alum	5.0	-16.7	-8.0	3-1 3-2 2A	2.5 2.6 2.4
14-Jan-25	3.1	0.2	8.1	-8.8	alum	40.0	-1.8	-10.5	3-1 3-2 2A	4.8 4.9 4.8
15-Jan-25	2.9	0.2	8.1	-7.9	alum	9.0	-15.6	-9.6	3-1 3-2 2A	3.7 3.7 3.8
11-Mar-25	2.5	0.2	8.1	-9.9	No coagulant	0.0	-11.1	-10.0	3-1 3-2 2A	0.3 0.2 0.1
01-Apr-25	4.2	1.1	8.1	-16.5	No coagulant	0.0	-14.8	-17.6	3-1 3-2 2A	0.2 0.3 0.2

Table L.2. Detailed *Cryptosporidium* oocysts removal data for Chapter 6 experiments, where oocysts were introduced into the raw water (raw water seeding method) at high concentrations and samples were collected by grab sampling for membrane filtration analysis. For any counts with a zero (ND) (except for T0) a count of one was assigned as a conservative adjustment. This change for NDs is reflected in the “Filter Effluent *Cryptosporidium* (oocysts/L)” column. All experiments were conducted during stable operation. Any oocyst counts with a * indicates counts that were estimated by enumerating only a portion of the microscope slide and extrapolating to the full slide because the number of oocysts was too high to count directly.

Date	Pilot Plant CAF										
	Filter Configuration	Sample Time (min)	Filter Influent Sample Volume (L)	Filter Influent <i>Cryptosporidium</i> (# oocysts)	Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Average Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Filter Effluent Sample Volume (L)	Filter Effluent <i>Cryptosporidium</i> (# oocysts)	Filter Effluent <i>Cryptosporidium</i> (oocysts/L)	<i>Cryptosporidium</i> Removal (%)	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
25-May-23	3-1	0	0.005	0	0.00E+00	9.53E+04	0.54	0	0.00E+00	0.00E+00	4.4
		15	0.005	10	2.00E+03		0.54	1	1.85E+00	1.94E-05	
		25	0.005	210	4.20E+04		0.54	4	7.41E+00	7.77E-05	
		35	0.005	380	7.60E+04		0.54	3	5.56E+00	5.83E-05	
		45	0.005	436	8.72E+04		0.54	0	0.00E+00	1.94E-05	
		55	0.005	560	1.12E+05		0.54	2	3.70E+00	3.89E-05	
		65	0.005	530	1.06E+05		0.54	2	3.70E+00	3.89E-05	
		75	0.005	589	1.18E+05		0.54	0	0.00E+00	1.94E-05	
		85	0.005	440	8.80E+04		0.54	0	0.00E+00	1.94E-05	
		95	0.005	278	5.56E+04		0.54	0	0.00E+00	1.94E-05	
25-May-23	3-2	0	0.005	0	0.00E+00	9.70E+04	0.54	0	0.00E+00	0.00E+00	4.6
		15	0.005	15	3.00E+03		0.54	1	1.85E+00	1.91E-05	
		25	0.005	261	5.22E+04		0.54	1	1.85E+00	1.91E-05	
		35	0.005	308	6.16E+04		0.54	2	3.70E+00	3.82E-05	
		45	0.005	500	1.00E+05		0.54	0	0.00E+00	1.91E-05	
		55	0.005	515	1.03E+05		0.54	0	0.00E+00	1.91E-05	
		65	0.005	617	1.23E+05		0.54	0	0.00E+00	1.91E-05	
		75	0.005	567	1.13E+05		0.54	0	0.00E+00	1.91E-05	
		85	0.005	480	9.60E+04		0.54	0	0.00E+00	1.91E-05	
		95	0.005	418	8.36E+04		0.54	0	0.00E+00	1.91E-05	
25-May-23	2A	0	0.005	0	0.00E+00	9.70E+04	0.54	0	0.00E+00	0.00E+00	3.3
		15	0.005	61	1.22E+04		0.54	4	7.41E+00	9.08E-05	
		25	0.005	214	4.28E+04		0.54	28	5.19E+01	6.36E-04	
		35	0.010	695	6.95E+04		0.54	31	5.74E+01	7.04E-04	
		45	0.010	1177	1.18E+05		0.54	26	4.81E+01	5.90E-04	
		55	0.005	641	1.28E+05		0.54	17	3.15E+01	3.86E-04	
		65	0.005	54	1.08E+04		0.54	18	3.33E+01	4.09E-04	
		75	0.005	579	1.16E+05		0.54	-	-	-	
		85	0.006	829	1.38E+05		0.54	-	-	-	
		95	0.005	439	8.78E+04		0.54	-	-	-	

10-Sep-24	3-1	0	0.005	0	0.00E+00	1.26E+05	0.54	0	0.00E+00	0.00E+00	4.7
		15	0.003	69	2.30E+04		0.54	0	1.85E+00	1.48E-05	
		25	0.005	501	1.00E+05		0.54	0	1.85E+00	1.48E-05	
		35	0.005	553	1.11E+05		0.54	1	1.85E+00	1.48E-05	
		45	0.005	453	9.06E+04		0.54	2	3.70E+00	2.95E-05	
		55	0.005	654	1.31E+05		0.54	2	3.70E+00	2.95E-05	
		65	0.005	850	1.70E+05		0.54	1	1.85E+00	1.48E-05	
		75	0.005	449	8.98E+04		0.54	0	1.85E+00	1.48E-05	
		85	0.005	305	6.10E+04		0.54	0	1.85E+00	1.48E-05	
10-Sep-24	3-2	0	0.005	0	0.00E+00	1.40E+05	0.54	0	0.00E+00	0.00E+00	4.7
		15	0.004	69	1.73E+04		0.54	0	1.85E+00	1.33E-05	
		25	0.005	335	6.70E+04		0.54	2	3.70E+00	2.65E-05	
		35	0.005	633	1.27E+05		0.54	2	3.70E+00	2.65E-05	
		45	0.005	680	1.36E+05		0.54	2	3.70E+00	2.65E-05	
		55	0.005	779	1.56E+05		0.54	0	1.85E+00	1.33E-05	
		65	0.005	698	1.40E+05		0.54	1	1.85E+00	1.33E-05	
		75	0.005	658	1.32E+05		0.54	0	1.85E+00	1.33E-05	
		85	0.005	479	9.58E+04		0.54	0	1.85E+00	1.33E-05	
10-Sep-24	2A	0	0.005	0	0.00E+00	1.35E+05	0.54	0	0.00E+00	0.00E+00	4.9
		15	0.005	153	3.06E+04		0.54	0	1.85E+00	1.37E-05	
		25	0.005	295	5.90E+04		0.54	1	1.85E+00	1.37E-05	
		35	0.005	464	9.28E+04		0.54	0	1.85E+00	1.37E-05	
		45	0.005	656	1.31E+05		0.54	1	1.85E+00	1.37E-05	
		55	0.005	769	1.54E+05		0.54	0	1.85E+00	1.37E-05	
		65	0.005	812	1.62E+05		0.54	1	1.85E+00	1.37E-05	
		75	0.005	779	1.56E+05		0.54	0	1.85E+00	1.37E-05	
		85	0.005	599	1.20E+05		0.54	1	1.85E+00	1.37E-05	
11-Sep-24	3-1	0	0.003	0	0.00E+00	2.73E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.004	70	1.75E+04		0.54	0	1.85E+00	6.79E-06	
		25	0.004	481	1.20E+05		0.54	2	3.70E+00	1.36E-05	
		35	0.003	612	2.04E+05		0.54	2	3.70E+00	1.36E-05	
		45	0.003	1011	3.37E+05		0.54	5	9.26E+00	3.39E-05	
		55	0.003	862	2.87E+05		0.54	2	3.70E+00	1.36E-05	
		65	0.003	789	2.63E+05		0.54	0	1.85E+00	6.79E-06	
		75	0.003	712	2.37E+05		0.54	0	1.85E+00	6.79E-06	
		85	0.003	621	2.07E+05		0.54	0	1.85E+00	6.79E-06	
11-Sep-24	3-2	0	0.003	0	0.00E+00	3.22E+05	0.54	0	0.00E+00	0.00E+00	4.7
		15	0.010	323	3.23E+04		0.54	1	1.85E+00	5.76E-06	
		25	0.003	483	1.61E+05		0.54	1	1.85E+00	5.76E-06	
		35	0.003	641	2.14E+05		0.54	2	3.70E+00	1.15E-05	
		45	0.003	1064	3.55E+05		0.54	2	3.70E+00	1.15E-05	
		55	0.003	1239	4.13E+05		0.54	8	1.48E+01	4.61E-05	
		65	0.003	915	3.05E+05		0.54	3	5.56E+00	1.73E-05	
		75	0.003	850	2.83E+05		0.54	2	2.83E+05	1.15E-05	
		85	0.003	328	1.09E+05		0.54	0	1.09E+05	5.76E-06	

11-Sep-24	2A	0	0.003	0	0.00E+00	3.75E+05	0.54	0	0.00E+00	0.00E+00	5.2
		15	0.005	123	2.46E+04		0.54	1	1.85E+00	4.94E-06	
		25	0.003	351	1.17E+05		0.54	1	1.85E+00	4.94E-06	
		35	0.003	701	2.34E+05		0.54	2	3.70E+00	9.88E-06	
		45	0.003	1302	4.34E+05		0.54	1	1.85E+00	4.94E-06	
		55	0.003	1293	4.31E+05		0.54	1	1.85E+00	4.94E-06	
		65	0.003	1203	4.01E+05		0.54	1	1.85E+00	4.94E-06	
		75	0.003	752	2.51E+05		0.54	1	1.85E+00	4.94E-06	
		85	0.003	337	1.12E+05		0.54	2	3.70E+00	9.88E-06	
01-Oct-24	3-1	0	0.005	0	0.00E+00	3.65E+05	0.54	0	0.00E+00	0.00E+00	1.5
		15	0.003	69	2.30E+04		0.54	7	1.30E+01	3.55E-05	
		25	0.002	273	1.37E+05		0.54	765*	1.42E+03	3.88E-03	
		35	0.002	586	2.93E+05		0.54	4301*	7.96E+03	2.18E-02	
		45	0.002	730	3.65E+05		0.54	8000*	1.48E+04	4.06E-02	
		55	0.002	838	4.19E+05		0.54	5011*	9.28E+03	2.54E-02	
		65	0.003	1152	3.84E+05		0.54	7766*	1.44E+04	3.94E-02	
		75	0.002	746	3.73E+05		0.54	9375*	1.74E+04	4.75E-02	
		85	0.002	367	1.84E+05		0.54	4612*	8.54E+03	2.34E-02	
01-Oct-24	3-2	0	0.005	0	0.00E+00	3.26E+05	0.54	0	0.00E+00	0.00E+00	1.4
		15	0.004	93	2.33E+04		0.54	5	9.26E+00	2.84E-05	
		25	0.002	244	1.22E+05		0.54	1265*	2.34E+03	7.19E-03	
		35	0.003	1134	3.78E+05		0.54	5671*	1.05E+04	3.22E-02	
		45	0.002	689	3.45E+05		0.54	8500*	1.57E+04	4.83E-02	
		55	0.002	498	2.49E+05		0.54	6881*	1.09E+04	3.34E-02	
		65	0.002	665	3.33E+05		0.54	7402*	1.37E+04	4.20E-02	
		75	0.002	961	4.81E+05		0.54	12076*	1.85E+00	5.68E-06	
		85	0.002	281	1.41E+05		0.54	3531*	6.54E+03	2.01E-02	
01-Oct-24	2A	0	0.005	0	0.00E+00	3.14E+05	0.54	0	0.00E+00	0.00E+00	1.5
		15	0.005	66	1.32E+04		0.54	6	1.11E+01	3.54E-05	
		25	0.003	338	1.13E+05		0.54	1040*	1.93E+03	6.14E-03	
		35	0.002	569	2.85E+05		0.54	3475*	6.44E+03	2.05E-02	
		45	0.002	748	3.74E+05		0.54	8000*	1.48E+04	4.73E-02	
		55	0.002	582	2.91E+05		0.54	5996*	1.11E+04	3.54E-02	
		65	0.002	609	3.05E+05		0.54	4888*	9.05E+03	2.89E-02	
		75	0.002	356	1.78E+05		0.32	5416*	1.85E+00	5.91E-06	
		85	0.002	303	1.52E+05		0.54	4247*	7.86E+03	2.51E-02	
02-Oct-24	3-1	0	0.003	0	0.00E+00	3.48E+05	0.54	0	0.00E+00	5.33E-06	1.1
		15	0.003	83	2.77E+04		0.54	14	2.59E+01	7.46E-05	
		25	0.002	492	2.46E+05		0.54	8508*	1.58E+04	4.53E-02	
		35	0.002	604	3.02E+05		0.54	13955*	2.58E+04	7.43E-02	
		45	0.002	698	3.49E+05		0.54	16211*	3.00E+04	8.64E-02	
		55	0.002	789	3.95E+05		0.54	11297*	2.09E+04	6.02E-02	
		65	0.002	690	3.45E+05		0.54	20094*	3.72E+04	1.07E-01	
		75	0.002	468	2.34E+05		0.35	6044*	1.73E+04	4.97E-02	
		85	0.002	290	1.45E+05		0.54	3091*	5.72E+03	1.65E-02	

02-Oct-24	3-2	0	0.003	0	0.00E+00	3.79E+05	0.54	0	0.00E+00	4.88E-06	1.1
		15	0.003	62	2.07E+04		0.54	8	1.48E+01	3.91E-05	
		25	0.002	398	1.99E+05		0.54	10924*	2.02E+04	5.33E-02	
		35	0.002	640	3.20E+05		0.54	9161*	1.70E+04	4.47E-02	
		45	0.002	717	3.59E+05		0.54	16387*	3.03E+04	8.00E-02	
		55	0.002	889	4.45E+05		0.54	12767*	2.36E+04	6.23E-02	
		65	0.002	789	3.95E+05		0.54	21250*	3.94E+04	1.04E-01	
		75	0.002	433	2.17E+05		0.43	6296*	1.46E+04	3.91E-02	
		85	0.002	327	1.64E+05		0.38	6070*	1.60E+04	4.26E-02	
02-Oct-24	2A	0	0.003	0	0.00E+00	3.52E+05	0.54	0	0.00E+00	5.26E-06	1.1
		15	0.003	51	1.70E+04		0.54	10	1.85E+01	5.26E-05	
		25	0.002	401	2.01E+05		0.54	7257*	1.34E+04	3.82E-02	
		35	0.002	608	3.04E+05		0.54	15820*	2.93E+04	8.32E-02	
		45	0.002	687	3.44E+05		0.54	16324*	3.02E+04	8.59E-02	
		55	0.002	740	3.70E+05		0.54	13584*	2.52E+04	7.15E-02	
		65	0.002	781	3.91E+05		0.54	21853*	4.05E+04	1.15E-01	
		75	0.002	511	2.56E+05		0.34	6497*	1.91E+04	5.10E-02	
		85	0.002	187	9.35E+04		0.38	5554*	1.46E+04	3.90E-02	
29-Oct-24	3-1	0	0.003	0	0.00E+00	3.11E+05	0.54	0	0.00E+00	0.00E+00	5.0
		15	0.003	56	1.87E+04		0.54		1.85E+00	5.96E-06	
		25	0.003	346	1.15E+05		0.54		1.85E+00	5.96E-06	
		35	0.003	711	2.37E+05		0.54	1	1.85E+00	5.96E-06	
		45	0.003	986	3.29E+05		0.54	0	1.85E+00	5.96E-06	
		55	0.005	1776	3.55E+05		0.54	2	3.70E+00	1.19E-05	
		65	0.003	969	3.23E+05		0.54	2	3.70E+00	1.19E-05	
		75	0.005	1550	3.10E+05		0.54		1.85E+00	5.96E-06	
		85	0.003	545	1.82E+05		0.54		1.85E+00	0.00E+00	
29-Oct-24	3-2	0	0.003	0	0.00E+00	3.63E+05	0.54	0	0.00E+00	0.00E+00	5.1
		15	0.003	115	3.83E+04		0.54		1.85E+00	5.10E-06	
		25	0.003	451	1.50E+05		0.54		1.85E+00	5.10E-06	
		35	0.003	836	2.79E+05		0.54	1	1.85E+00	5.10E-06	
		45	0.003	1260	4.20E+05		0.54	1	1.85E+00	5.10E-06	
		55	0.005	1846	3.69E+05		0.54	3	5.56E+00	1.53E-05	
		65	0.005	1926	3.85E+05		0.54	0	1.85E+00	5.10E-06	
		75	0.005	1636	3.27E+05		0.54		1.85E+00	5.10E-06	
		85	0.005	758	1.52E+05		0.54		1.85E+00	5.10E-06	
29-Oct-24	2A	0	0.003	0	0.00E+00	2.98E+05	0.54	0	0.00E+00	0.00E+00	4.7
		15	0.003	75	2.50E+04		0.54		1.85E+00	6.21E-06	
		25	0.003	-	-		0.54		1.85E+00	6.21E-06	
		35	0.003	735	2.45E+05		0.54	0	1.85E+00	6.21E-06	
		45	0.003	801	2.67E+05		0.54	3	5.56E+00	1.86E-05	
		55	0.005	1701	3.40E+05		0.54	6	1.11E+01	3.72E-05	
		65	0.005	1705	3.41E+05		0.54	4	7.41E+00	2.48E-05	
		75	0.005	1966	3.93E+05		0.54		1.85E+00	6.21E-06	
		85	0.005	985	1.97E+05		0.54		1.85E+00	6.21E-06	

03-Dec-24	3-1	0	0.005	0	0.00E+00	1.02E+05	0.54	0	0.00E+00	0.00E+00	2.5
		15	0.005	17	3.40E+03		0.54		1.85E+00	1.82E-05	
		25	0.003	95	3.17E+04		0.54		1.85E+00	1.82E-05	
		35	0.004	308	7.70E+04		0.54	165	3.06E+02	3.01E-03	
		45	0.003	269	8.97E+04		0.54	208	3.85E+02	3.79E-03	
		55	0.003	362	1.21E+05		0.54	161	2.98E+02	2.94E-03	
		65	0.003	356	1.19E+05		0.54	180	3.33E+02	3.28E-03	
		75	0.003	177	5.90E+04		0.54		1.85E+00	1.82E-05	
		85	0.003	115	3.83E+04		0.54		1.85E+00		
03-Dec-24	3-2	0	0.005	0	0.00E+00	1.12E+05	0.54	0	0.00E+00	0.00E+00	2.6
		15	0.005	25	5.00E+03		0.54		1.85E+00	1.66E-05	
		25	0.003	141	4.70E+04		0.54		1.85E+00	1.66E-05	
		35	0.005	600	1.20E+05		0.54	119	2.20E+02	1.97E-03	
		45	0.004	351	8.78E+04		0.54	157	2.91E+02	2.60E-03	
		55	0.003	298	9.93E+04		0.54	165	3.06E+02	2.73E-03	
		65	0.003	420	1.40E+05		0.54	148	2.74E+02	2.45E-03	
		75	0.003	241	8.03E+04		0.54		1.85E+00	1.66E-05	
		85	0.003	109	3.63E+04		0.54		1.85E+00		
03-Dec-24	2A	0	0.005	0	0.00E+00	9.68E+04	0.54	0	0.00E+00	0.00E+00	2.4
		15	0.005	79	1.58E+04		0.54		1.85E+00	1.91E-05	
		25	0.003	145	4.83E+04		0.54		1.85E+00	1.91E-05	
		35	0.003	236	7.87E+04		0.54	169	3.13E+02	3.23E-03	
		45	0.004	489	1.22E+05		0.54	200	3.70E+02	3.83E-03	
		55	0.003	260	8.67E+04		0.54	257	4.76E+02	4.92E-03	
		65	0.003	299	9.97E+04		0.54	148	2.74E+02	2.83E-03	
		75	0.004	518	1.30E+05		0.54		1.85E+00	1.91E-05	
		85	0.003	97	3.23E+04		0.54		1.85E+00	1.91E-05	
14-Jan-25	3-1	0	0.003	0	0.00E+00	1.65E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.003	76	2.53E+04		0.54	0	1.85E+00	1.12E-05	
		25	0.003	-	-		0.54	1	1.85E+00	1.12E-05	
		35	0.003	461	1.54E+05		0.54	3	5.56E+00	3.37E-05	
		45	0.003	474	1.58E+05		0.54	0	1.85E+00	1.12E-05	
		55	0.003	491	1.64E+05		0.54	1	1.85E+00	1.12E-05	
		65	0.003	551	1.84E+05		0.54	0	1.85E+00	1.12E-05	
		75	0.003	360	1.20E+05		0.54	1	1.85E+00	1.12E-05	
		85	0.003	133	4.43E+04		0.54	0	1.85E+00	0.00E+00	
14-Jan-25	3-2	0	0.003	0	0.00E+00	1.70E+05	0.54	0	0.00E+00	0.00E+00	4.9
		15	0.003	35	1.17E+04		0.54	0	1.85E+00	1.09E-05	
		25	0.003	162	5.40E+04		0.54	1	1.85E+00	1.09E-05	
		35	0.003	437	1.46E+05		0.54	1	1.85E+00	1.09E-05	
		45	0.003	519	1.73E+05		0.54	1	1.85E+00	1.09E-05	
		55	0.003	487	1.62E+05		0.54	2	3.70E+00	2.18E-05	
		65	0.003	598	1.99E+05		0.54	0	1.85E+00	1.09E-05	
		75	0.003	132	4.40E+04		0.54	0	1.85E+00	1.09E-05	
		85	0.003	98	3.27E+04		0.54	0	1.85E+00	1.09E+00	

14-Jan-25	2A	0	0.003	0	0.00E+00	1.97E+05	0.54	0	0.00E+00	0.00E+00	4.8
		15	0.003	96	3.20E+04		0.54	0	1.85E+00	9.41E-06	
		25	0.003	-	-		0.54	0	1.85E+00	-	
		35	0.003	347	1.16E+05		0.54	0	1.85E+00	9.41E-06	
		45	0.003	541	1.80E+05		0.54	3	5.56E+00	2.82E-05	
		55	0.003	698	2.33E+05		0.54	2	3.70E+00	1.88E-05	
		65	0.003	776	2.59E+05		0.54	0	1.85E+00	9.41E-06	
		75	0.003	438	1.46E+05		0.54	1	1.85E+00	9.41E-06	
15-Jan-24	3-1	85	0.003	201	6.70E+04	8.98E+04	0.54	0	1.85E+00	9.41E+00	3.7
		0	0.004	0	0.00E+00		0.54	0	0.00E+00	0.00E+00	
		15	0.004	63	1.58E+04		0.54	2	3.70E+00	4.12E-05	
		25	0.004	85	2.13E+04		0.54	3	5.56E+00	6.19E-05	
		35	0.004	314	7.85E+04		0.54	11	2.04E+01	2.27E-04	
		45	0.004	334	8.35E+04		0.54	8	1.48E+01	1.65E-04	
		55	0.004	389	9.73E+04		0.54	3	5.56E+00	6.19E-05	
		65	0.004	400	1.00E+05		0.54	14	2.59E+01	2.89E-04	
15-Jan-24	3-2	75	0.004	92	2.30E+04	9.38E+04	0.54	9	1.67E+01	1.86E-04	3.7
		85	0.004	62	1.55E+04		0.54	5	9.26E+00	1.03E-04	
		0	0.004	0	0.00E+00		0.54	0	0.00E+00	0.00E+00	
		15	0.004	16	4.00E+03		0.54	2	3.70E+00	3.95E-05	
		25	0.004	106	2.65E+04		0.54	4	7.41E+00	7.90E-05	
		35	0.004	354	8.85E+04		0.54	10	1.85E+01	1.97E-04	
		45	0.004	358	8.95E+04		0.54	7	1.30E+01	1.38E-04	
		55	0.004	467	1.17E+05		0.54	6	1.11E+01	1.18E-04	
15-Jan-24	2A	65	0.004	322	8.05E+04	1.06E+05	0.54	15	2.78E+01	2.96E-04	3.8
		75	0.004	69	1.73E+04		0.54	6	1.11E+01	1.18E-04	
		85	0.004	63	1.58E+04		0.54	3	5.56E+00	5.92E-05	
		0	0.004	0	0.00E+00		0.54	0	0.00E+00	0.00E+00	
		15	0.004	10	2.50E+03		0.54	0	1.85E+00	1.75E-05	
		25	0.004	65	1.63E+04		0.54	2	3.70E+00	3.50E-05	
		35	0.004	240	6.00E+04		0.54	10	1.85E+01	1.75E-04	
		45	0.004	468	1.17E+05		0.54	8	1.48E+01	1.40E-04	
11-Mar-25	3-1	55	0.004	445	1.11E+05	6.16E+04	0.54	9	1.67E+01	1.58E-04	0.3
		65	0.004	539	1.35E+05		0.54	8	1.48E+01	1.40E-04	
		75	0.004	121	3.03E+04		0.54	3	5.56E+00	5.25E-05	
		85	0.004	102	2.55E+04		0.54	1	1.85E+00	1.75E-05	
		0	0.004	0	0.00E+00		0.54	0	0.00E+00	0.00E+00	
		15	0.004	26	6.50E+03		0.54	58	1.85E+00	1.74E-03	
		25	0.004	71	1.78E+04		0.54	3795*	1.85E+00	1.14E-01	
		35	0.004	110	2.75E+04		0.54	15369*	2.85E+04	4.62E-01	
		45	0.004	265	6.63E+04		0.54	14451*	2.68E+04	4.35E-01	
		55	0.004	332	8.30E+04		0.54	23901*	4.43E+04	7.19E-01	
		65	0.004	278	6.95E+04		0.54	20634*	3.82E+04	6.21E-01	
		75	0.004	42	1.05E+04		0.54	3682*	6.82E+03	1.11E-01	
		85	0.004	75	1.88E+04		0.54	3921*	7.26E+03	1.18E-01	

11-Mar-25	3-2	0	0.004	0	0.00E+00	5.58E+04	0.54	0	0.00E+00	0.00E+00	0.2
		15	0.004	12	3.00E+03		0.54	47	1.85E+00	1.56E-03	
		25	0.004	54	1.35E+04		0.54	6245*	1.85E+00	2.07E-01	
		35	0.004	154	3.85E+04		0.54	12340*	2.29E+04	4.10E-01	
		45	0.004	147	3.68E+04		0.54	21325*	3.95E+04	7.08E-01	
		55	0.004	286	7.15E+04		0.54	16261*	3.01E+04	5.40E-01	
		65	0.004	305	7.63E+04		0.54	21715*	4.02E+04	7.21E-01	
		75	0.004	102	2.55E+04		0.54	10418*	1.93E+04	3.46E-01	
		85	0.004	47	1.18E+04		0.54	3330*	6.17E+03	1.11E-01	
11-Mar-25	2A	0	0.004	0	0.00E+00	5.18E+04	0.54	0	0.00E+00	0.00E+00	0.1
		15	0.004	38	9.50E+03		0.54	-	1.85E+00	-	
		25	0.004	53	1.33E+04		0.54	6208*	1.85E+00	2.22E-01	
		35	0.004	108	2.70E+04		0.54	16500*	3.06E+04	5.90E-01	
		45	0.004	162	4.05E+04		0.54	17819*	3.30E+04	6.37E-01	
		55	0.004	298	7.45E+04		0.54	35286*	6.53E+04	1.26E+00	
		65	0.004	261	6.53E+04		0.54	27445*	5.08E+04	9.81E-01	
		75	0.004	121	3.03E+04		0.54	8394*	1.55E+04	3.00E-01	
		85	0.004	81	2.03E+04		0.54	6044*	1.12E+04	2.16E-01	
01-Apr-25	3-1	0	0.010	0	0.00E+00	4.78E+04	0.54	0	0.00E+00	0.00E+00	0.2
		15	0.001	4	4.00E+03		0.54	19	3.52E+01	7.36E-04	
		25	0.001	49	4.90E+04		0.54	7238	1.34E+04	2.80E-01	
		35	0.003	140	4.67E+04		0.10	4120	4.12E+04	8.62E-01	
		45	0.004	159	3.98E+04		0.10	5592	5.59E+04	1.17E+00	
		55	0.004	216	5.40E+04		0.20	3252	1.63E+04	3.40E-01	
		65	0.004	203	5.08E+04		0.20	4185	2.09E+04	4.38E-01	
		75	0.001	115	1.15E+05		0.54	1357	2.51E+03	5.26E-02	
		85	0.001	38	3.80E+04		0.54	779	1.44E+03	3.02E-02	
01-Apr-25	3-2	0	0.010	0	0.00E+00	5.44E+04	0.54	0	0.00E+00	0.00E+00	0.3
		15	0.001	6	6.00E+03		0.54	21	3.89E+01	7.15E-04	
		25	0.001	36	3.60E+04		0.54	1118	2.07E+03	3.81E-02	
		35	0.003	180	6.00E+04		0.15	5027	3.35E+04	6.16E-01	
		45	0.004	209	5.23E+04		0.10	3519	3.52E+04	6.47E-01	
		55	0.004	220	5.50E+04		0.20	4059	2.03E+04	3.73E-01	
		65	0.004	201	5.03E+04		0.20	4788	2.39E+04	4.40E-01	
		75	0.001	45	4.50E+04		0.54	716	1.33E+03	2.44E-02	
		85	0.001	31	3.10E+04		0.54	764	1.41E+03	2.60E-02	
01-Apr-25	2A	0	0.010	0	0.00E+00	4.80E+04	0.54	0	0.00E+00	0.00E+00	0.2
		15	0.001	6	6.00E+03		0.54	37	6.85E+01	1.43E-03	
		25	0.001	28	2.80E+04		0.54	1118	2.07E+03	4.32E-02	
		35	0.003	112	3.73E+04		0.15	3770	2.51E+04	5.24E-01	
		45	0.004	187	4.68E+04		0.10	2953	2.95E+04	6.16E-01	
		55	0.004	213	5.33E+04		0.20	5667	2.83E+04	5.91E-01	
		65	0.004	218	5.45E+04		0.20	5868	2.93E+04	6.12E-01	
		75	0.200	47	2.35E+02		0.54	1772	3.28E+03	6.84E-02	
		85	0.200	26	1.30E+02		0.54	957	1.77E+03	3.70E-02	

Table L.3. Raw water quality, pilot plant operational data, seed suspension data, and detailed *Cryptosporidium* oocyst removal for direct in-line CAF experiments in Chapter 6, where oocysts were introduced into the raw water (raw water seeding method) at low concentrations and a single continuous effluent sample was collected for each individual filter for EPA Method 1623.1 analysis. Any oocyst counts with a * indicates counts that were estimated by enumerating only a portion of the microscope slide and extrapolating to the full slide because the number of oocysts was too high to count directly.

Date	Raw Water Quality				Pilot Plant Coagulation			Oocyst seed suspension	Pilot Plant CAF						
	Temperature (°C)	Turbidity (NTU)	pH	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Zeta Potential (mV)	Zeta Potential (mV)	Filter Configuration	Filter Effluent Sample Volume (L)	Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Filter Effluent <i>Cryptosporidium</i> (# oocysts)	Filter Effluent <i>Cryptosporidium</i> (oocysts/L)	<i>Cryptosporidium</i> Removal (%)	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
26-May-25	6.3	0.5	8.3	-12.6	alum	40.0	-0.7	-12.2	3-1	384	5.21E+03	26	6.77E-02	1.30E-05	4.9
									3-2	360	5.56E+03	22	6.11E-02	1.10E-05	5.0
									2A	384	5.21E+03	270	7.03E-01	1.35E-04	3.9
10-Jun-25	7.5	0.4	8.2	-13.2	alum	5.0	-15.1	-12.1	3-1	342	9.75E+02	149	4.36E-01	4.47E-04	3.4
									3-2	292	1.14E+03	261	8.94E-01	7.83E-04	3.1
									2A	342	9.75E+02	280	8.19E-01	8.40E-04	3.1
17-Jun-25	9.2	0.4	8.2	-11.8	alum	0.0	-10.6	-13.0	3-1	262	8.91E+02	9940*	3.79E+01	4.26E-02	1.4
									3-2	246	9.49E+02	7124*	2.90E+01	3.05E-02	1.5
									2A	258	9.04E+02	4438*	1.72E+01	1.90E-02	1.7

Table L.4. Raw water quality, pilot plant operational data, seed suspension data, and detailed *Cryptosporidium* oocyst removal for conventional CAF experiments in Chapter 6, where oocysts were introduced into the raw water at high concentrations and a single continuous effluent sample was collected for each individual filter for EPA Method 1623.1 analysis. Any oocyst counts with a * indicates counts that were estimated by enumerating only a portion of the microscope slide and extrapolating to the full slide because the number of oocysts was too high to count directly.

Date	Raw Water Quality				Pilot Plant Coagulation			Oocyst seed suspension	Pilot Plant CAF						
	Temperature (°C)	Turbidity (NTU)	pH	Zeta Potential (mV)	Coagulant Type	Dose (mg/L)	Zeta Potential (mV)	Zeta Potential (mV)	Filter Configuration	Filter Effluent Sample Volume (L)	Filter Influent <i>Cryptosporidium</i> (oocysts/L)	Filter Effluent <i>Cryptosporidium</i> (# oocysts)	Filter Effluent <i>Cryptosporidium</i> (oocysts/L)	<i>Cryptosporidium</i> Removal (%)	<i>Cryptosporidium</i> Removal as OELR (log ₁₀)
24-Jun-25	5.0	0.2	8.0	-10.3	alum	43.0	-0.7	-7.8	3-1	520	6.41E+05	1.00	1.92E-03	3.00E-09	8.5
									3-2	540	6.17E+05	1.00	1.85E-03	3.00E-09	8.5
									2A	518	6.44E+05	1.00	1.93E-03	3.00E-09	8.5
22-Jul-25	13.4	0.5	8.4	-12.4	alum	5.0	-17.7	-11.2	3-1	623	4.30E+05	405063*	6.50E+02	1.51E-03	2.8
									3-2	631	4.25E+05	197162*	3.12E+02	7.35E-04	3.1
									2A	615	4.36E+05	497692*	8.09E+02	1.86E-03	2.7
29-Jul-25	12.7	0.4	8.0	-10.3	alum	0.0	-9.4	-6.6	3-1	578	7.01E+04	20000000*	3.46E+04	4.94E-01	0.3
									3-2	586	6.91E+04	21000000*	3.58E+04	5.19E-01	0.3
									2A	593	6.83E+04	20000000*	3.37E+04	4.94E-01	0.3
12-Aug-25	20.4	0.4	8.1	-6.5	alum	5.0	-6.9	-8.8	3-1	584	6.93E+04	318600*	5.46E+02	7.87E-03	2.1
									3-2	615	6.59E+04	278388*	4.53E+02	6.87E-03	2.2
									2A	644	6.29E+04	603490*	9.37E+02	1.49E-02	1.8
26-Aug-25	6.0	0.2	7.8	-9.1	alum	40.0	-5.4	-5.7	3-1	630	6.35E+05	43	6.83E-02	1.08E-07	7.0
									3-2	601	6.66E+05	25	4.16E-02	6.25E-08	7.2
									2A	664	6.02E+05	28	4.22E-02	7.00E-08	7.2

Appendix M

Raw water dissolved organic carbon (DOC) concentration & character

Natural organic matter (NOM) plays an important role in coagulation because it reacts with alum, influences particle charge, and can shift the coagulant dose required for effective destabilization. In addition to NOM concentration, the character of the NOM also affects the extent to which it governs coagulant dosing needs and is removed during coagulation, which tends to preferentially target higher molecular weight, more hydrophobic fractions. For this reason, NOM concentration and character were evaluated in this study using DOC analysis and LC-OCD fractionation to determine if NOM is a potential indicator of the need to adjust coagulant dose to achieve 3-log or greater *Cryptosporidium* oocyst removal by CAF. Pilot- and full-scale raw and settled water DOC concentrations, DOC character, pH, alkalinity, UV₂₅₄, and SUVA for multiple samples are presented in Table L.1.

Table M.1. Raw water characteristics for pilot- and full-scale. Samples were collected at various points of treatment (i.e., raw, settled, and filter effluent).

Samples	13-Oct-21					10-Nov-21				
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	Alkalinity (mg/L CaCO ₃)	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	Alkalinity (mg/L CaCO ₃)
Pilot raw	0.02	2.8	0.6	8.0	95.0	0.02	2.9	0.5	7.8	96.0
Pilot settled	0.02	2.5	0.6	7.9	94.0	0.01	2.6	0.5	7.8	94.0
Full raw	0.02	2.7	0.8	8.0	96.0	0.03	3.1	0.8	7.9	96.0
Full settled	0.02	2.6	0.6	7.8	91.0	0.01	2.6	0.5	7.8	91.0
Samples	19-Nov-21					04-Mar-22				
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	Alkalinity (mg/L CaCO ₃)	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	Alkalinity (mg/L CaCO ₃)
Pilot raw	0.02	2.8	0.6	7.8	95.0	0.02	2.1	0.9	8.0	94.0
Pilot settled	0.01	2.5	0.5	7.7	94.0	0.02	1.9	0.8	7.8	93.0
Full raw	0.02	2.6	0.8	7.9	96.0	0.03	2.3	1.1	7.9	96.0
Full settled	0.01	2.4	0.6	7.6	91.0	0.02	1.8	0.8	7.9	92.0
Samples	13-Sep-22					12-Oct-22				
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	Alkalinity (mg/L CaCO ₃)	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	Alkalinity (mg/L CaCO ₃)
Pilot raw	0.02	2.2	0.8	8.2	91.7	0.02	2.0	0.9	8.1	96.0
Pilot effluent	0.01	1.8	0.8	8.0	88.3	0.02	1.8	0.9	8.1	93.0
Full raw	0.02	2.1	0.9	8.1	92.0	0.03	1.9	1.5	7.1	98.0
Full effluent	0.02	1.8	0.8	8.0	87.0	0.01	1.7	0.8	7.9	93.0

As would be expected for high-quality, Great Lakes source water, and consistent with the TOC data presented in the body of this thesis, DOC levels in the source water were very low and did not vary significantly.

Nevertheless, DOC was monitored for most pilot-scale experimental runs, and SUVA was measured for selected samples. The corresponding sampling data are presented below.

Table M.2. Raw water characteristics for pilot-scale. Samples were collected at various points of treatment (i.e., raw, filter influent, and filter effluent).

Samples	30-Jul-24				20-Aug-24				21-Aug-24			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	0.02	2.3	0.7		0.01	2.1	0.5		0.01	2.2	0.6	
Pilot Influent	-	-	-	8.4	0.01	1.5	0.4	8.4	0.00	1.5	0.2	8.5
Pilot Effluent	0.01	1.5	0.5		0.00	1.4	0.3		0.01	1.4	0.4	
Samples	10-Sep-24				11-Sep-24				1-Oct-24			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	-	2.0	-		-	2.0	-		-	2.3	-	
Pilot Influent	-	1.4	-	8.0	-	1.3	-	8.0	-	2.0	-	8.5
Pilot Effluent	-	1.2	-		-	1.3	-		-	2.0	-	
Samples	2-Oct-24				29-Oct-24				3-Dec-24			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	-	2.2	-		0.02	2.0	0.8		-	2.0	-	
Pilot Influent	-	2.0	-	8.4	0.03	1.4	1.8	8.1	-	1.7	-	8.0
Pilot Effluent	-	2.0	-		0.00	1.4	-0.3		-	1.7	-	
Samples	14-Jan-25				15-Jan-25				11-Feb-25			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	0.02	1.9	0.8		0.02	1.9	1.0		-	1.9	-	
Pilot Influent	0.02	1.5	1.2	8.1	0.02	1.6	1.1	8.1	-	2.1	-	8.1
Pilot Effluent	0.01	1.4	0.9		0.01	1.6	0.9		-	2.0	-	
Samples	12-Feb-25				26-May-25				10-Jun-25			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	-	2.1	-		0.02	2.0	1.0		0.02	1.9	1.2	
Pilot Influent	-	1.6	-	8.1	0.04	1.3	2.8	8.3	0.02	2.1	0.9	8.2
Pilot Effluent	-	1.5	-		0.01	1.3	0.9		0.02	2.0	0.9	
Samples	17-Jun-25				24-Jun-25				22-Jul-25			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	-	2.2	-		0.02	2.0	0.9		-	2.2	-	
Pilot Influent	-	2.2	-	8.2	0.01	1.3	1.0	8.0	-	1.9	-	8.4
Pilot Effluent	-	2.3	-		0.01	1.3	0.9		-	2.0	-	
Samples	29-Jul-25				12-Aug-25				26-Aug-25			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	-	2.4	-		0.02	2.4	0.9		0.02	2.1	1.0	
Pilot Influent	-	2.4	-	8.0	0.02	2.1	0.8	8.1	0.01	1.4	0.7	7.8
Pilot Effluent	-	2.5	-		0.02	2.1	0.8		0.01	1.5	0.7	
Samples	2-Sep-25				9-Sep-25				11-Sep-25			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	0.02	2.7	0.8		0.02	2.3	0.9		0.02	2.5	0.9	
Pilot Influent	0.02	2.5	0.7	7.9	0.02	1.9	1.0	5.6	0.02	2.5	0.9	7.9
Pilot Effluent	0.02	1.9	0.9		0.02	1.9	0.9		0.02	2.2	0.9	
Samples	16-Sep-25				18-Sep-25				23-Sep-25			
	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH	UV254 (1/cm)	DOC (mg/L)	SUVA (L/mg.m)	pH
Pilot Raw	0.02	2.4	0.8		0.02	2.4	0.8		0.02	2.5	0.8	
Pilot Influent	0.02	2.4	0.8	8.2	0.02	2.2	0.9	8.3	0.02	2.2	0.9	8.2
Pilot Effluent	0.02	3.1	0.6		0.02	2.2	0.9		0.02	2.2	0.9	

Similarly, pilot- and full-scale raw and effluent water DOC fractions on four sampling occasions are presented in Table L.3. The samples for this analysis were processed using LC-OCD fractionation.

Table M.3. DOC fractions for pilot- and full-scale raw and filter effluent samples.

Fractions	13-Sep-22		13-Oct-22		25-Oct-22	
	Pilot raw	Pilot effluent	Pilot raw	Pilot effluent	Pilot raw	Pilot effluent
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
Biopolymers	0.5	0.2	0.3	0.2	0.3	0.2
Humic Substances	1.1	0.9	1.0	0.9	1.1	0.9
Building Blocks	0.3	0.3	0.4	0.3	0.2	0.3
LMW Neutrals	0.2	0.2	0.2	0.2	0.2	0.2
LMW Acids	0.1	0.1	0.1	0.1	0.1	0.1

Fractions	13-Sep-22		13-Oct-22		25-Oct-22	
	Full-scale raw	Full-scale effluent	Full-scale raw	Full-scale effluent	Full-scale raw	Full-scale effluent
	mg/L C	mg/L C	mg/L C	mg/L C	mg/L C	mg/L C
Biopolymers	0.4	0.2	0.3	0.2	0.3	0.1
Humic Substances	1.0	0.9	1.0	0.9	1.1	0.9
Building Blocks	0.3	0.3	0.3	0.3	0.2	0.2
LMW Neutrals	0.2	0.2	0.2	0.2	0.2	0.1
LMW Acids	0.1	0.1	0.1	0.1	0.1	0.1

Notably, the pilot- and full-scale DOC data are very consistent across all parameters presented in these tables. DOC affects coagulant demand, however, coagulation in systems reliant on high-quality source water (i.e., Toronto) does remove some of the humic substances fractions of DOC that are known to be removed by coagulation. Despite this, none of the investigated forms of DOC characterization were sensitive enough to indicate sufficiency of particle destabilization for achieving 3-log removal of *Cryptosporidium* by CAF.

Regardless, the DOC and LC-OCD analysis for pilot-scale samples throughout this study was conducted to ensure that no major variability is observed when conducting these experiments and the data are shown below. As the data shown here indicates, the raw water, influent, and effluent water quality remained consistent with no significant variations across all experiments similar to what was observed in Table L.3.

Table M.4. DOC fractions for pilot-scale raw, filter influent, and filter effluent samples.

DOC Fractions	30-Jul-24			20-Aug-24			21-Aug-24		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.3	-	0.1	0.3	0.1	0.1	0.3	0.1	0.1
Humic Substances	1.1	-	0.6	1.1	0.6	0.5	1.0	0.6	0.5
Building Blocks	0.3	-	0.3	0.2	0.2	0.3	0.2	0.3	0.2
LMW Neutrals	0.2	-	0.2	0.2	0.2	0.2	0.2	0.2	0.2
LMW Acids	0.1	-	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DOC Fractions	10-Sep-24			11-Sep-24			1-Oct-24		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.1	0.0	0.0	0.1	0.0	0.0	0.2	0.2	0.2
Humic Substances	0.6	0.3	0.2	0.8	0.2	0.3	0.6	0.5	0.6
Building Blocks	0.1	0.2	0.2	0.3	0.2	0.2	0.1	0.1	0.1
LMW Neutrals	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1
LMW Acids	0.1	0.1	0.0	0.1	0.1	0.0	0.1	0.1	0.1
DOC Fractions	2-Oct-24			29-Oct-24			14-Jan-25		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.2	0.2	0.1	0.4	0.1	0.1	0.3	0.1	0.1
Humic Substances	0.6	0.5	0.5	1.1	1.0	1.0	1.1	1.0	1.0
Building Blocks	0.2	0.2	0.2	0.2	0.1	0.1	0.2	0.1	0.1
LMW Neutrals	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.2
LMW Acids	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1
DOC Fractions	15-Jan-25			26-May-25			10-Jun-25		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.3	0.2	0.2	0.3	0.1	0.1	0.2	0.3	0.3
Humic Substances	1.3	1.0	1.1	1.1	0.6	0.7	0.9	1.0	1.0
Building Blocks	0.2	0.2	0.1	0.4	0.3	0.2	0.5	0.4	0.5
LMW Neutrals	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
LMW Acids	-	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.0
DOC Fractions	17-Jun-25			24-Jun-25			22-Jul-25		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.3	0.4	0.4	0.2	0.0	0.0	0.3	0.2	0.2
Humic Substances	0.9	1.0	1.2	0.8	0.5	0.5	1.0	0.9	0.8
Building Blocks	0.4	0.4	0.4	0.3	0.2	0.1	0.4	0.3	0.3
LMW Neutrals	0.1	0.2	0.3	0.2	0.2	0.1	0.2	0.1	0.2
LMW Acids	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DOC Fractions	29-Jul-25			12-Aug-25			26-Aug-25		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.4	0.4	0.4	0.5	0.3	0.3	0.3	0.1	0.1
Humic Substances	1.0	1.1	1.1	1.1	0.9	1.1	1.0	0.7	0.7
Building Blocks	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2
LMW Neutrals	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.2	0.3
LMW Acids	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-	-

DOC Fractions	2-Sep-25			9-Sep-25			11-Sep-25		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.4	0.2	0.2	0.3	0.2	0.1	0.4	0.2	0.2
Humic Substances	1.2	1.1	0.9	1.1	0.9	0.9	1.1	1.2	1.1
Building Blocks	0.3	0.4	0.2	0.3	0.2	0.3	0.4	0.2	0.3
LMW Neutrals	0.4	0.3	0.3	0.3	0.3	0.2	0.2	0.3	0.2
LMW Acids	0.1	0.2	0.1	0.1	0.1	0.2	0.2	0.2	0.1
DOC Fractions	16-Sep-25			18-Sep-25			23-Sep-25		
	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)	Pilot Raw (mg/L)	Pilot Influent (mg/L)	Pilot Effluent (mg/L)
Biopolymers	0.4	0.3	0.3	0.4	0.3	0.3	0.5	0.3	0.3
Humic Substances	1.1	1.0	1.1	1.0	0.9	1.1	1.2	1.1	1.0
Building Blocks	0.3	0.4	0.3	0.4	0.4	0.3	0.3	0.2	0.3
LMW Neutrals	0.3	0.4	1.1	0.3	0.3	0.3	0.4	0.3	0.4
LMW Acids	0.1	0.1	0.2	0.1	0.1	-	-	-	-

Appendix N

Time series modeling

A discrete-time modelling exercise was performed to confirm that the oocyst seeding and sampling protocol used for Chapter 6, where oocysts were introduced to raw water in conventional CAF for a one-hour continuous seeding period followed by seven hours of effluent sample collection, was sufficient to capture the full oocyst breakthrough response under pilot operating conditions.

The flocculation basins were modelled as continuous-flow stirred tank reactors (CSTRs) and the rest of the treatment configuration (i.e., sedimentation and filters) were modelled as plug flow reactors. The simulated breakthrough curve generated for oocysts, using the intended seeding concentration, mixing basin and sedimentation basin volumes, and pilot hydraulic parameters, showed that oocyst arrival, peak, and tailing behavior occurred within a timeframe consistent with the tracer response observed during pilot hydraulic characterization (Appendix B).

Based on the model results, it was determined that approximately 99.7% of the concentration introduced at the beginning of the treatment plant would be present in the filter effluent by the end of a 7-hour filter run. This outcome provided confidence that an experimental duration of 7 hours was sufficient for the conventional CAF system and therefore informed the selection of this run time for all subsequent experiments.

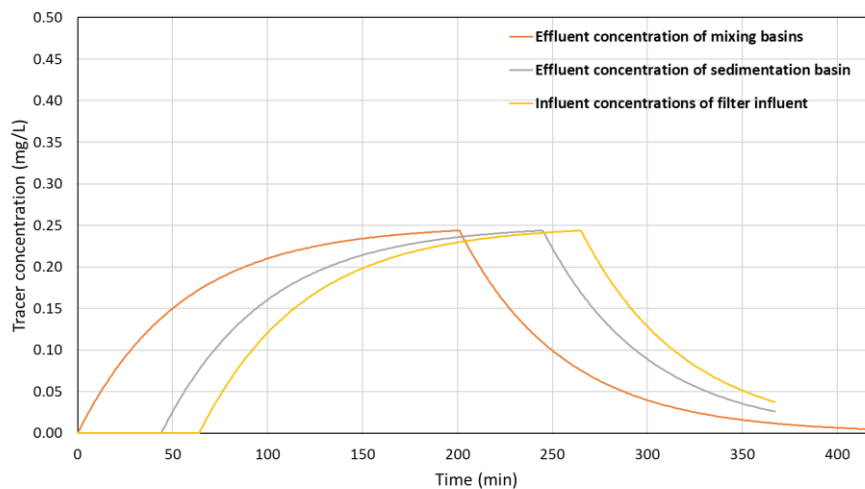


Figure N.1. Modelled tracer concentrations breakthrough profiles showing simulated effluent concentrations following a one-hour seed pulse. The curves illustrate expected behavior under pilot

operating conditions and closely match the timing of the measured tracer response presented in Appendix B Figure B.4.

Appendix O

Observations on raw water quality variability and its impact on sample processing

As temperature changes and lake turnover occurs, the raw water quality in Lake Ontario can naturally vary and is influenced by both seasonal and hydrodynamic conditions. Since these experiments were conducted over a span of two years, with each set of three experiments performed on different days, the raw water quality was inherently variable. Consequently, the coagulant dose required to achieve specific destabilization conditions also differed between runs.

In particular, during some periods of higher temperature ($>12\text{ }^{\circ}\text{C}$), the coagulant dose required to achieve optimal destabilization was observed to be greater than on cooler days under otherwise comparable conditions. This was attributed to increased biological activity and particle load in the water due to season changes (i.e., temperature, pH, turnover, algae growth).

It was also noted that for these experiments, the sample processing time for the methods described in Section 2.4 of the body of the paper was considerably longer. Processing an effluent sample of $\sim 700\text{ mL}$ took nearly a week, compared to the typical one hour. When examined under the microscope, slides from these experiments showed increased amounts of particulate debris that fluoresced. Representative images of these slides are included below.

This information highlights the natural variability of raw water quality and underscores the importance of accounting for environmental and seasonal factors when conducting performance demonstrations and interpreting experimental results.

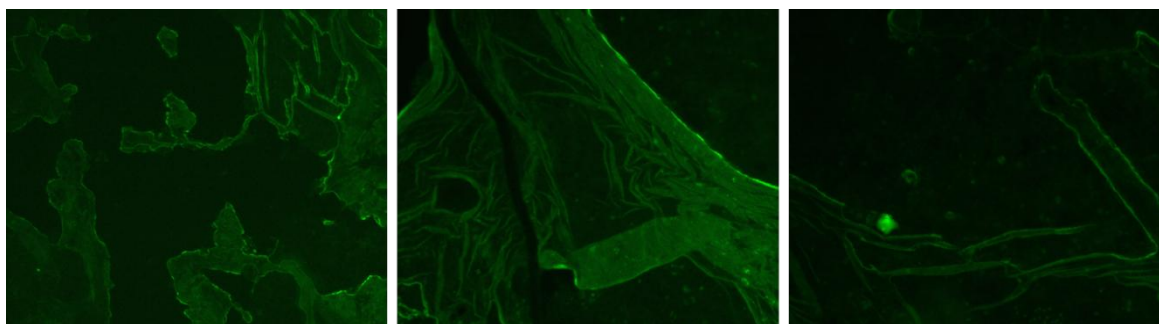


Figure O.1. Microscopic images of effluent water samples exhibiting elevated particulate loading and fluorescent interference. These samples correspond to runs in which raw water quality variability likely resulted in prolonged membrane filtration times and overcrowded slides during enumeration.

Appendix P

Microscope images of *Cryptosporidium* oocysts and microplastics

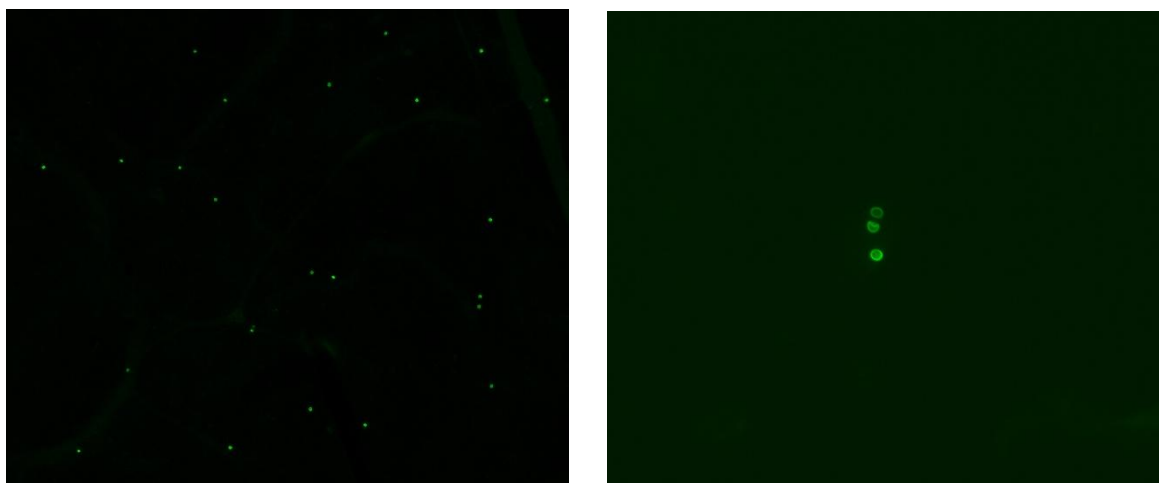


Figure P.1. *Cryptosporidium* oocysts under the microscope: Left-Oocysts at 10x magnification, Right-Oocysts at 20x magnification.

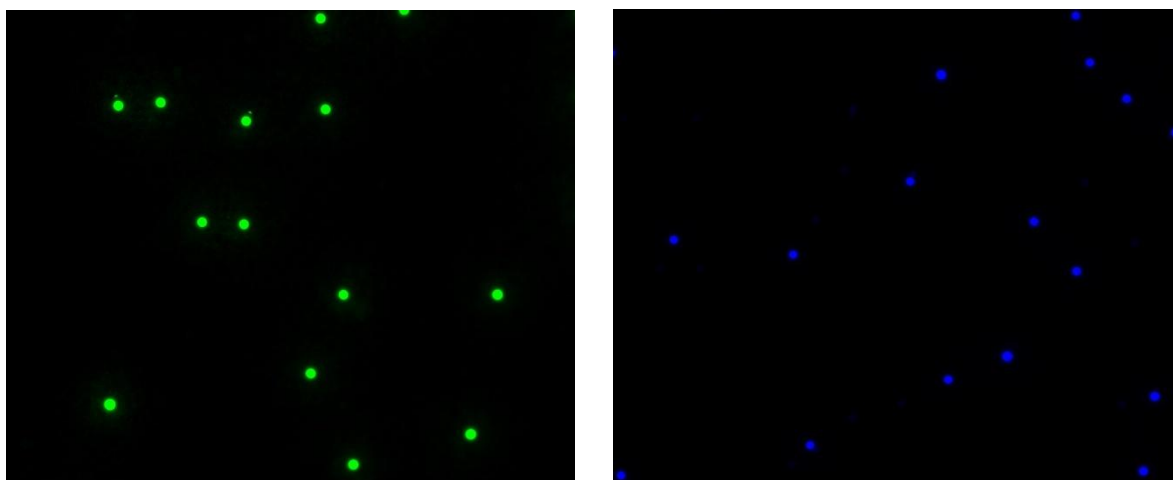


Figure P.2. Microspheres (or Microplastics [MPs]) under the microscope: Left- Carboxylated YG MPs at 20x magnification, Right-Pristine BB MPs at 20x magnification.