

Rethinking filtration performance assessment for public health protection

by

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AUTHOR'S DECLARATION

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

I understand that my thesis may be made electronically available to the public.

STATEMENT OF CONTRIBUTIONS

Elyse Batista was the sole author for Chapters 1 and 4, which were written under the supervision of Dr. Monica B. Emelko and Dr. William B. Anderson and were not written for publication.

This thesis consists in part of two manuscripts that are being prepared for submission to peer-reviewed journals. Exceptions to sole authorship of material are as follows:

Research presented in Chapter 2:

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ABSTRACT

Minimizing acute health risks from waterborne pathogens such as *Cryptosporidium* is the paramount goal of drinking water treatment. Because oocysts of the protozoan *Cryptosporidium* resist chlorine-based disinfectants and require complex and expensive detection methods, removal by physico-chemical filtration (CAF) is critical. Regulatory frameworks such as the US EPA suite of Surface Water Treatment Rules (SWTRs) and their Canadian analogs prescribe treatment credits based on filtered water turbidity, assuming the achievement of turbidity targets must reflect well-operated treatment and ≥ 3 -log oocyst removal. However, in systems reliant on low turbidity (< 2 NTU), low dissolved organic carbon (DOC; < 2 mg/L) source water, raw water turbidity often meets or exceeds filtered water targets, obscuring whether coagulant dosing is resulting in sufficient particle destabilisation. As a result, treatment plants may unknowingly operate at coagulant doses that fail to achieve the particle destabilization required for pathogen removal. This challenge is further compounded because low turbidity, low DOC waters have fewer interactions between particles (as particle concentrations are low) resulting in the need for higher doses of coagulant to increase contact opportunities by precipitating additional particles. Here, pilot-scale CAF investigations confirmed that oocyst removal was dependent on sufficient particle destabilization. Filter challenge studies using *Cryptosporidium* oocysts were run using low turbidity, low DOC source water and various coagulant doses. The experiments were replicated at similar operational conditions over several years and consistently demonstrated an increased risk of oocyst passage when insufficient coagulant was added and inadequate particle destabilization occurred. The results incontrovertibly demonstrated that turbidity is inadequate as a sole indicator of particle destabilization necessary for ensuring sufficient oocyst removal by CAF, particularly for low turbidity, low DOC source waters. Zeta potential analysis proved to be a useful tool for indicating sufficiency of particle destabilization. Zeta potential values within ± 5 mV of zero were required to consistently achieve ≥ 3 -log removal of *Cryptosporidium* oocysts by filtration of low turbidity, low DOC Lake Ontario source water; in these cases, ≥ 4 -log removal of oocysts was often achieved. As expected, higher coagulant doses than those typically practiced for low turbidity, low DOC source waters—specifically, coagulant doses that led to aluminum hydroxide solid precipitation—were required to achieve these levels of *Cryptosporidium* removal by CAF. These findings highlight the dangers of sole reliance on turbidity as an indicator of post-filtration water quality and treatment performance and underscore the need for complimentary monitoring tools to ensure protection of public health in systems reliant on higher quality source waters. Integrating zeta potential monitoring into routine coagulation control could provide operators—especially those dealing with the challenge of determining coagulant dose in the absence of substantial turbidity—with an indication of sub-optimal particle destabilization and associated poor filtration performance. These insights also point to broader implications for regulatory policy, as current turbidity-based treatment credits may not always adequately reflect true pathogen removal performance. Further operational guidance for zeta potential operationalization alongside turbidity analysis is needed to help ensure sufficient *Cryptosporidium* removal by CAF.

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DEDICATION

For Bill Anderson, of course.

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LIST OF ACRONYMS

AGI – Acute gastrointestinal illness

Alum – Aluminum sulfate

CAF – Chemically-assisted filtration

DOC – Dissolved organic carbon

GAC – Granular activated carbon

US EPA – United States Environmental Protection Agency

HLR – Hydraulic loading rate

IFA – Immunofluorescence assay

LT2ESWTR – Long-Term 2 Enhanced Surface Water Treatment Rule

mV – Millivolt

NOM – Natural organic matter

NTU – Nephelometric turbidity unit

PACl – Polyaluminum chloride

PBS – Phosphate buffered saline

PBST – Phosphate buffered saline with tween

SWTRs – Surface Water Treatment Rules

TOC – Total organic carbon

UV – Ultraviolet

WTP – Water treatment plant

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND

The minimization of acute health risks—particularly those associated with waterborne pathogens—remains the primary objective of drinking water treatment (Hrudey and Hrudey, 2004; WHO, 2016). Despite major advancements in treatment technologies, both outbreaks and endemic waterborne disease continue to pose substantial threats to public health, ranking among the most common risks linked to drinking water globally (Ramírez-Castillo et al., 2015; Bourli et al., 2023; Lee et al., 2018; Kunz, 2024). Historically, the introduction of safe water technologies substantially reduced mortality: in major U.S. cities in the early 1900s, these interventions accounted for nearly half of the total decline in mortality, with even greater reductions observed in child mortality (Cutler and Miller, 2005). This enduring public-health benefit underscores the importance of maintaining robust treatment barriers against microbial contaminants.

Cryptosporidium emerged as a pathogen of global concern due to its resistance to chlorination and its ability to cause severe gastrointestinal illness at low infectious doses (Korich et al., 1990; EPA, 1991; Finch et al., 1994; 1997). While several protozoan pathogens can cause waterborne illness, *Cryptosporidium* garners particular regulatory attention because of its heightened resistance to oxidant-based disinfectants. Although ultraviolet (UV) irradiation is effective for inactivating oocysts, its performance depends on adequate upstream filtration to reduce particle loads and prevent shielding effects (Templeton et al., 2005; Mamane and Linden, 2006). Consequently, physico-chemical filtration, also called chemically-assisted filtration (CAF), remains a critical barrier to ensure protozoan pathogen removal.

Despite the importance of protozoan control during drinking water treatment, treated-water concentrations of *Cryptosporidium* are not routinely monitored due to the large sample volumes required (i.e., thousands of liters), high analytical costs, long processing times, and variable recovery rates (Regli et al., 1991; Haas et al., 1996; Signor and Ashbolt, 2006). While Maximum Contaminant Levels (MCLs) or Maximum Acceptable Concentrations (MACs) are common regulatory mechanisms for ensuring that chemical contaminants are sufficiently removed during drinking water treatment, they are not feasible for protozoa because of their low infectious dose, sporadic occurrence, and laborious and costly detection methods (Regli et al., 1991; Haas et al., 1996). To address these challenges, the U.S. suite of Surface Water Treatment Rules (SWTRs) and their Canadian analogs establish treatment, monitoring, and operational requirements designed to ensure “well-operated” drinking water treatment (EPA, 1989, 1999, 2002, 2006; Health Canada, 2019). These rules rely on Treatment Technique (TT)–based approaches that assign pathogen removal credits based on surrogate performance parameters rather than direct pathogen measurement. Within this framework, turbidity removal performance serves as the primary surrogate indicator of particulate and protozoan removal by CAF (EPA, 2003; Health Canada, 2012).

Turbidity is a valuable water quality parameter because it is affordable, reproducible, and easily monitored in real time (EPA, 2006; Payment and Locas, 2011; WHO, 2017). Turbidity reflects light scattering by suspended particles, but scattering intensity depends on particle size, shape, color, and refractive index, meaning similar NTU values can correspond to very different particle loads (Patania et al., 1995; Emelko

et al., 2005; Ballantyne et al., 2024). Larger, aggregated particles scatter light more efficiently, while smaller particles contribute less to measured turbidity (Lawler, 1997; Crittenden et al., 2012; HACH, n.d.). Turbidity is routinely measured throughout the treatment process beginning from raw water characterization to post-filtration assessment. Although it is not a reliable surrogate for *Cryptosporidium* oocyst removal by CAF, lower turbidity is *generally* associated with better treatment performance, including *Cryptosporidium* oocyst removal by CAF (Patania et al., 1995; Huck et al., 2002a; 2002b; Emelko et al., 2003; 2005).

The Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) specifically targets *Cryptosporidium* removal from water and mandates that treatment systems achieve at least 3-log oocyst removal through filtration, disinfection, or a combination thereof (EPA, 2006). Systems without UV inactivation may comply by meeting turbidity performance standards: ≤ 0.3 NTU in at least 95% of monthly combined filter effluent (CFE) measurements, with each individual filter maintaining ≤ 1.0 NTU at all times during operation. Canada's Drinking Water Guidelines adopt a similar structure, assigning filtration credits for *Cryptosporidium* and *Giardia* removal based on turbidity limits and supported by key research demonstrating filtration performance (Nieminski and Ongerth, 1995; Patania et al., 1995; Edzwald and Kelley, 1998; Dugan et al., 2001; Huck et al., 2002a; 2002b; Emelko, 2001; Emelko et al., 2003; 2005; Assavasilavasukul et al., 2008). An additional 0.5-log treatment credit is available under LT2ESWTR for systems achieving ≤ 0.15 NTU in at least 95% of monthly CFE measurements. The Guidelines for Canadian Drinking Water Quality (Health Canada, 2019) and the U.S. Partnership for Safe Water program (EPA, 2012) further encourage systems to strive for individual filter effluent turbidity levels of ≤ 0.1 NTU 95% of the time as a benchmark for optimized treatment.

CAF or equivalent treatment is required for *Cryptosporidium* removal during drinking water treatment. Since oocysts are not inactivated using chlorine-based disinfectants (Korich et al., 1990; EPA, 1991; Finch et al., 1994; 1997), physical removal of oocysts by filtration is critical. However, CAF is not a simple size-exclusion process; it relies on particle destabilization mechanisms for attachment to media surfaces (Crittenden et al., 2012; Edzwald, 2013; Ballantyne et al., 2024). In such waters, turbidity measurements may already meet treated-water targets, masking the need for coagulant addition. Several studies have documented *Cryptosporidium* breakthrough and removals below 3-log despite effluent turbidities well below 0.3 NTU and even 0.1 NTU (West et al., 1994; Patania et al., 1995; States et al., 1997; Huck et al., 2001; Emelko et al., 2003; Emelko and Huck, 2004; Hendricks et al., 2005; Assavasilavasukul et al., 2008). Although low counts, non-detects, and variable recovery rates contribute to uncertainty in data reporting and interpretation (Emelko et al., 2008; Chik et al., 2018), they do not fully explain the observations.

In natural waters, *Cryptosporidium* oocysts carry a net negative surface charge, in part because of natural organic matter (NOM) adsorption, which impacts how they interact, both with one another and other surfaces (O'Melia and Stumm, 1967; Edzwald, 2013). Coagulant addition prior to CAF is therefore essential to overcome the electrostatic and other forces preventing oocysts and other particles from aggregating and being retained by granular filter media. This well-known dependence of filtration performance on coagulation for particle destabilization is the basis for the term 'chemically-assisted filtration' (Ballantyne et al., 2024).

Zeta potential analysis may provide much-needed insight into the sufficiency of coagulant addition to ensure oocyst removal by CAF. Zeta potential analysis has long been used in water treatment research

(Riddick, 1961; Erdei, 1963; Bean et al., 1964), but its widespread adoption in the drinking water industry is limited. Most investigations have focused on minimizing clarified-water turbidity or maximizing 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), rather than ensuring CAF performance specifically for protozoan removal. In low turbidity, low DOC source waters, low particle concentrations limit the interactions between particles required for effective destabilization, and as such may require higher than expected coagulant doses to increase contact opportunities and form micro-precipitates. Zeta potential analysis should be useful for informing coagulant dosing in low turbidity, low DOC source waters as it indicates net charge at the boundary layer of particles suspended in water.

The challenges associated with treating low turbidity, low DOC source waters underscore the need for operational approaches that more directly reflect the underlying CAF process necessary for ensuring *Cryptosporidium* oocyst removal. As utilities continue to depend on well-operated filtration to meet regulatory expectations for protozoan pathogen removal, there remains a critical gap in the capacity to ascertain whether coagulation is truly sufficient to meet treatment targets. Zeta potential may offer support to turbidity-based practices by providing insight into particle destabilization under conditions where turbidity and associated coagulant demand is minimal. The work presented in this thesis examines the limitations of sole reliance on turbidity and the potential for zeta potential analysis to provide insight into particle destabilization to ensure sufficient *Cryptosporidium* removal by CAF during treatment of low turbidity, low DOC source waters.

1.2 RESEARCH OBJECTIVES

The overall goal of this work was to investigate whether 3-log removal of *Cryptosporidium* oocysts was consistently achievable during stable operation under a range of coagulant conditions. To address this goal, the following research objectives were developed:

1. Evaluate whether clarified water turbidity is a sufficient indicator of particle destabilization by coagulation for ensuring *Cryptosporidium* removal by CAF in low turbidity, low DOC source waters.
2. Assess the utility of zeta potential analysis for indicating sufficiency of particle destabilization for ensuring *Cryptosporidium* removal by CAF in low turbidity, low DOC source waters.

1.3 RESEARCH APPROACH

A literature review was conducted to establish what work had already been published investigating *Cryptosporidium* removal by filtration. The scope of publications included was limited to studies that quantified the removal of oocysts by granular media filtration—whether introduced experimentally or present naturally in source waters. The limited number of studies examining oocyst removal from low turbidity, low DOC source waters supported the pilot-scale experimental design by identifying these conditions as requiring more focused investigation.

Oocysts were added upstream of pilot-scale filters at a constant rate throughout each experiment. Samples collected from filter influent and effluent at fixed intervals enabled calculation of both

instantaneous and experiment-wide removals. This methodology is well established 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).

A total of 119 pilot-scale performance demonstrations were conducted, yielding 600 filter effluent samples. Experiments evaluated a range of conditions, including coagulant dose (optimal, sub-optimal, and no addition), temperature (warm $\geq 8^{\circ}\text{C}$ and cold $< 8^{\circ}\text{C}$), and hydraulic state (stable operation, ripening, and hydraulic surge) across seven filter configurations representative of Great Lakes source waters. Conventional indicators such as turbidity were used alongside zeta potential analysis to better quantify particle destabilization, which is essential for effective removal of particles and protozoan pathogens in low turbidity, low DOC source waters.

1.4 THESIS STRUCTURE

This thesis is organized as a compendium of two papers, Chapters 2 and 3, prepared as refereed papers for publication that will be submitted to peer-reviewed journals. Therefore, some introductory material is reiterated in Chapters 2 and 3.

Chapter 1 is an introduction and provides rationale for this research. Chapter 2 presents research demonstrating the risk of relying solely on turbidity as an indication of protozoan pathogen removal by filtration and calls for supporting indicators of well-operated filtration in order to protect public health. Chapter 3 investigates zeta potential analysis as a supporting measurement of well-operated filtration alongside turbidity in systems reliant on low turbidity, low DOC source water. Chapter 4 integrates key findings from both manuscripts and potential implications for the drinking water treatment industry.

Each data chapter (i.e., Chapters 2 and 3) includes a reference list and a detailed methods section to be consistent with the as-submitted manuscript versions. The reference sections at the end of this thesis compiles references from the remaining chapters. Additional materials and methods are included in Appendices B and C.

CHAPTER 2. SOLE RELIANCE ON TURBIDITY IS INSUFFICIENT FOR ENSURING REMOVAL OF PROTOZOAN PATHOGENS BY FILTRATION

Batista, E. J., De Silva, K. S., Ballantyne, L., Ruecker, N. J., Lee, K., Scott, D. J., Anvari, A., Anderson, W. B., and Emelko, M. B. (2026). Sole reliance on turbidity is insufficient for ensuring removal of protozoan pathogens by filtration. In preparation for submission for peer-reviewed journal.

2.1 SUMMARY

Minimizing health risks from waterborne pathogens is the central goal of drinking water treatment. *Cryptosporidium* remains challenging 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, data collected during this pilot-plant-based research clearly demonstrates that reliance on turbidity alone is insufficient to indicate treatment adequacy in systems treating source waters with low turbidity (<2 NTU) and dissolved organic carbon (<2 mg/L) because it does not assure sufficient particle destabilization by coagulant addition prior to filtration. Additional tools are therefore needed in these systems to ensure treatment credits in U.S. Surface Water Treatment Rules and their international counterparts are justified.

2.2 INTRODUCTION

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 physico-chemical filtration and chlorination were instrumental in reducing mortality. These interventions contributed to nearly half of the total mortality reduction observed in major U.S. cities between 1900 and 1936, 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). The severity of waterborne disease outbreaks has been significantly reduced by implementation of filtration and disinfection processes (Rochelle and Clancey, 2006), but they continue to pose significant public health concerns globally (Aboytes et al., 2004; Hrudey and 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 Levels (MCLs) or Maximum Acceptable Concentrations (MACs) in treated water is not feasible for regulating treatment of *Cryptosporidium* oocysts because of their low-level occurrence (e.g., <5 oocysts/100 L), 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 including treatment, monitoring, and operational requirements (i.e., primarily filtration [or equivalent technology], disinfection, turbidity performance, and microbe log-removal standards) is used to protect public health by ensuring “well-operated” drinking water treatment is maintained (EPA, 1989; EPA, 1996; EPA, 1998; EPA, 2002; MECP, 2003; EPA, 2006; Health Canada, 2019).

The set of Surface Water Treatment Rules (SWTRs) 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 using two years of treatment-plant-specific source water monitoring to determine necessary minimum levels of oocyst removal 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 *Cryptosporidium* 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; this 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, 2006). Whether systems treating source water with low turbidity and low dissolved organic carbon (DOC) 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 (nephelometric turbidity units) in at least 95% of monthly combined filter effluent 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, 2012). Systems identified as having higher risk based on source water oocyst concentration require additional treatment under the LT2ESWTR. An additional 0.5-log *Cryptosporidium* removal credit is prescribed for maintaining ≤ 0.15 NTU in at least 95% of monthly CFE measurements (EPA, 2006).

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, colour, and refractive index, meaning similar NTU values can correspond to widely different particle loads (Davies-Colley and Smith, 2001; Crittenden et al., 2012; HACH, n.d.). Larger or aggregated particles scatter light more efficiently than smaller particles (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 (LeChevallier and Norton, 1992; EPA, 2006; Payment and Locas, 2011; WHO 2017). It is routinely monitored at key points throughout the treatment process to inform performance. Raw/untreated water turbidity (together with DOC concentration and character) is a

primary factor governing coagulant dosing requirements (Edzwald, 1993; Edzwald and 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, are not only plausible but also likely in systems treating source water with low turbidity (<2 NTU) and low DOC (<2 mg/L). This is because turbidity may often 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 by De Silva et al. (2026), 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” (CAF). When source water turbidity and DOC are low, turbidity measurements provide limited to no diagnostic value for determining 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) on 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, regulatory requirements beyond filter effluent turbidity monitoring 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, a closer examination of the literature suggests 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. The objectives of this study were to: (1) demonstrate that—despite the greater potential for coagulant underdosing that may lead to increased oocyst passage through filters—*Cryptosporidium* removal by CAF of low turbidity, low DOC source waters has not been explicitly investigated, and (2) identify the potential for systematic risk of protozoan pathogen passage through drinking water systems reliant on low turbidity, low DOC source waters compliant with current regulatory requirements. The removal of parasitic protozoa, specifically *Cryptosporidium*, by pilot-scale conventional filtration was evaluated under varying conditions over a period of several years 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 such systems.

2.3 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 that are generally perceived to present greater protozoan contamination and associated

public health risk (Mann et al., 2007; LeChevallier and 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 absence of oocysts in treated water (Gammie et al., 1998; Aboytes et al., 2004; Emelko and 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 [Crittenden et al., 2012]) at which 2.5-, 3-log, or greater *Cryptosporidium* removals were not attained (LeChevallier and Norton, 1992; Kelley et al., 1995; Nieminski and Ongerth, 1995; States et al., 1997; Baudin and 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 when filter operation was considered stable and “well-operated” because of compliance with regulatory turbidity limits (i.e., filter effluent turbidity ≤ 0.3 NTU).

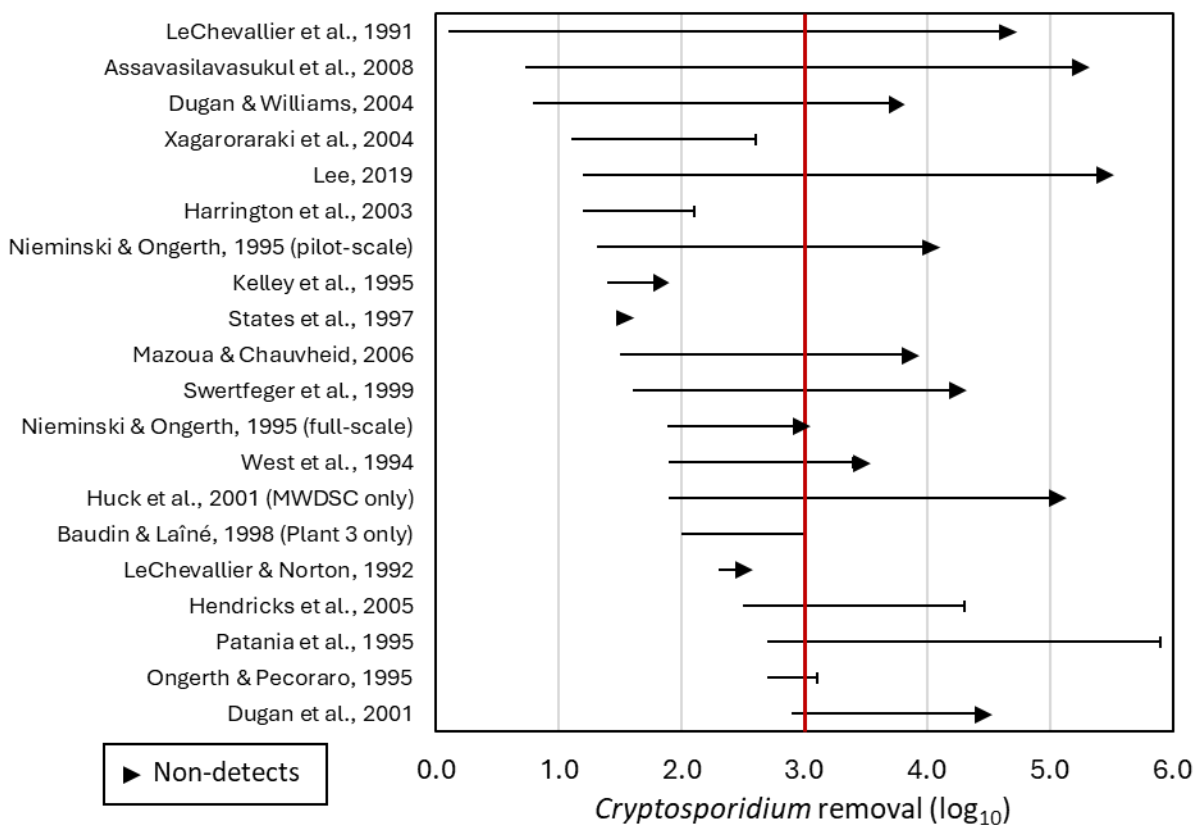


Figure 2.1: *Cryptosporidium* removal by stable, “well-operated” (i.e., filter effluent turbidity ≤ 0.3 NTU) filtration during which ≥ 3 -log oocyst removal was not consistently achieved. Studies presented here met the following criteria: (i) filter challenge studies using *Cryptosporidium* oocysts, (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. In those studies, all effluent non-detects were treated as a value of “1” (in place of the zero/non-detect) to enable calculation of oocyst removal, which is believed to be greater than or equal to that value.

Analytical limitations that lead to the prevalence of non-detects in filter effluents may contribute to some of these *Cryptosporidium* removal values 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 to calculate 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 were not consistently met during stable filter operation (Figure 2.1; Appendix A, Table A.1). A summary of published filter challenge studies investigating *Cryptosporidium* removal by granular media filters is provided in Appendix A, Table A.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 removal estimates fail to meet the treatment credits prescribed by the suite of SWTRs. Coagulant under-dosing prior to filtration may help explain some of these observations because it can be undetected in systems treating low turbidity, low DOC source water and can lead to periodic or even chronic insufficiency of 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 (with turbidity rarely exceeding 1 NTU and often <0.3 NTU) under varying particle-destabilization conditions achieved by coagulant addition. Pre-chlorinated raw and filter effluent turbidity for each filter run is provided in Appendix F. 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 threshold 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.

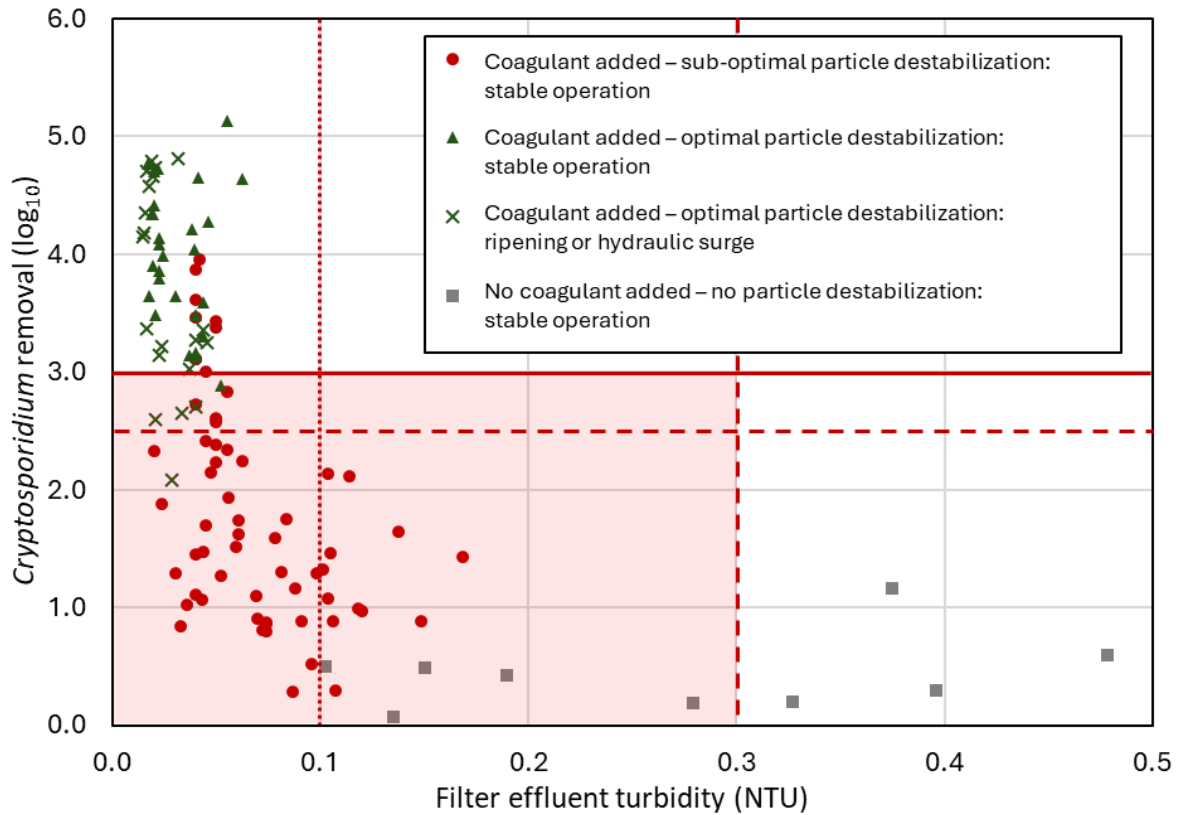


Figure 2.2: Overall effective log reduction of *Cryptosporidium* oocysts by pilot-scale filtration vs. filter effluent turbidity during experiments conducted with different degrees of particle destabilization (optimal, sub-optimal, and no coagulant addition) during stable operation, filter ripening, and hydraulic surge. Dotted and dashed red 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 the Guidelines for Canadian Drinking Water Quality, respectively. Solid and dashed red 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.

Throughout a typical filter run, filter effluent turbidity remained consistently low (frequently below 0.3 NTU), including during the seeding and sample collection period when oocysts were introduced to the influent and grab samples were collected. This behaviour was consistent across all stable operation experiments (steady-state filtration with consistent effluent water quality), except for those intentionally operated during ripening or under hydraulic disturbance (conditions following filter backwash or during abrupt flow changes, respectively). Filter effluent turbidity values for individual experiments can be found in Appendix F.

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). As expected, 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 and would thus lead to 3-log *Cryptosporidium* treatment credits when they are clearly unwarranted. Coagulant doses during the sub-optimal coagulation experiments (e.g., <15 mg/L alum; Appendix A) reflected typical

practices at plants treating low turbidity, low DOC source water (Son and 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. This could be because coagulant adsorption is rarely uniform, leading to 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 NTU and often below 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 lower processed sample volume which led to low oocyst counts and non-detects resulting in more uncertain removal values (Emelko et al., 2008; Chik et al., 2018). For low turbidity, low DOC source waters, especially those with pH >7.5, hydrolyzed alum species are predominant and sufficient particle destabilization for maximizing filtration performance requires the coagulation regime to shift from adsorption and charge neutralization toward micro-precipitate formation and sweep flocculation (Stumm and O’Melia, 1968; Amirtharajah and Mills, 1982; Amirtharajah and O’Melia, 1990; Crittenden et al., 2012; Chapter 3). Under 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 and O’Melia, 1988; Edzwald and Kelley, 1998).

These particle destabilization experiments align with previous investigations that have discussed the importance of coagulation prior to filtration (LeChevallier et al., 1991; Ongerth and Pecoraro, 1995; Patania et al., 1995; Edzwald and 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). The experiments performed further emphasize the critical importance of ensuring sufficient coagulant addition in systems treating low turbidity, low DOC water—regardless of filter effluent turbidity—to ensure particle destabilization so that particles, including oocysts, are effectively removed by physico-chemical filtration. 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 is further discussed in De Silva et al. (2026).

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 and Huck, 2004; Amburgey et al., 2005; Amburgey and 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 and 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. 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, 2006; Health Canada, 2012).

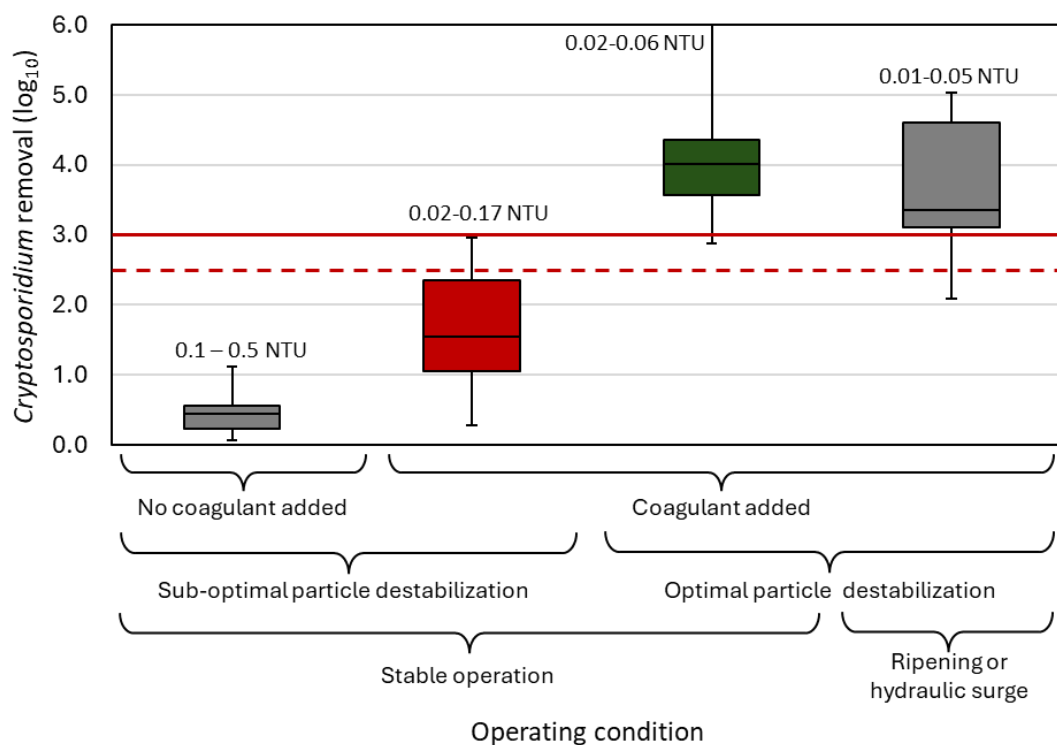


Figure 2.3: Overall effective log reduction of *Cryptosporidium* oocysts by pilot-scale filtration at different operational conditions. Each boxplot summarizes *Cryptosporidium* oocyst removals by filtration that were observed at each operational condition investigated, including coagulant addition and particle destabilization for stable operation 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 and dashed red 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 the expected absence of naturally-occurring environmental oocysts (as opposed to oocysts that were introduced to the filter influent streams) due to generally low environmental occurrence and expectations of removal by coagulation, flocculation, and sedimentation processes, they 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 typically not human infective (LeChevallier and Norton, 1992; Ryan et al., 2021; Helmy and 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 that these instances of environmental oocyst presence did not affect the overall study results because the few associated experiments were excluded from subsequent analyses.

Figures 2.4(a) and 2.4(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 2.4(c) and 2.4(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 2.4(e) and 2.4(f) show oocysts as they appeared on the membrane surface during enumeration at 200x magnification. Figure 2.4(e) also shows other particulate material among the visible oocysts in filter effluent samples. Figure 2.4(f) show the presence of interior cellular structures typical of *Cryptosporidium* spp. oocysts (though not always visible under microscopy).

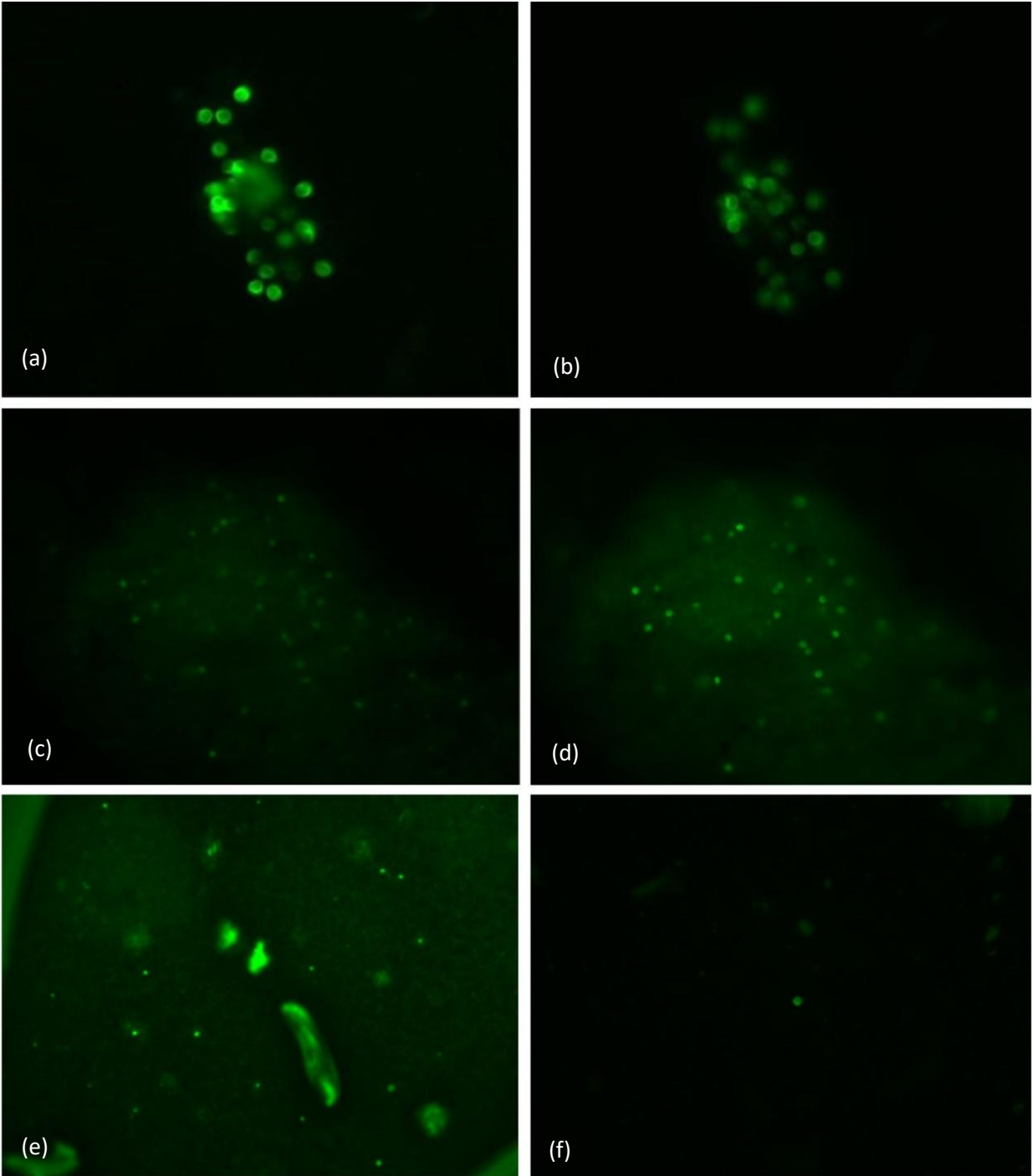


Figure 2.4: *Cryptosporidium* oocysts in negative control samples collected from filter influent and effluent streams. Images (a) through (d) are examples of oocysts detected in pilot-scale filter influent samples prior to any oocyst addition to filter influent streams. Images (a) and (b) show the same 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 small volume (i.e., 1 L) influent samples (e.g., as depicted in Figure 2.4(a) and 2.4(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 that 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; Kuczynska et al., 2005).

More critically, the occasional detection of *Cryptosporidium* oocysts in filter effluent streams (Figure 2.4(e) and (f)) 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, 2006). 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 filter 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 filter 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. 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 in the IJC report (IJC, 2021) 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). These challenges may be further amplified intermittent presence of human-infective oocysts, resulting in too few reportable illnesses to signal outbreaks and draw attention to underlying vulnerability of affected areas. Although reliance on turbidity may be sufficient for ensuring adequate *Cryptosporidium* removal by filtration of other types of source water, turbidity measurement cannot meaningfully inform coagulant dose selection in systems reliant on low turbidity, low DOC source water; 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.

2.4 CONCLUSIONS

1. Monitoring filter effluent turbidity alone is insufficient for universally ensuring removal of protozoan pathogens by filtration.
2. 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 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.
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.

2.5 MATERIALS AND METHODS

2.5.1 GENERAL RESEARCH APPROACH

To highlight the risk of protozoan pathogen passage through drinking water systems that are compliant with current regulatory turbidity requirements, 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 low turbidity, low DOC 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., 2002b; Emelko, 2003; Emelko and Huck, 2004; Assavasilavasukul et al., 2008a; Hijnen and Medema, 2010; Nascimento et al., 2020; Lee, 2019; Ballantyne et al., 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. 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 2.5. Seed suspensions were coagulated prior

to introduction into the filter influent to create a range of particle destabilization conditions informed by zeta potential analysis.

Optimal particle destabilization was operationally defined in De Silva et al. (2026); 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 to indicate sub-optimal particle destabilization.

2.5.2 PILOT-SCALE 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 most testing was performed at 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 B.

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.

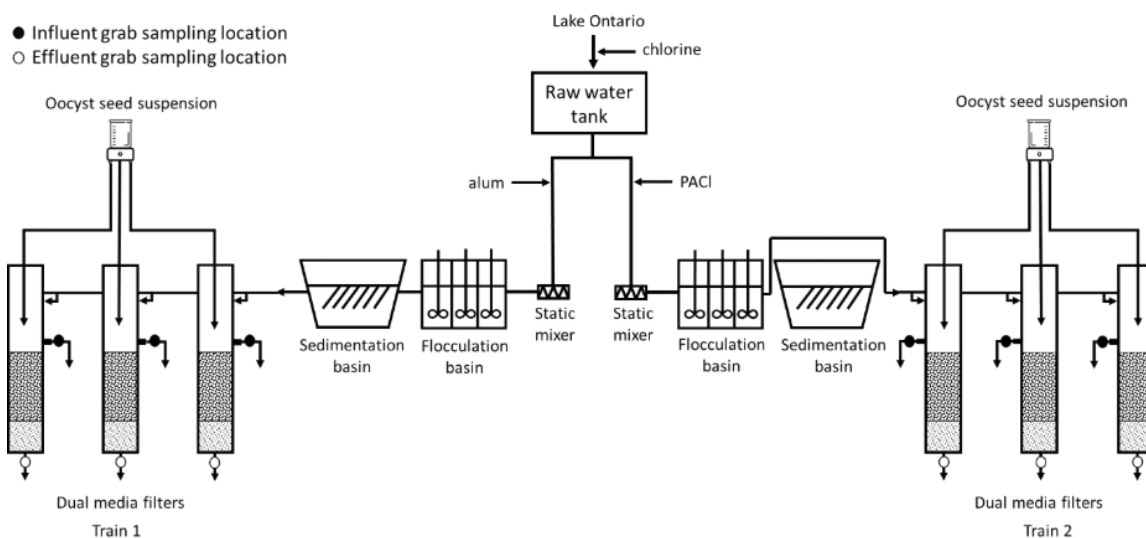


Figure 2.5: Schematic flow diagram of pilot-scale filtration plant at R.C. Harris WTP, Toronto (not to scale). Train 1 was representative of conventional filtration (i.e., flocculation, sedimentation, and filtration) whereas Train 2 was

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 F.

Cryptosporidium oocyst removal by both conventional 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 low turbidity, low DOC 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 Horgan WTP, details of which can be found in Appendix B.

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

2.5.3 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-buffered saline (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 to the filter influents. Zeta potential analysis (see Section 2.5.5.2) 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 2.5) 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 (T_0), 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 filter backwashing (typically 24 hours prior) during 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 2.5) 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 2.6. Pilot-scale experiments at the Horgan WTP followed the same procedures, with influent and effluent samples collected at 10-minute intervals (Scott, 2008).

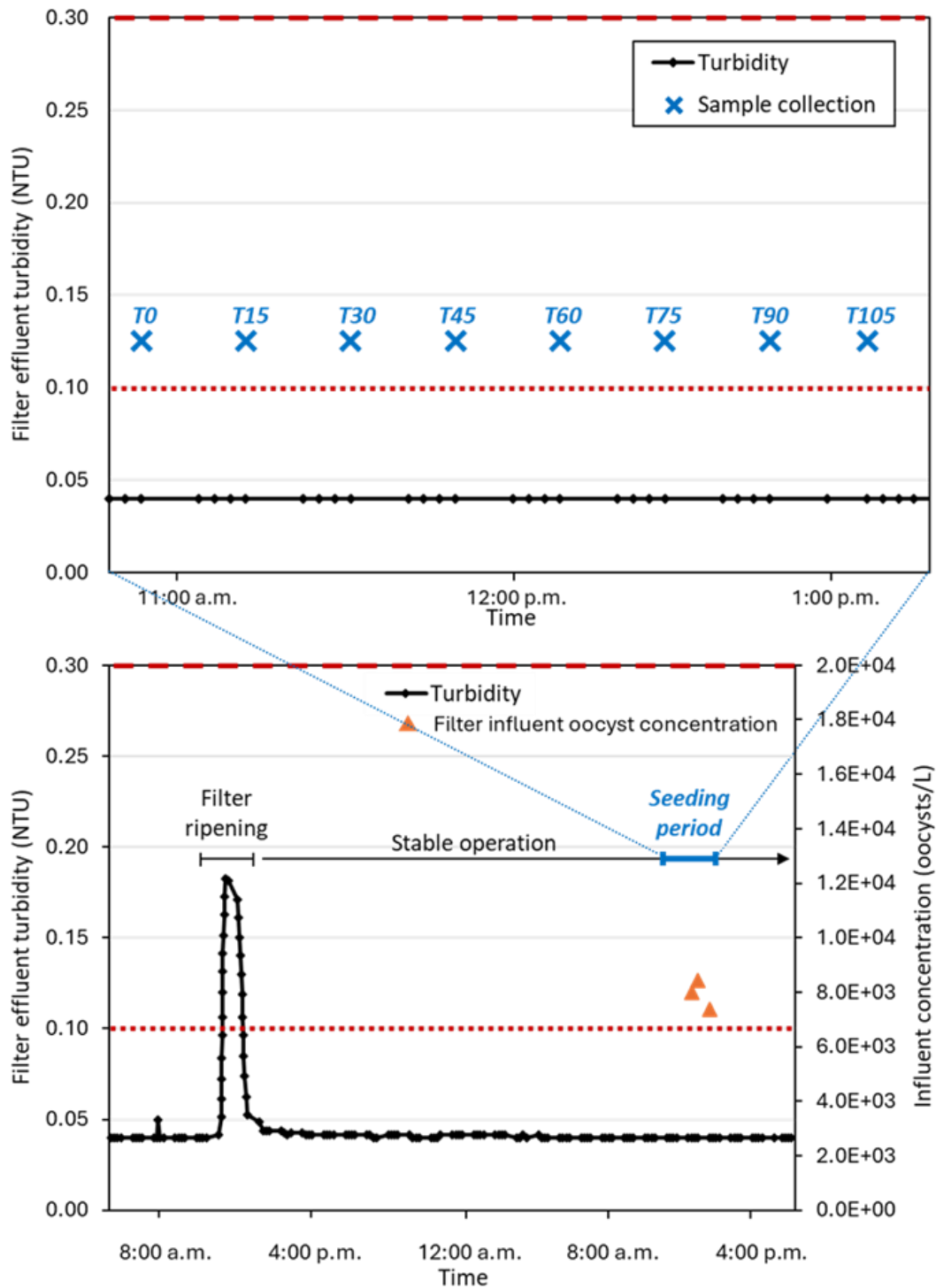


Figure 2.6: Sample collection timing relative to turbidity during a typical filter run (as shown and described by Figure 2.2). Turbidity changes are shown throughout the run, highlighting *Cryptosporidium* oocyst seeding and sampling during stable operation. The inset provides higher-resolution timing 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.

2.5.4 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, 0.7–1 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 in 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. The membranes 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 dependent 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; Patania et al., 1995; Edzwald and Kelley, 1997; Dugan et al., 2001; Hashimoto et al., 2001; Huck et al., 2001; 2002b; Emelko et al., 2005; Mazoua and Chauveheid, 2005; Ballantyne et al., 2014). For these reasons, and consistent with regulatory practice (EPA, 2006; Health Canada, 2012) that 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.

2.5.5 WATER QUALITY ANALYSIS

2.5.4.1 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.

2.5.4.2 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 the final 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 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 report 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 to be inconsequential (i.e., typically within 1-2 mV). Accordingly, zeta potential is reported herein as average values only.

2.6 CHAPTER 2 REFERENCES

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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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3.1 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 low turbidity, low DOC 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 low turbidity, low DOC 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 low turbidity, low DOC 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 low turbidity, low DOC 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 low turbidity, low DOC 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 low turbidity, low DOC source water.

3.2 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, 2006; Health Canada, 2012). 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, 2006). 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 low turbidity, low DOC source water (Ballantyne et al., 2024; Chapter 2).

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; Tobiasson 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 low turbidity, low DOC source waters was also assessed.

3.3 METHODS

3.3.1 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 low turbidity, low DOC 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 low turbidity, low DOC 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 D). 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 and 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 and 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 low turbidity, low DOC 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.

3.3.2 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 B.

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.

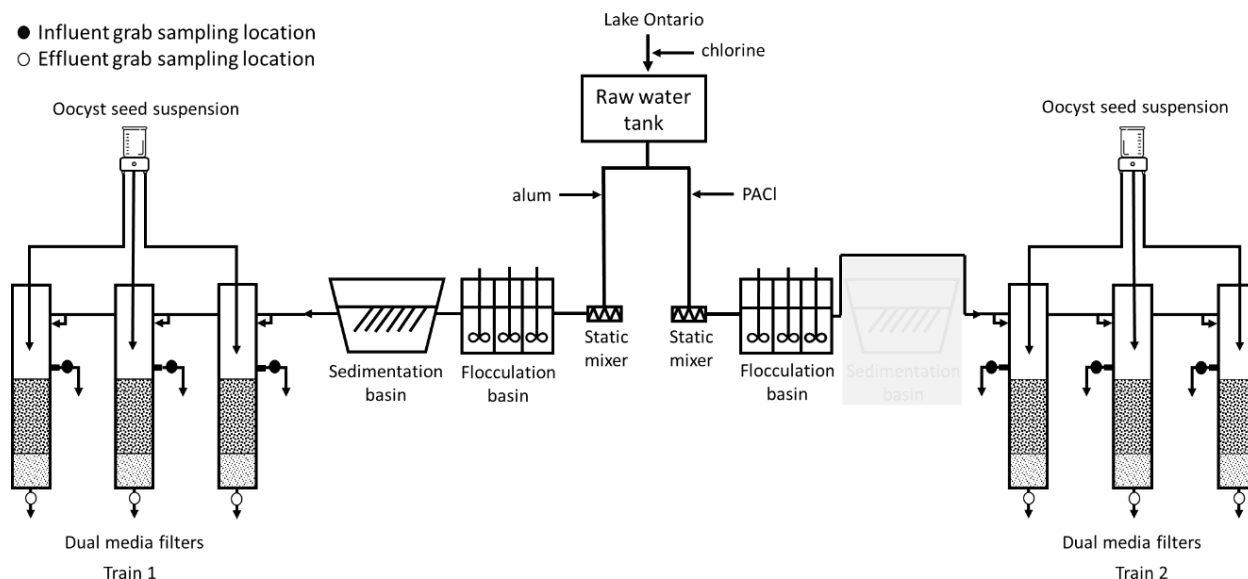


Figure 3.1: Schematic flow diagram of pilot-scale filtration plant at R.C. Harris WTP, Toronto (not to scale). The study examined *Cryptosporidium* oocyst removal by CAF with conventional filter media designs and loading rates comparable to those used by systems dependent on low turbidity, low DOC Great 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 low turbidity, low DOC 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 B). 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	300	300	300	300	300

3.3.3 CRYPTOSPORIDIUM HANDLING AND ANALYSIS

3.3.3.1 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 107 oocysts/L, resulting in an expected concentration of ~105 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 104–105 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 3.3.4) 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.

3.3.3.2 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 (T_0) when seeding was initiated. These T_0 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 C). Hence, the first sample after T_0 was collected at T_{15} . 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).

3.3.3.3 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, 2006; Health Canada, 2012)—log removal values in this study are presented as point estimates.

3.3.4 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.

3.4 RESULTS AND DISCUSSION

3.4.1 *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.

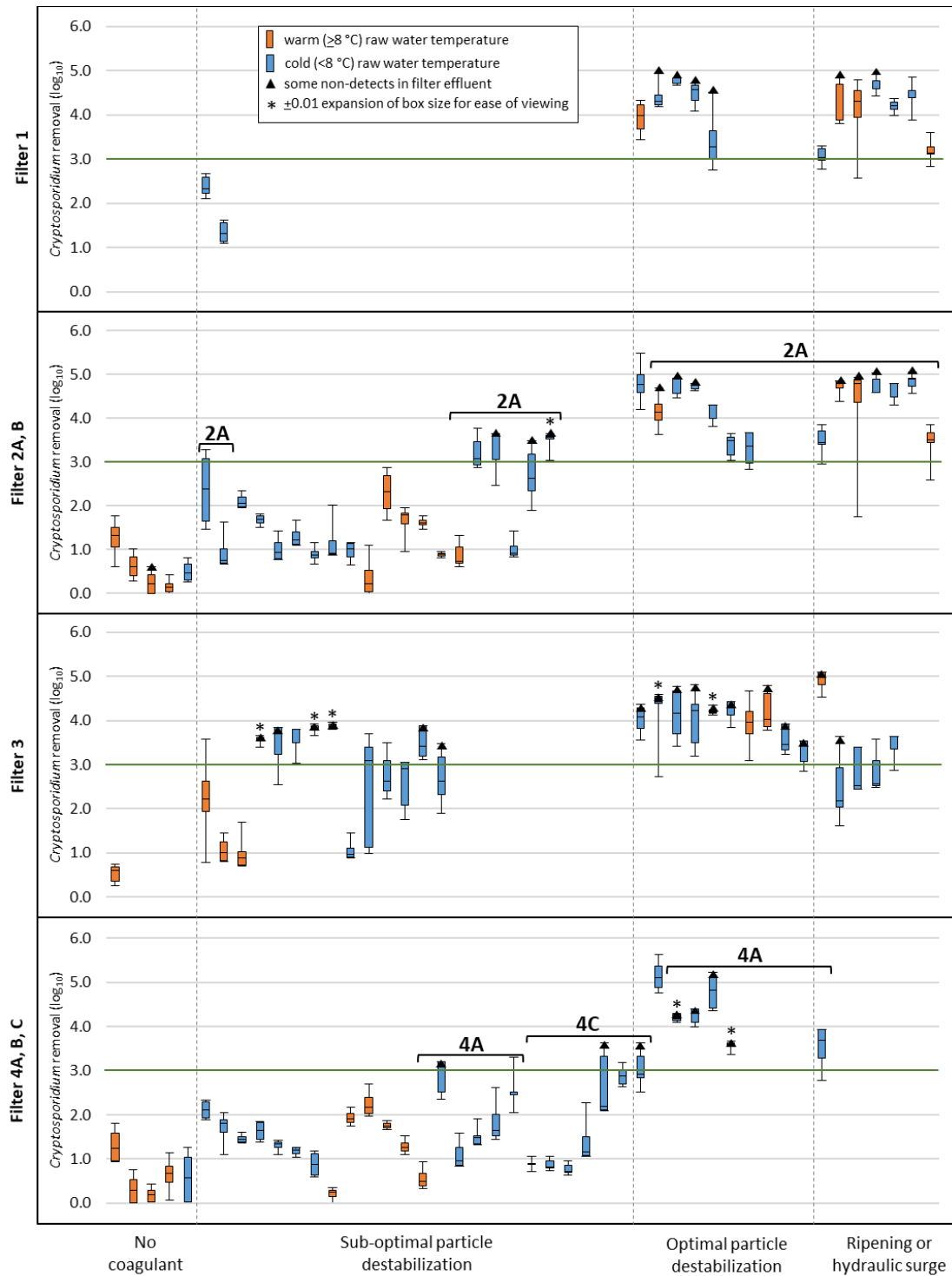


Figure 3.2: *Cryptosporidium* oocyst removal by pilot-scale conventional CAF configurations described in Table 3.1. Each box and whisker combination represents one individual filter run/experiment. Dashed vertical lines separate different operational conditions. The whiskers indicate maximum and minimum 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 3.3.1. 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).

3.4.2 ZETA POTENTIAL AS A CONTROL FOR ENSURING ADEQUATE COAGULANT DOSE 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.

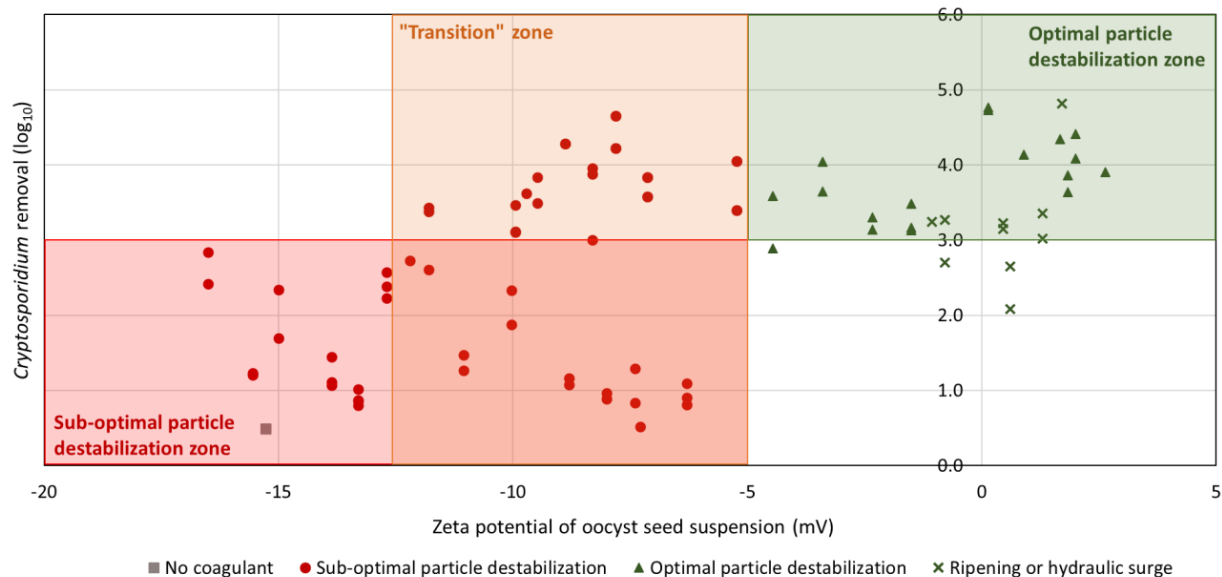


Figure 3.3: *Cryptosporidium* oocyst removal by pilot-scale conventional CAF as a function of zeta potential after coagulant addition. Each point is the effective log reduction calculated from 4-5 samples collected during a filter run. Data are overlaid with color-shaded regions: the optimal particle 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 low turbidity, low DOC source waters in which low turbidity and low DOC concentrations can create a misleading sense of lesser treatment needs. Low turbidity, low DOC 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, 2006; 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.

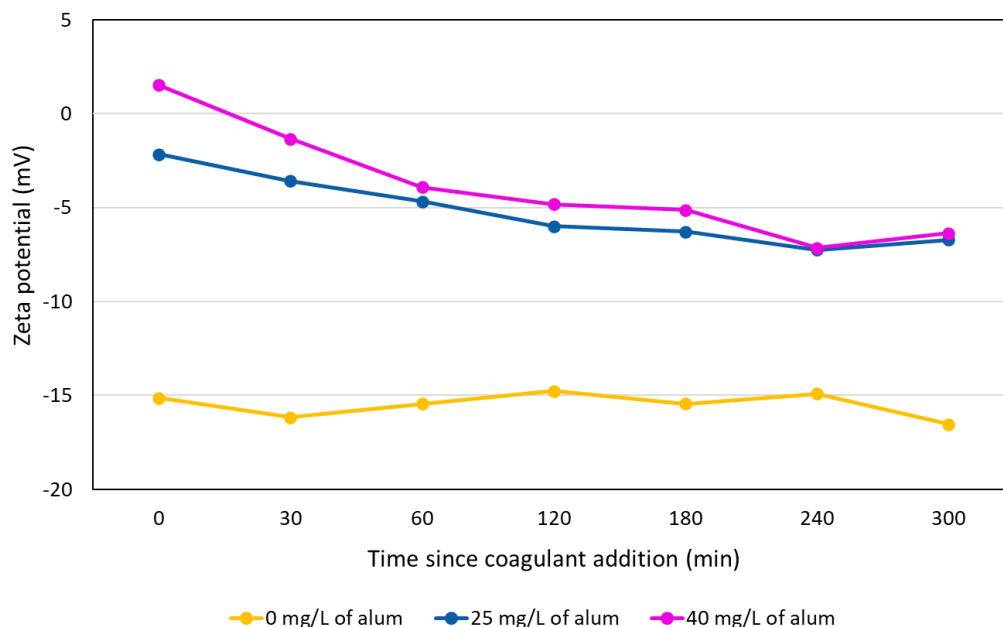


Figure 3.4: Zeta potential of coagulated pilot plant pre-chlorinated raw water as a function of time (further details can be found in Appendix E, Table E.1).

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 low turbidity, low DOC 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 low turbidity, low DOC 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.

3.5 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 CAF in systems reliant on low turbidity, low DOC 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 low turbidity, low DOC 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 low turbidity, low DOC 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 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.

3.6 CHAPTER 3 REFERENCES

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CHAPTER 4. CONCLUSIONS AND IMPLICATIONS

4.1. CONCLUSIONS

The main conclusions from this research are presented below:

- Monitoring filter effluent turbidity alone is insufficient for universally ensuring removal of *Cryptosporidium* oocysts by filtration.
- 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 oocyst removal expectations.
- Previously established regulatory expectations of 2.5- and 3-log *Cryptosporidium* oocyst removal by well-operated CAF during typical operating conditions when performance is stable remain reasonable and can be achieved in systems treating low turbidity, low DOC source waters when particle destabilization by coagulant addition is sufficient.
- Temperature and filter media depth were not primary drivers of oocyst removal by CAF; rather, performance was governed by the sufficiency of particle destabilization.
- Zeta potential analysis is a valuable operational tool for assessing coagulant dose sufficiency and supporting effective by CAF in systems reliant on low turbidity, low DOC source water.
- A system-specific zeta potential target can be established to guide coagulant dosing for reliable CAF performance.

4.2. IMPLICATIONS AND FUTURE WORK

This work confirmed established understanding of metal-salt based coagulation for particle destabilization that indicates low turbidity, low DOC source waters require higher coagulant doses than typically expected in practice to ensure particle destabilization sufficient for achieving the 3-log *Cryptosporidium* removal targets prescribed the suite of U.S. SWTRs and their Canadian analogs for well-operated CAF. However, determining the coagulant dose required to ensure particle destabilization is dynamic. While zeta potential analysis can be helpful in determining the dose required to ensure adequate particle destabilization, it is important that zeta potential analysis not be interpreted as a direct indicator of oocyst removal or filter performance. It also cannot be used as a replacement for turbidity, regardless of source water quality, and must only be used as a supporting tool to help guide coagulant dosing during conditions where turbidity is unable to provide insight into coagulant requirements. The use of zeta potential analysis alongside turbidity measurements in low turbidity, low DOC source waters may aid drinking water treatment utilities in reducing the risk of sub-optimal particle destabilization and poor oocyst removal. Future work should continue to investigate the utility of zeta potential analysis as a tool for determining coagulant dosing. Evaluation of online zeta potential analysis at pilot-scale would be beneficial to gain further insight into system-specific changes impacting coagulant addition. Future work may also investigate removals of other protozoan pathogens not investigated in this thesis (e.g., *Giardia*, *Toxoplasma*).

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APPENDIX A: LITERATURE SUMMARY AND ADDITIONAL DETAILS SUPPORTING FIGURE 2.1

Several studies have assessed *Cryptosporidium* removal by granular media filtration. Table A.1 summarizes existing investigations reporting *Cryptosporidium* oocyst removals by granular media filtration.

Table A.1: Investigations of *Cryptosporidium* oocyst removal by granular media filtration.

Raw water turbidity					Source water parameters		Operational period(s) investigated			<i>Cryptosporidium</i> oocysts			Filter effluent turbidity during investigation	
	Investigation	Site	Scale	Filtration type	Turbidity (NTU)	TOC (mg/L)	Stable operation	Ripening, hydraulic surge or step	End-of-run, breakthrough	Origin or addition point	Removal range (log ₁₀)	Non-detects?	<0.3 NTU? ^a	<0.1 NTU? ^b
<2 NTU	West et al., 1994	Hetch Hetchy Reservoir; San Francisco, CA	pilot	direct	0.3-0.7	2.6-3.9 [†]	✓	✓		seeded prior to coagulant addition point	1.9-3.4	✓	✓	✓
	Ongerth & Pecoraro, 1995	Tolt & Cedar Rivers; Seattle, WA	pilot	direct	0.3-0.5	1.6-1.8 [†]	✓			seeded prior to coagulant addition point	2.7-3.1* 1.5* [§]		✓	
	Edzwald et al., 2000	Hemlock Reservoir; Fairfield, CT	pilot	conventional	0.7-0.9	2.5-3.3	✓			seeded prior to coagulant addition point	5.4-5.5	✓	✓	✓
	Dugan & Williams, 2004	Ohio River; OH	pilot	in-line	0.2-0.3	1.0-3.0 [†]	✓			seeded prior to coagulant addition point	3.6-4.3 0.7-4.3 [§]	✓	✓	✓
	Amburgey et al., 2001	Lake Lanier; Buford, GA	pilot	direct	1.8*	2.0	✓	✓		seeded into filter influent	0.9-1.8		✓	
	Edzwald et al., 1996	Hemlock Reservoir; Fairfield, CT	pilot	conventional	0.5-1.5	2.5-3.0	✓			seeded into settled water	4.3-5.5*	✓	✓	✓
≥2.0 NTU	LeChevallier et al., 1991	North America	full	multiple	range	range	✓			present in environment	0.1-4.6	✓	✓	
	LeChevallier & Norton, 1992	Ohio River; OH	full	conventional	5.0-240	1.0-3.0 [†]	✓			present in environment	2.4	✓		
		Central Pennsylvania			2.0-75	NR					2.5	✓		
		Central Canada			0.3-150	NR					2.3	✓		
	Hall et al., 1995	Thames River; UK	pilot	conventional	2.5-11*	NR	✓	✓		seeded prior to coagulant addition point	2.9-4.4	✓		
	Kelley et al., 1995	not reported	full	conventional	1.7-99	NR	✓			present in environment	1.8*	✓	✓	
											1.4*	✓		
	Nieminski, 1994; Nieminski & Ongerth, 1995	Provo River; Bluffdale, UT	pilot	conventional direct	4.0-23	1.5-3.0	✓			seeded into filter influent	1.9-4.0 1.3-3.8	✓	✓	
		Huntington Creek; Price, UT	full	conventional direct	2.5-28	1.2-2.4	✓				1.9-2.8 2.6-2.9			
	Patania et al., 1995	San Gabriel Reservoir; Azusa, CA	pilot	conventional	1.0	2.6-3.9 [†]	✓			seeded prior to coagulant addition point	4.3-5.2	✓	✓	✓
		San Gabriel River; Azusa, CA			10.0-13	2.6-2.9 [†]	✓				5.0			
		Mallard Reservoir; Contra Costa, CA			4.0	3.9	✓				4.2-4.7			
		Tolt Reservoir; Seattle, WA			1.4	1.6-1.8	✓				2.7-3.1			
		Willamette River; Tualatin, OR			2.0-2.5	1.5-1.9	✓				5.1-5.9			

Van Duser et al., 1996	Tualatin River; OR	full	conventional	1.2-4.0*	1.5-1.9 [†]	✓		present in environment	3.2-4.1	✓	✓	
		pilot		4.6-29*	1.5-1.9 [†]				2.9-4.1	✓	✓	
Scott et al., 1997	La Verne, CA	pilot	conventional	0.7-8.0	2.6-2.9 [†]	✓		seeded prior to coagulant addition point	1.7-4.3			
States et al., 1997	Allegheny & Youghiogheny Rivers; Pittsburgh, PA	full	conventional	NR	NR	✓		present in environment	1.5	✓	✓	
Yates et al., 1997	La Verne, CA	pilot	direct	0.7-8.0 [†]	2.6-2.9 [†]	✓		seeded into filter influent	3.7-4.5		✓	
Edzwald & Kelley, 1998	New Haven, CT	pilot	conventional	1.6-2.1	2.7-2.8 [†]	✓		seeded prior to coagulant addition point	4.7*		✓	
Baudin & Lainé, 1998	France	full	conventional	10*	1.4*	✓	✓	✓	present in environment	NR	✓	✓
			direct	1.0*	1.4*					4.0	✓	✓
			conventional	15*	3.0*					2.0-3.0		✓
Swertfeger et al., 1999	Ohio River; OH	pilot	conventional	7.7-196*	1.0-3.0 [†]	✓		seeded into settled water	2.5-4.0 ^W	✓	✓	
									1.6-4.2 ⁵	✓	✓	
Dugan et al., 2001	Ohio River; OH	pilot	conventional	2.3-63	2.0-3.0	✓		seeded prior to coagulant addition point	0.2-3.6* [§]			
		pilot	conventional	0.8-103	1.7-2.7			seeded prior to coagulant addition point	2.9-4.4*	✓	✓	
Harrington et al., 2001, 2003	Lake Mendota; WI	pilot	conventional	5.5*	3.0-6.0 ^{††}	✓	✓	seeded prior to coagulant addition point	1.4-1.8			
		pilot	conventional	8.6*	3.0-6.0 ^{††}	✓		seeded prior to coagulant addition point	1.2-2.1	✓		
Hashimoto et al., 2001	Sagami River; Kanagawa, Japan	full	conventional	5.8-67	NR	✓		present in environment	2.5*	✓		
2002a	Ottawa River; Ottawa, ON	pilot	conventional	1.0-30 [†]	5.0-7.0 [†]	✓	✓	✓	seeded into filter influent	5.5	✓	✓
	La Verne, CA	pilot	conventional	0.7-8.0 [†]	2.6-2.9 [†]	✓	✓	✓	seeded into filter influent	3.0	✓	✓
	Detroit River; Windsor, ON	pilot	conventional	1.0-40 [†]	1.6-2.3 [†]	✓			seeded into filter influent	4.2*	✓	✓
Huck et al., 2001; 2002b	Colorado River; La Verne, CA	pilot	conventional	0.4-2.4	2.6-2.9	✓	✓	✓	seeded into filter influent	2.0-5.0	✓	✓
									0.0-2.0 [§]	✓		
									1.9-4.9 ^R			
Emelko et al., 2000, 2003, 2001	Ottawa River; Ottawa, ON	pilot	conventional	1.0-2.7	5.0	✓	✓	✓	seeded into filter influent	1.9-3.1 ^B		
									4.8-6.0	✓	✓	
									0.0-5.5 [§]			
Emelko et al., 2000, 2003	Ottawa River; Ottawa, ON	pilot	conventional	1.0-30 [†]	5.0-7.0	✓		✓	seeded into filter influent	4.0-6.0 ^B		
									0.9-3.2 ^B			
									4.7-5.8	✓	✓	
Emelko et al., 2001	Ottawa River; Ottawa, ON	pilot	conventional	1.0-30 [†]	5.0-7.0 [†]	✓		✓	seeded into filter influent	1.3-3.3 ^B	✓	
									3.9-5.1	✓	✓	
Emelko, 2001	Ottawa River; Ottawa, ON	pilot	conventional	1.0-30	5.0-7.0	✓	✓	✓	seeded into filter influent	4.4-5.4 ^B	✓	
									4.9-5.8*	✓	✓	
									0.2-5.1* ^R	✓		
									1.4-3.0* ^B			
Emelko, 2001	Detroit River; Windsor, ON	pilot	conventional	1.0-40	1.6-2.3	✓			seeded into filter influent	4.1-4.2*	✓	✓
	University of Waterloo; Waterloo, ON (tap water)	pilot	direct	1.5	<1.0	✓	✓		seeded into filter influent	5.0-5.6*	✓	✓
									4.2-4.6* ^R	✓	✓	

Emelko & Huck, 2004	Ottawa River; Ottawa, ON	pilot	conventional	1.0-30	5.0-7.0	✓		seeded into filter influent	4.1-4.4 ^ø		
	University of Waterloo; Waterloo, ON (tap water)	pilot	conventional	1.5-1.7	<1.0	✓	✓	seeded into influent stream	4.8-5.6 1.5-2.5 ^ø 3.4-4.6 ^R	✓	✓
Xagarorarakis et al., 2004	Lake Mendota; WI	pilot	conventional	0.5-5.0	3.0-6.0 ^{††}	✓	✓	seeded prior to coagulant addition point	0.3-2.6		
Hendricks et al., 2005	Horsetooth Reservoir; CO	pilot	conventional	1.2-3.5	3.0	✓		seeded into settled water	2.5-4.3*	✓	✓
Amburgey et al., 2005	Lake Lanier; Buford, GA	pilot	direct	1.5-2.6	2.0*	✓	✓	seeded into filter influent	1.5-1.9		
Mazoua & Chauvheid, 2006	Meuse River; Belgium	full	conventional	5.0-30 [†]	NR	✓		present in environment	1.5-3.8	✓	✓
Assavasilavasukul et al., 2008a 2008b	Lake Mendota; WI	pilot	conventional	0.5-3.6*	3.0-6.0 [†]	✓		seeded prior to coagulant addition point	1.5-5.1 ^H 1.1-2.3 ^L	✓	✓
										✓	✓
Brown & Emelko, 2009	University of Waterloo; Waterloo, ON (tap water)	pilot	in-line	3.1-4.9*	<1.0 [†]	✓		seeded into filter influent	3.8-4.8 0.1-2.7 ^ø	✓	✓

- * Averaged parameter; average parameters were only reported where ranges or individual parameter measurements were not reported in investigations
† Parameter not stated; included value is an estimate based on other available literature from comparable source waters
‡ DOC value reported in place of TOC value
† Checkmark included only if turbidity threshold was met consistently throughout experimentation
H Removal reported for experiments using a high oocyst concentration
L Removal reported for experiments using a low oocyst concentration
W Removal reported for experiments run during winter
S Removal reported for experiments run during summer
R Removal reported for experiments performed during ripening or hydraulic surge or step
B Removal reported for experiments performed during end-of-run or filter breakthrough
ø Removal reported for experiments performed using sub-optimal coagulant addition during stable operation
NR Parameter not reported

Table A.1 only contains investigations using granular media filtration as part of the treatment process. Investigations into riverbank filtration, up-flow filtration, membrane filtration, and investigations using a surrogate (e.g., microspheres) in place of *Cryptosporidium* oocysts were omitted.

APPENDIX B: PILOT-SCALE HORGAN WATER TREATMENT PLANT

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 process that was similar to Train 2 of the Harris WTP, incorporating coagulation, flocculation, and dual-media filtration at hydraulic loading rates 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 Tables 2.1 and 3.1. 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 B.1: Filter media depth 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 B.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).

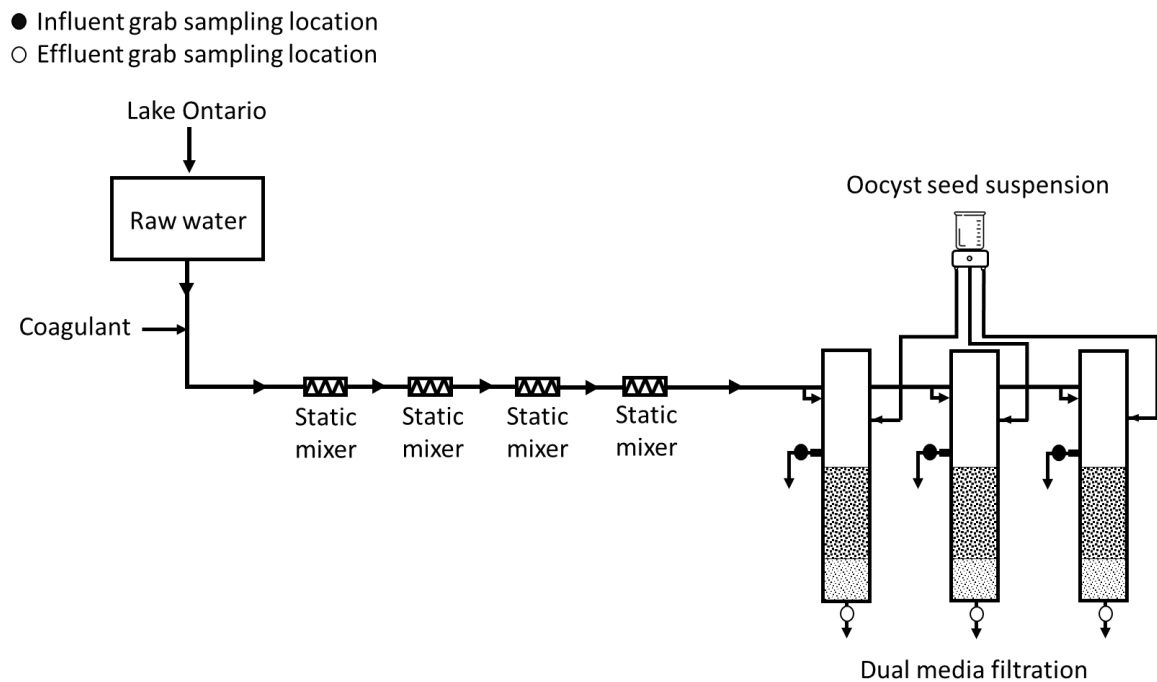


Figure B.1: Schematic flow diagram of pilot-scale filtration plant at Horgan WTP, Toronto (not to scale). During the filter runs, a continuous input of *Cryptosporidium* oocyst seed suspension was introduced into the filters. Influent and effluent grab samples were collected to estimate *Cryptosporidium* oocyst removal by the filters (Scott, 2008).

APPENDIX C: TRACER TESTS

Tracer tests were conducted to (i) ensure adequate mixing of oocysts introduced to the filter influents by visual assessment and (ii) estimate seed suspension residence time in the filters to inform sample collection times. In these experiments, food grade dye (Red No. 40 Dye - Allura Red) and salt (NaCl) tracers were used. The dye test enabled rapid assessment and visualization of flow; thus, it provided a good indication of oocyst mixing and dispersion after introduction to the filter influent streams. The salt test involved conductivity measurements that enabled quantitative estimation of water residence time in the filters from the filter seeding point. A continuous feed (step-input) containing both tracers was introduced to the filter influent streams, as shown in Figure C.1. Filter effluent samples were collected at 2-minute intervals until the tracer concentrations stabilized/plateaued. Once the tracer concentration stabilized, tracer addition was discontinued, and samples were collected every 10 to 20 minutes until conductivity returned to baseline levels observed prior to the start of the experiments.

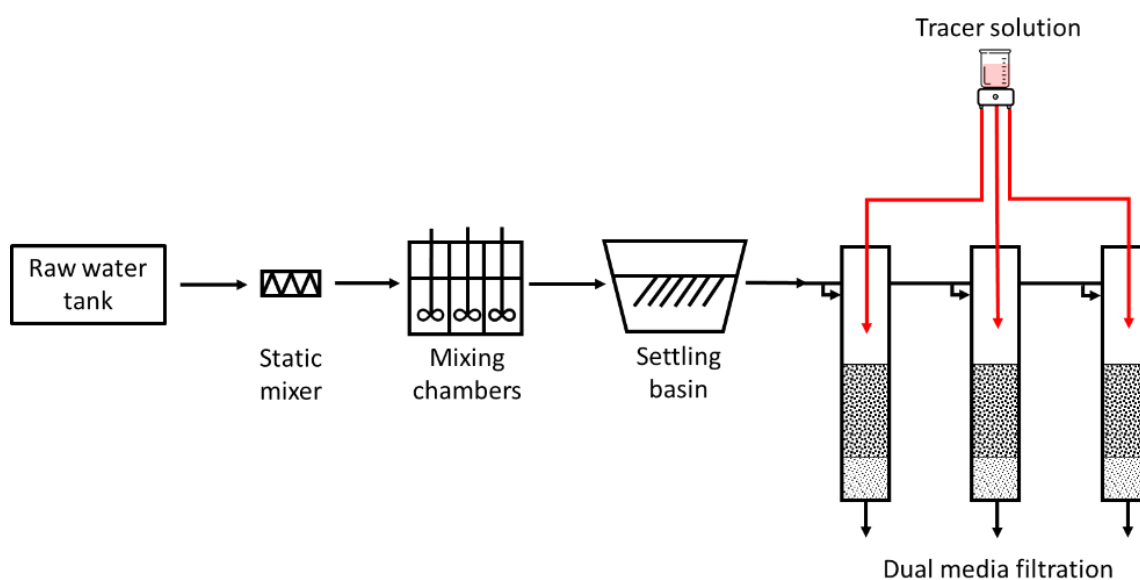


Figure C.1: Tracer study general experimental configuration.

The red dye tracer test demonstrated that the oocyst 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 (Figure C.1). This caused turbulence leading to upward dispersion. However, overall, the experiments demonstrated that oocyst 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 oocyst 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, using the oocyst seed suspension addition point, is shown in Figure C.2. The initial detection of the tracer occurred at approximately 15 minutes and based on this data the mean filter residence time was estimated to be around 30 minutes.

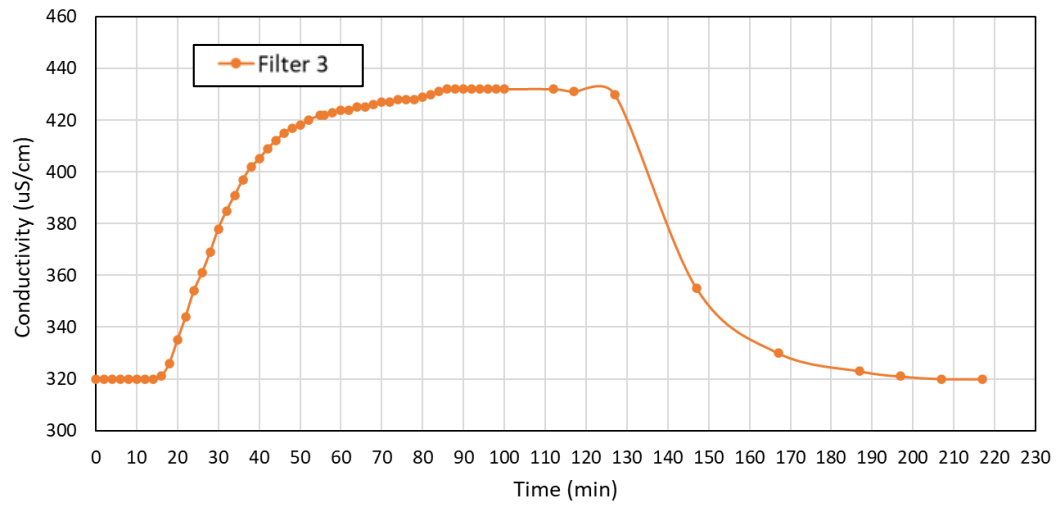


Figure C.2: Example conductivity breakthrough curves from the NaCl tracer test on Filter 3 using the oocyst seed suspension addition point.

APPENDIX D: 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 and 3). Figure D.1 illustrates an example of possible changes in turbidity and zeta potential that can be observed during preparation of the *Cryptosporidium* oocyst seed suspension.

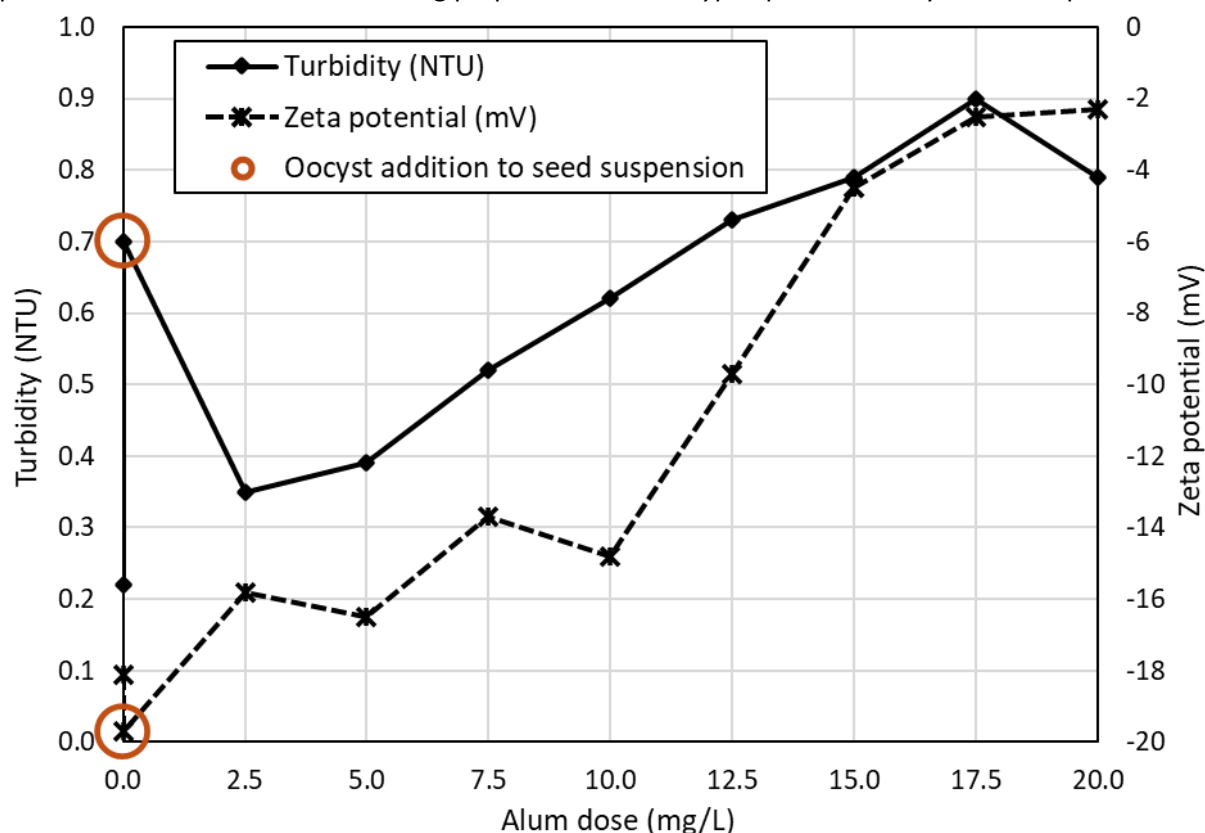


Figure D.1: Turbidity and zeta potential response to *Cryptosporidium* oocyst and incremental coagulant dosing in seed suspension. Coagulant was added in 2.5 mg/L increments, with periods of rapid mixing and settling occurring prior to turbidity and zeta potential readings. The initial alum addition 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 low turbidity, low DOC source waters, this illustrates how oocyst addition alters raw-water quality, sometimes enough that it can be measured as a change in turbidity. Regardless, it affects coagulant demand relative to raw water alone. 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 behaviour 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 (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 E: BENCH-SCALE INVESTIGATION OF 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 to assess changes in particle destabilization over time after coagulant addition. The raw data collected from this bench-scale experiment are presented in Table E.1 and used to generate Figure 3.4 in Chapter 3.

Table E.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 F: RAW DATA FROM CHAPTERS 2 AND 3

Table F.1: Raw water quality, pilot plant operational data, seed suspension data, and average *Cryptosporidium* oocyst removal for Chapters 2 and 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	Ripening	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	Ripening	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	-8.88	Stable	3	3.5
	2.2	1.0	8.36	-	PACI	0.9	PACI	12.5		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	Ripening	3	2.1
	6.0	0.2	8.44	-	PACI	0.9	PACI	12.5	-1.07	Ripening	3	2.6
30-May-19	10.5	0.8	7.18	-	alum	4.0	alum	40.0	-3.4	End of the run	4A	3.2
	7.7	0.3	8.5	-	PACI	0.9	PACI	12.5	-7.8		3	3.6
02-Aug-19	10.2	0.5	8.68	-	alum	4.0	alum	0.0	-15.27	Stable	3	4.0
13-Oct-21	18.0	0.5	8.0	-9.7	alum	5.0	alum	5.0	-6.3	Stable	3	0.5
					PACI	1.0	PACI	1.0	-7.3		3	1.1
10-Nov-21	6.7	0.2	8.0	-7.7	alum	4.0	alum	6.0	-9.7	Stable	2A	0.9
					PACI	0.9	PACI	1.4	-12.2		4A	0.8
19-Nov-21	4.9	0.2	8.0	-6.0	alum	4.0	alum	10.0	-10.0	Stable	3	3.1
					PACI	0.9	PACI	1.2	-13.3		3	3.5
14-Dec-21	4.8	0.4	8.0	-12.9	alum	4.0	alum	6.0	-8.3	Stable	2A	3.1
					PACI	0.9	PACI	2.4	-4.5		4A	1.0
15-Dec-21	4.9	0.4	8.0	-11.1	alum	4.0	alum	6.0	-13.9	Stable	4C	0.9
					PACI	0.9	PACI	2.0	-11.1		4C	0.8
16-Dec-21	4.7	1.8	8.0	-18.4	alum	4.0	alum	10.0	-12.7	Stable	4C	0.9
					PACI	0.9	PACI	2.4	-15.0		3	2.6
16-Dec-21	4.7	1.8	8.0	-18.4	alum	4.0	alum	10.0	-11.8	Stable	3	2.2
					PACI	0.9	PACI	2.4	-16.5		2A	2.4
04-Mar-22	2.0	0.4	7.9	-16.6	alum	5.0	alum	13.5	-0.8	Hydraulic surge	4A	1.7
12-Apr-22	4.5	0.2	8.0	-6.2	alum	5.0	alum	25.5	-1.5	Stable	4C	2.3
											3	2.8

Table F.2: Detailed *Cryptosporidium* oocyst removal data for Chapters 2 and 3. For counts of zero (i.e., non-detects, ND) a count of “1” was assigned as a conservative adjustment. This change is reflected in the “Filter Effluent *Cryptosporidium* (oocysts/L)” column (not performed for T₀ negative controls).

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	0.006	6	9.17E+02	2.31E+04	0.7	1	1.00E+00	4.33E-05	3.6
			15	0.006	15	2.42E+03		0.7	1	1.00E+00	4.33E-05	
			30	0.0045	90	2.51E+04		0.7	5	7.00E+00	3.03E-04	
			45	0.0045	85	2.55E+04		0.355	2	3.00E+00	1.30E-04	
			60	0.0045	70	2.24E+04		0.4	3	1.30E+01	5.63E-04	
			75	0.003	58	1.93E+04		0.7	1	1.00E+00	4.33E-05	
03-Aug-17	2A	Stable	0	0.006	0	0.00E+00	2.00E+04	0.7	0	0.00E+00	0.00E+00	3.8
			15	0.006	2	3.34E+02		0.7	1	1.00E+00	5.01E-05	
			30	0.003	80	2.65E+04		0.7	2	3.00E+00	1.50E-04	
			45	0.003	17	5.67E+03		0.7	2	3.00E+00	1.50E-04	
			60	0.003	71	2.37E+04		0.4	2	5.00E+00	2.51E-04	
			75	0.003	72	2.40E+04		0.7	0	1.00E+00	5.01E-05	
05-Oct-17	1	Stable	0	0.006	0	0.00E+00	6.42E+04	0.7	0	0.00E+00	0.00E+00	3.8
			15	0.006	0	0.00E+00		0.7	0	1.00E+00	1.56E-05	
			30	0.003	116	3.87E+04		0.7	3	4.00E+00	6.23E-05	
			45	0.003	159	5.30E+04		0.7	8	1.10E+01	1.71E-04	
			60	0.003	325	1.08E+05		0.7	2	3.00E+00	4.68E-05	
			75	0.003	171	5.68E+04		0.7	16	2.30E+01	3.59E-04	
05-Oct-17	2A	Stable	0	0.006	0	0.00E+00	4.74E+04	0.7	0	0.00E+00	0.00E+00	4.0
			15	0.006	0	0.00E+00		0.7	0	1.00E+00	2.11E-05	
			30	0.003	94	3.13E+04		0.7	0	1.00E+00	2.11E-05	
			45	0.003	207	6.90E+04		0.7	2	1.14E+01	2.41E-04	
			60	0.003	121	4.03E+04		0.7	2	3.00E+00	6.33E-05	
			75	0.003	147	4.90E+04		0.7	3	4.00E+00	8.44E-05	
23-Oct-17	1	Stable	0	0.006	0	0.00E+00	8.83E+04	0.7	0	0.00E+00	0.00E+00	4.3
			15	0.006	3	5.00E+02		0.7	0	1.00E+00	1.13E-05	
			30	0.006	180	3.00E+04		0.7	0	1.00E+00	1.13E-05	
			45	0.003	129	3.38E+04		0.7	3	4.30E+00	4.87E-05	
			60	0.006	486	1.27E+05		0.7	2	2.90E+00	3.28E-05	
			75	0.003	270	8.98E+04		0.7	3	4.30E+00	4.87E-05	
			90	0.003	358	1.19E+05		0.7	4	5.70E+00	6.45E-05	
			105	0.003	392	1.31E+05		0.7	4	5.70E+00	6.45E-05	

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 50 55 61 68 73 80 100	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	2 74 77 72 73 94 107 107	1.67E+02 7.40E+04 7.65E+04 7.15E+04 7.30E+04 9.40E+04 1.07E+05 1.07E+05	8.61E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 1 3 1 3 5 160 9	0.00E+00 1.40E+00 4.30E+00 1.40E+00 4.30E+00 7.10E+00 2.29E+02 1.29E+01	0.00E+00 1.63E-05 5.00E-05 1.63E-05 5.00E-05 8.25E-05 2.66E-03 1.50E-04	3.4
28-Nov-17	2A	Hydraulic Surge	0 50 55 61 68 71 80 100	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	0 59 68 61 80 116 118 100	0.00E+00 5.90E+04 6.75E+04 6.10E+04 8.00E+04 1.16E+05 1.18E+05 1.00E+05	8.58E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 1 0 1500 10 1 1 1	0.00E+00 1.00E+00 1.00E+00 1.50E+03 1.00E+01 1.40E+00 1.40E+00 1.40E+00	0.00E+00 1.17E-05 1.17E-05 1.75E-02 1.17E-04 1.63E-05 1.63E-05 1.63E-05	2.6
22-Jan-18	1	Hydraulic Surge	0 50 55 61 66 73 80 100	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	0 49 35 56 78 87 121 149	0.00E+00 4.90E+04 3.50E+04 5.55E+04 7.80E+04 8.70E+04 1.21E+05 1.49E+05	8.20E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 1 2 2 1 1 1 1	0.00E+00 1.00E+00 3.00E+00 3.00E+00 1.40E+00 1.40E+00 1.40E+00 1.40E+00	0.00E+00 1.22E-05 3.66E-05 3.66E-05 1.71E-05 1.71E-05 1.71E-05 1.71E-05	4.7

22-Jan-18	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	2 59 64 79 89 104 152 215	1.67E+02 5.90E+04 6.35E+04 7.85E+04 8.90E+04 1.04E+05 1.52E+05 2.15E+05	1.09E+05	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 0 1 1 2 1 2 2	0.00E+00 1.00E+00 1.43E+00 1.43E+00 2.86E+00 1.43E+00 2.86E+00 2.86E+00	0.00E+00 9.20E-06 1.32E-05 1.32E-05 2.63E-05 1.32E-05 2.63E-05 2.63E-05	4.7
06-Feb-18	1	Hydraulic Surge	0 50 55 61 66 73 80 100	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	0 42 45 62 81 73 84 89	0.00E+00 4.15E+04 4.50E+04 6.20E+04 8.05E+04 7.30E+04 8.35E+04 8.90E+04	6.78E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 2 2 3 3 3 4 5	0.00E+00 2.86E+00 2.86E+00 4.29E+00 4.29E+00 4.29E+00 5.71E+00 7.14E+00	0.00E+00 4.22E-05 4.22E-05 6.33E-05 6.33E-05 6.33E-05 8.43E-05 1.05E-04	4.2
06-Feb-18	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	0 26 35 102 57 102 119 159	0.00E+00 2.60E+04 3.50E+04 1.02E+05 5.70E+04 1.02E+05 1.19E+05 1.59E+05	8.56E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 1 1 1 2 1 2 3	0.00E+00 1.43E+00 1.43E+00 1.43E+00 2.86E+00 1.43E+00 2.86E+00 4.29E+00	0.00E+00 1.67E-05 1.67E-05 1.67E-05 3.34E-05 1.67E-05 3.34E-05 5.01E-05	4.6
21-Feb-18	1	Hydraulic Surge	0 50 55 61 66 73 80 100	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	0 60 41 136 147 111 119 92	0.00E+00 6.00E+04 4.05E+04 1.36E+05 1.47E+05 1.11E+05 1.19E+05 9.15E+04	1.01E+05	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 9 1 2 2 2 4 2	0.00E+00 1.29E+01 1.43E+00 2.86E+00 2.86E+00 2.86E+00 5.71E+00 2.86E+00	0.00E+00 1.28E-04 1.42E-05 2.84E-05 2.84E-05 2.84E-05 5.68E-05 2.84E-05	4.4
21-Feb-18	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	0 73 84 124 122 122 126 131	0.00E+00 7.25E+04 8.40E+04 1.24E+05 1.22E+05 1.22E+05 1.26E+05 1.31E+05	1.12E+05	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 0 1 1 2 2 1 1	0.00E+00 1.00E+00 1.40E+00 1.40E+00 3.00E+00 3.00E+00 1.43E+00 1.43E+00	0.00E+00 8.96E-06 1.25E-05 1.25E-05 2.69E-05 2.69E-05 1.28E-05 1.28E-05	4.8
06-Mar-18	1	Stable	0 15 30 45 60 75 90 105	0.006 0.001 0.001 0.001 0.001 0.001 0.001 0.001	0 1 16 48 63 87 89 100	0.00E+00 5.00E+02 1.60E+04 4.80E+04 6.25E+04 8.70E+04 8.85E+04 1.00E+05	6.70E+04	0.7 0.7 0.7 0.7 0.7 0.7 0.7 0.7	0 0 1 1 0 0 0 0	0.00E+00 1.00E+00 1.43E+00 1.43E+00 1.00E+00 1.00E+00 1.00E+00 1.00E+00	0.00E+00 1.49E-05 2.13E-05 2.13E-05 1.49E-05 1.49E-05 1.49E-05 1.49E-05	4.8

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		0.7	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		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	2.26E+04	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 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 36 89 72 166 99	0.00E+00 7.20E+03 1.78E+04 1.44E+04 3.32E+04 1.98E+04	1.85E+04	0.8 0.8 0.8 0.8 0.8 0.8	0 31 997 2156 2200 515	0.00E+00 3.88E+01 1.25E+03 2.70E+03 2.75E+03 6.44E+02	0.00E+00 2.10E-03 6.74E-02 1.46E-01 1.49E-01 3.48E-02	1.1
13-Oct-21	3	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 56 52 72 55 54	0.00E+00 1.12E+04 1.04E+04 1.44E+04 1.10E+04 1.08E+04	1.16E+04	0.5 0.5 0.5 0.3 0.3 0.3	2 114 748 665 652 326	4.00E+00 2.28E+02 1.50E+03 2.22E+03 2.17E+03 1.09E+03	3.46E-04 1.97E-02 1.29E-01 1.92E-01 1.88E-01 9.40E-02	0.9
13-Oct-21	2A	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 29 65 70 64 79	0.00E+00 5.80E+03 1.30E+04 1.40E+04 1.28E+04 1.58E+04	1.23E+04	0.5 0.5 0.5 0.3 0.3 0.3	0 288 553 911 684 775	0.00E+00 5.76E+02 1.11E+03 3.04E+03 2.28E+03 2.58E+03	0.00E+00 4.69E-02 9.01E-02 2.47E-01 1.86E-01 2.10E-01	0.8
13-Oct-21	4A	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 24 73 21 35 52	0.00E+00 4.80E+03 1.46E+04 4.20E+03 7.00E+03 1.04E+04	8.20E+03	0.8 0.8 0.7 0.8 0.8 0.8	0 762 2294 1408 2155 3056	0.00E+00 9.53E+02 3.28E+03 1.76E+03 2.69E+03 3.82E+03	1.52E-04 1.16E-01 4.00E-01 2.15E-01 3.29E-01 4.66E-01	0.5
10-Nov-21	3	Stable	0 30 45 60 75 90	0.010 0.010 0.010 0.010 0.010 0.010	0 38 5 78 101 89	0.00E+00 3.80E+03 5.00E+02 7.80E+03 1.01E+04 8.90E+03	6.22E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 1 2 0 1 0	1.25E+00 1.25E+00 2.50E+00 1.25E+00 1.25E+00 1.25E+00	0.00E+00 2.01E-04 4.02E-04 2.01E-04 2.01E-04 2.01E-04	3.6
10-Nov-21	4A	Stable	0 30 45 60 75 90	0.010 0.010 0.010 0.010 0.010 0.010	0 12 15 19 23 31	0.00E+00 1.20E+03 1.50E+03 1.90E+03 2.30E+03 3.10E+03	2.00E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 5 7 0 1 1	0.00E+00 6.25E+00 8.75E+00 1.25E+00 1.25E+00 1.25E+00	6.25E-04 3.13E-03 4.38E-03 6.25E-04 6.25E-04 6.25E-04	2.7
19-Nov-21	3	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 19 43 49 58 42	0.00E+00 3.80E+03 8.60E+03 9.80E+03 1.16E+04 8.40E+03	8.44E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 0 0 19 1 4	0.00E+00 0.00E+00 0.00E+00 2.38E+01 1.25E+00 5.00E+00	0.00E+00 1.48E-04 1.48E-04 2.81E-03 1.48E-04 5.92E-04	3.1
19-Nov-21	3	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 40 21 47 37 55	0.00E+00 8.00E+03 4.20E+03 9.40E+03 7.40E+03 1.10E+04	8.00E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 6 2 1 1 1	0.00E+00 7.50E+00 2.50E+00 1.25E+00 1.25E+00 1.25E+00	0.00E+00 9.38E-04 3.13E-04 1.56E-04 1.56E-04 1.56E-04	3.5

19-Nov-21	2A	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 22 33 32 30 67	0.00E+00 4.40E+03 6.60E+03 6.40E+03 6.00E+03 1.34E+04	7.36E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 1 2 5 7 8	0.00E+00 1.25E+00 2.50E+00 6.25E+00 8.75E+00 1.00E+01	0.00E+00 1.70E-04 3.40E-04 8.49E-04 1.19E-03 1.36E-03	3.1
19-Nov-21	4A	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 42 71 62 50 89	0.00E+00 8.40E+03 1.42E+04 1.24E+04 1.00E+04 1.78E+04	1.26E+04	0.8 0.8 0.8 0.8 0.8 0.8	0 546 1106 260 1475 1421	0.00E+00 6.83E+02 1.38E+03 3.25E+02 1.84E+03 1.78E+03	9.95E-05 5.43E-02 1.10E-01 2.59E-02 1.47E-01 1.41E-01	1.0
19-Nov-21	4C	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 72 69 111 81 129	0.00E+00 1.44E+04 1.38E+04 2.22E+04 1.62E+04 2.58E+04	1.85E+04	0.8 0.8 0.8 0.8 0.8 0.8	1 1313 1954 1916 2847 1938	1.25E+00 1.64E+03 2.44E+03 2.40E+03 3.56E+03 2.42E+03	6.76E-05 8.88E-02 1.32E-01 1.30E-01 1.93E-01 1.31E-01	0.9
19-Nov-21	4C	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	0 88 33 97 108 111	0.00E+00 1.76E+04 6.60E+03 1.94E+04 2.16E+04 2.22E+04	1.75E+04	0.8 0.8 0.8 0.8 0.8 0.8	1 1220 1540 2218 2546 2108	1.25E+00 1.53E+03 1.93E+03 2.77E+03 3.18E+03 2.64E+03	7.15E-05 8.72E-02 1.10E-01 1.59E-01 1.82E-01 1.51E-01	0.9
19-Nov-21	4C	Stable	0 30 45 60 75 90	0.005 0.005 0.005 0.005 0.005 0.005	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.6 0.8 0.8 0.8 0.8 0.8	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	0.020 0.020 0.020 0.020 0.020 0.020	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.6 0.8 0.8 0.8 0.8 0.8	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.4 0.4 0.4 0.4 0.4 0.4	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.6 0.8 0.8 0.8 0.8 0.8	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.6 0.8 0.8 0.8 0.8 0.8	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	0.020 0.020 0.020 0.020 0.020 0.020	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.4 0.5 0.4 0.4 0.4 0.4	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.4 0.5 0.5 0.4 0.5 0.4	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.020 0.020 0.020 0.020 0.020 0.020	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.020 0.020 0.020 0.020 0.020 0.020	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.4 0.4 0.4 0.4 0.4 0.4	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.4 0.4 0.4 0.4 0.4 0.4	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	0.010 0.010 0.010 0.010 0.010 0.010	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	0.8 0.8 0.8 0.8 0.8 0.8	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	0.020 0.020 0.020 0.020 0.020 0.020	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	0.8 0.8 0.8 0.8 0.8 0.8	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 30 45 60 75 90	0.010 0.010 0.010 0.010 0.010 0.010	0 19 128 83 26 16	0.00E+00 1.90E+03 1.28E+04 8.30E+03 2.60E+03 1.60E+03	5.44E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 0 4 0 0 1	0.00E+00 0.00E+00 5.00E+00 0.00E+00 0.00E+00 1.25E+00	0.00E+00 2.30E-04 9.19E-04 2.30E-04 2.30E-04 2.30E-04	3.4
16-Dec-21	4A	Stable	0 30 45 60 75 90	0.010 0.010 0.010 0.010 0.010 0.010	14 29 95 55 23 47	1.40E+03 2.90E+03 9.50E+03 5.50E+03 2.30E+03 4.70E+03	4.98E+03	0.4 0.4 0.4 0.4 0.4 0.4	0 6 7 1 18 6	0.00E+00 1.50E+01 1.75E+01 2.50E+00 4.50E+01 1.50E+01	5.02E-04 3.01E-03 3.51E-03 5.02E-04 9.04E-03 3.01E-03	2.4

16-Dec-21	4C	Stable	0 30 45 60 75 90	0.010 0.010 0.010 0.010 0.010 0.010	14 66 56 24 122 109	1.40E+03 6.60E+03 5.60E+03 2.40E+03 1.22E+04 1.09E+04	7.54E+03	0.4 0.4 0.4 0.4 0.4 0.4	0 2 7 4 6 3	0.00E+00 5.00E+00 1.75E+01 1.00E+01 1.50E+01 7.50E+00	3.32E-04 6.63E-04 2.32E-03 1.33E-03 1.99E-03 9.95E-04	2.8
04-Mar-22	3	Hydraulic surge	0 30 45 60 75 90	0.020 0.020 0.020 0.020 0.020 0.020	2 111 156 93 59 43	1.00E+00 5.55E+03 7.80E+03 4.65E+03 2.95E+03 2.15E+03	4.62E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 12 3 11 0 10	0.00E+00 1.50E+01 3.75E+00 1.38E+01 0.00E+00 1.25E+01	0.00E+00 3.25E-03 8.12E-04 2.98E-03 2.71E-04 2.71E-03	2.7
04-Mar-22	3	Hydraulic surge	0 30 45 60 75 90	0.020 0.020 0.020 0.020 0.020 0.020	2 28 107 123 152 144	1.00E+02 1.40E+03 5.35E+03 6.15E+03 7.60E+03 7.20E+03	5.54E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 6 2 0 2 0	0.00E+00 7.50E+00 2.50E+00 0.00E+00 2.50E+00 0.00E+00	0.00E+00 1.35E-03 4.51E-04 2.26E-04 4.51E-04 2.26E-04	3.3
12-Apr-22	3	Stable	0 30 45 60 75 90	0.100 0.100 0.100 0.100 0.100 0.100	0 717 1107 1210 649 1633	0.00E+00 7.17E+03 1.11E+04 1.21E+04 6.49E+03 1.63E+04	1.06E+04	0.8 0.8 0.8 0.8 0.8 0.8	0 4 0 3 1 5	0.00E+00 5.00E+00 0.00E+00 3.75E+00 1.25E+00 6.25E+00	0.00E+00 4.70E-04 1.18E-04 3.53E-04 1.18E-04 5.88E-04	3.5
12-Apr-22	3	Stable	0 30 45 60 75 90	0.100 0.100 0.100 0.100 0.100 0.100	0 130 142 328 1354 238	0.00E+00 1.30E+03 1.42E+03 3.28E+03 1.35E+04 2.38E+03	4.38E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 3 0 5 1 3	0.00E+00 3.75E+00 0.00E+00 6.25E+00 1.25E+00 3.75E+00	0.00E+00 8.55E-04 2.85E-04 1.43E-03 2.85E-04 8.55E-04	3.1
12-Apr-22	2A	Stable	0 30 45 60 75 90	0.100 0.100 0.100 0.100 0.100 0.100	0 253 199 526 1083 856	0.00E+00 2.53E+03 1.99E+03 5.26E+03 1.08E+04 8.56E+03	5.83E+03	0.8 0.8 0.8 0.8 0.8 0.8	0 1 1 5 7 2	0.00E+00 1.25E+00 1.25E+00 6.25E+00 8.75E+00 2.50E+00	0.00E+00 2.14E-04 2.14E-04 1.07E-03 1.50E-03 4.29E-04	3.2