Evaluation and Improvement of Coagulant Disinfectant Products for Humanitarian Emergency Relief

by

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BASc, University of Victoria, 2017

A Thesis Submitted in Partial Fulfillment
of the Requirements for the Degree of

MASTER OF APPLIED SCIENCE

in the Department of Civil Engineering

We acknowledge with respect the Lekwungen peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

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Abstract

As climate change progresses, the number of extreme weather events are predicted to rise and generate an increase in climate related humanitarian emergencies. These emergencies result in complex displacements of populations, unsanitary conditions, and a corresponding increase in diarrheal disease risks within affected communities. Because diarrheal disease ranks as one of the major contributors to overall morbidity and mortality rates following a disaster, it is critically important that aid agencies are prepared to make informed decisions regarding the prevention of disease transmission. As water is one of the main transmission routes of diarrheal disease, providing clean and safe drinking water is acknowledged as one of the most important and effective interventions. Once we acknowledge the importance of this resource, we also acknowledge the need for quick, simple, and effective water treatment solutions.

The term point-of-use (POU) water treatment defines water treatment systems and technologies that are used at the point of consumption. These systems often treat relatively small batches of water and are operated by the consumer or head of household. POU water treatment systems and safe storage techniques have been shown to improve water quality and decrease diarrheal disease incidence and are therefore an effective option in humanitarian emergencies. One type of POU water treatment product - coagulant/disinfection products (CDPs) which are also known as flocculant/disinfectants, have been increasingly used in response to humanitarian emergencies. CDPs are shown to provide microbial and aesthetic (i.e. turbidity reductions) water quality improvements and post-treatment protective free chlorine residuals (FCRs). The relative simplicity of CDPs allows quick intervention for communities with few resources plus CDPs are durable, small, and ready for quick deployment. However, limited research has been completed on the different CDPs on the market or on methods to improve them.

This thesis explores CDPs and their role in emergency response through two interlinked perspectives:

1. First, in an overall review compiled as Manuscript #1 (Chapter 2), I assess the existing and current CDPs, how they perform in comparison to global water treatment guidelines, and where their limitations lie. The outcomes of this study provide a simple analysis for aid agencies to carefully select the CDPs used in emergency interventions; and
2. I take the findings from the research completed in Chapter 2 to develop a computational modelling approach to improving the residual protective capacity of the CDPs. These results are presented in Manuscript #2 (Chapter 3) . The outcomes are intended to serve two purposes: (1) to provide a baseline computational model to guide and encourage improvement and testing of these products by manufacturers; and (2) to provide an educational tool to facilitate understanding of these products and the key functions taking place during their treatment.

This thesis addressed the research objective of invoking conversation surrounding effective emergency response through developing solutions to provide clean drinking water in at-risk communities during complex humanitarian emergencies.

Table of Contents

List of Tables

List of Figures

Chapter 2: Manuscript #1

Chapter 3: Manuscript #2

List of Abbreviations

Abbreviation	Meaning
AFL	Aquafloc and Aquatab
AQS	Aquasure
AS	Aluminum Sulphate
BG	Bishan Gari
CDP	Coagulant Disinfectant Product
CF	Chlor-Floc
CFU	Coliform Forming Units
CH	Calcium Hypochlorite
CT	Concentration-Time
DBPs	Disinfectant By-Products
DOC	Dissolved Organic Carbon
FCR	Free Chlorine Residual
FS	Ferric Sulphate
HAAs	Haloacetic acids
JN	Jar Nirmal
LR	Log Reduction
MPN	Most probable number
NADCC	Sodium dichloroisocyanurate
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Units
PIT	Pureit
PODR	Point of Diminishing Return
POU	Point-of-use
PSW	Primary Settled Wastewater
PUR	P&G Purifier of Water
SD	Standard Deviation
SDS	Safety Data Sheets
SPHERE	A set of principles and minimum humanitarian standards in four technical areas of humanitarian response inclusive of Water supply, sanitation and hygience promotion, food security and nutrition, shelter and settlement, and health.
SUVA	Specific ultraviolet absorbance
THMs	Total Trihalomethanes
TOC	Total Organic Carbon
UNRD	Universal natural organic matter removal dosage
USEPA	United States Environmental Protection Agency
UV254	Ultraviolet light at 254 nm wavelength
WASH	Water Sanitation and Hygiene
WHMIS	Workplace Hazardous Materials Information System
WHO	World Health Organization
WM	Watermaker

Acknowledgments

I would like to acknowledge my supervisor Dr. Caetano Dorea for his support throughout an ever-changing project, ability to arrange unique opportunities and contribute honest and effective feedback . Thank you to Dr. Vic Neufeld for welcoming me into the Global Health community and encouraging me to question the status quo. Thank you to Dr. Travis Yates for not only the wisdom and field expertise but also the honesty, transparency and mentorship. Thank you to Dr. Heather Buckley for her insights into the world of chemistry. Thank you to the civil technical team, UVic Lab Safety group, and special thanks to Arielle Garrett for her commitment to continued lab assistance and staying calm and collected even when I managed to flood the lab.

I would like to acknowledge my teammates within the Public Health & Environmental Engineering (PH2E) Group at the University of Victoria inclusive of Jefferson, Camille, Kelsey, Anne, Alex and Claire for the strong sense of community they provided, as well as all members of E-hut.

I would like to acknowledge the support from the team at the Université Laval for their assistance during my short time in Quebec City. Thank you to Dr. Rodriguez, Samuel and Sabrina for helping me get set up in the lab and showing me around Laval. I would like to thank Anne for introducing me to Quebec City and teaching me how to cope with eastern winters.

I would like to acknowledge the support I received from the University of Women in Bangladesh and JSKS for providing me opportunity to learn about the field applications of the products I was investigating. I would also like to acknowledge Grant Challenges Canada, NSERC and the Faculty of Graduate Studies for the funding required to be able to complete my masters.

On a more personal note, I would like to thank my parents, Carol and Berk, for their dedication, involvement and ability to keep me grounded, and my sister and grandmother for their ongoing inspiration. Thank you to my friends and community for numerous rounds of edits and presentation revisions. I must also acknowledge and thank the Jaseckhos for fueling me through my masters and their continuous enthusiasm towards my research.

Dedication

This thesis is dedicated to the group of individuals at JSKS (Jhanjlra Samaj Kallyan Sangstha) a non-profit, non-governmental, humanitarian development organization in Bangladesh. JSKS continues to play a strong role in the socio-economic development of the disadvantaged in Bangladesh dedicating time and resources to the preparation of emergency response. Efforts such as theirs offer continued motivation to conduct this research. Thank you for all the work you do.

1. Introduction

I am a Civil Engineering graduate from the University of Victoria where I am part of the Public Health to Environmental Engineering (PH2E) lab. My research with the PH2E lab exists at the intersect of climate change, humanitarian aid and public health engineering.

I believe it is of great importance to centre my research around sustainability and the Earth's ever-changing climate. Because of this, my research is motivated by the increase in extreme weather events predicted to take place due to climate change [1]. With this increase in natural weather-related events, there follows an increased risk of complex humanitarian emergencies [2] characterized by political instability, armed conflict, large population displacements, food shortages, social disruption, and collapse of public health infrastructure [3]. These humanitarian emergencies often hit hardest in low- and middle-income countries that are vulnerable to extremes of normal climatic variability [4]. Within these complex humanitarian emergencies, impacted communities face a corresponding increase in the complex displacement of populations, unsanitary conditions and diarrheal disease risks [5]. Because diarrheal disease ranks as one of the major contributors to overall morbidity and mortality rates following a disaster [6], it is vital that response systems are ready and that aid agencies are prepared to make important decisions regarding the prevention of disease transmission. As water is one of the main transmission routes of diarrheal disease [5], providing clean and safe drinking water is acknowledged as one of the most important and effective interventions in complex humanitarian emergencies [7]

Emergency water treatment interventions range from bulk centralized systems (10 m^3/h) to fully decentralized (10 to 20 L batches) point-of-use technologies (POU). My research focused on POU interventions, a system or technology that is used at the point of consumption and operated by the consumer to treat relatively small batches of water. POU water treatment systems and safe storage techniques have been shown to improve water quality and decrease diarrheal disease incidence [3] and are therefore an effective option in humanitarian emergencies. POU technologies vary from physical filtration devices to chemical based formulas. One chemical-based treatment method consists of coagulant disinfectant products (CDPs). CDPs aim to include all components of a conventional water treatment process (coagulation, flocculation, settling, filtration and disinfection) into one small packet to serve a single household while requiring only a couple widely available materials (bucket and cloth). CDPs claim to effectively treat water for drinking then leave a disinfectant residual to protect the water from further contamination [8].These products have a strong potential to aid in providing clean water in emergency scenarios and were the basis of this research project and thesis work.

This thesis explores CDPs and their role in emergency response through two interlinked perspectives, evaluation and improvement. In addition to these perspectives, I also connected my work back to the "bigger picture" through my discussion on CDPs real world application. I addressed these topics through three main questions:

1. **Evaluation:** How do the wide range of CDPs perform in terms to household water treatment guidelines?
2. **Improvement:** How can CDPs be improved? What tools can be developed to improve them?
3. **Application:** How does this research fit into the bigger picture of influencing global health research and equity?

The first two questions regarding evaluation and improvement were compiled into two manuscripts, referred to throughout this thesis as Chapter 2 (Manuscript #1) and Chapter 3 (Manuscript #2) respectively. Alongside these two manuscripts intended and formatted for submission, several presentations and conference entries resulted, all of which are presented in Table 1.

Chapter 2 acts as an overview and evaluation of commercially available (or trial) CDPs. This study and laboratory work identified the treatment performance of eight CDPs under challenging test water conditions. This evaluation determined general influences of test water conditions (pH and temperature) while highlighting the vast differences of performance across these products. Recommendations are made to highlight areas of improvement for the CDPs and a comparison of the products' performance in reference to WHO [9] and SPHERE [10]drinking water quality guidelines was completed.

The findings from Chapter 2 established that there was room for improvement in many of the evaluated CDPs. These findings formed the basis of Chapter 3. Applying principles commonly followed in conventional water treatment, the objective of this analysis was to develop methods for improving CDPs. While the original intent and plan of this work was to be completed in the laboratory at the Université Laval, scheduled work was significantly disrupted due to COVID-19. Given the uncertainty of the global pandemic, resuming lab work was not feasible within the project time period. Therefore, this lab work shifted to the use of computational modelling to attempt to further investigate CDPs without the use of a laboratory. While model validation will still be of great value, and motivation for future work, this shift in my research provided an opportunity to enhance my skillset in computational modelling and further investigate the base mechanics and kinetics in the CDPs. The outcomes of Chapter 3 were intended to serve two purposes: to provide a baseline model to guide and encourage improvement of CDPs by the manufacturers and to provide an educational tool to facilitate understanding of CDPs and the key functions taking place during their treatment.

Throughout my master's program, I was deeply immersed in the study of global health. An unanticipated benefit of my research was the opportunity to learn from a variety of health professionals and a strong community focused on ensuring public and global health equity in complex humanitarian scenarios. The application portion of my discussion uses the information I gained through the global health elements of my master's program to link my work back to the bigger picture.

Ultimately, my goal throughout this thesis is to invoke conversation surrounding effective emergency response through developing solutions to provide clean drinking water in at-risk communities during complex humanitarian emergencies.

Table 1 Manuscripts and presentations generated from the work completed in this thesis

Thesis Chapter	Manuscript or Presentation
Chapter 2 (Manuscript #1)	Borrett, L., Dorea, C. (2020). "Comparison and evaluation of coagulant/disinfectant point-of-use water treatment performance". (*In preparation for submission).*
	Borrett, L., Dorea, C. (2020). "Comparison and evaluation of coagulant/disinfectant point-of-use water treatment performance". Accepted for oral presentation at for 2020 Canadian Association of Water Quality (CAWQ) Virtual Conference
	Borrett, L., Dorea, C. (2020). "Comparison and evaluation of coagulant/disinfectant point-of-use water treatment performance". Accepted for oral presentation at for 2020 IEEE Global Humanitarian Technology Conference (GHTC) (GHTC 2020)
Chapter 3 (Manuscript #2)	Borrett, L., Dorea, C. (2020). "Model based evaluation of coagulant disinfectant emergency water treatment products using principles of enhanced coagulation" (*In preparation for submission)*
Additional Work	Borrett, L., Dorea, C., Yates, T. (2019). "Point of Collection Water Treatment using Coagulant/Disinfectant Products". Accepted for poster presentation at UNC Water and Health Conference 2019, Chapel Hill, North Carolina.
	Borrett, L., Dorea, C., Yates T. (2020). "Coagulant/Disinfectant Point-of-Collection Water Treatment for Humanitarian Emergencies". Accepted for oral presentation at Western Environment Student Talks Conference at University of British Columbia, British Columbia
	Borrett, L., Dorea, C., Yates T. (2020). "Coagulant/Disinfectant Point-of-Collection Water Treatment for Humanitarian Emergencies". Accepted for oral presentation at Women in Engineering and Computer Science Conference at University of Victoria, British Columbia.

2. Comparison of point-of-use water treatment coagulant-disinfectant products

2.1 Abstract:

In humanitarian emergencies, water quality becomes increasingly more important as sanitary conditions diminish and risk of diarrheal disease outbreak increases. To mitigate these risks, Point-of-Use (POU) water treatment is often deployed at the household or community level. Coagulant/disinfection products (CDPs), also referred to as flocculant/disinfectants, are a POU technology (usually in powdered form) that typically come in sachets containing at least two main active ingredients (i.e. coagulant and disinfectant) and are increasingly used in humanitarian contexts. Most studies on CDP treatment performance have concentrated on one product; however, many such products exist, and little work has been done of a comparative nature. The objective of this study is to provide a comparative survey of a selection of CDPs, evaluating their performance using a standardized testing protocol under varied water quality conditions. Treatment efficacies (i.e., bacterial log reductions (LRs), turbidity reductions, and free chlorine residuals (FCRs) were evaluated against current relevant (i.e., for development and humanitarian contexts) drinking water quality objectives. Results found seven of the eight CDPs achieved "highly protective" bacterial reduction status but products performed poorly in regard to achieving FCR targets, with only one product achieving the 0.5 mg/L requirement set out by the World Health Organization (WHO). While pH and temperature did not influence the bacterial LRs of all of the products, results showed statistically significant differences on half of the products independently. Turbidity removal was found to be impacted by temperature and pH and varied greatly across products. This study has served to identify the treatment performance of eight CDPs under challenging test water conditions. The study determined general influences of test water conditions (pH and temperature), while highlighting the vast variety of performance across these products. Recommendations are made to improve and motivate research surrounding CDPs and important considerations to be included in further alterations of their formulations.

2.2 Introduction

As of 2015, it is estimated that 663 million people worldwide still use unimproved drinking water sources [11] and are at risk of waterborne diarrheal diseases. Furthermore, in humanitarian emergencies, water quality becomes exponentially more important as sanitary conditions diminish and risk of diarrheal disease outbreak increases [5,15]. POU water treatment and safe storage techniques can improve water quality and decrease diarrheal disease incidence [12]. POU water treatment has been explored as an effective water treatment option in particular contexts such as humanitarian emergencies[13]. Unsanitary conditions may occur following natural or man-made hazards. These conditions can bolster diarrheal disease risks, which are considered one of the major contributors to the overall morbidity and mortality rates within affected communities following a disaster [5- 7].

Coagulant/disinfection products (CDPs), also referred to as flocculant/disinfectants, have been increasingly used in the response to humanitarian emergencies. CDPs (usually in powdered form) typically come in sachets containing at least two main active ingredients (i.e. coagulant and disinfectant). Their advantage is to provide microbial and aesthetic (i.e. turbidity reductions) water quality improvements as well as post-treatment protective free chlorine residuals (FCRs) typically in a single product.

Most laboratory studies on CDP water treatment performance have concentrated on one product, for example, Chlorfloc [16], P&G Water Purifier [9,10], Pureit [19] and, more recently, Aquasure [20]. Comparative studies between POU water treatment methods involving CDPs have not reflected the variety of other commercially-available CDPs. Most products have different formulations with regard

to species and concentration of the known active ingredients, in addition to proprietary additives inclusive of clay and polymers. Furthermore, their performances have not yet been comprehensively compared. The objective of this study is to provide a comparative survey of available CDPs and comparison of their treatment performance was based on a standardized testing protocol [9] under varied water quality conditions.

2.3 Materials and methods

2.3.1 Product Descriptions

Eight CDPs were surveyed and tested according to the World Health Organization testing protocols set out in *Evaluating household water treatment options: health-based targets and microbiological performance specifications* [9]. CDPs were either obtained through donations from the manufacturers and non-governmental organisations or purchased. All products were tested within three months of receipt and within their labelled shelf life (when stated). Table 2 summarises the characteristics of the selected products (products come in different formats capable of treating a range of volumes). Although the specific formulation of most products was undisclosed or proprietary, the two main active ingredients were: the coagulant (i.e. aluminum sulphate or ferric sulphate – AS or FS, respectively) and the disinfectant (i.e. calcium hypochlorite or sodium dichloroisocyanurate – CH or NADCC, respectively). Because the exact product formulation was often unknown (beyond listed coagulant and disinfectants), a standardised testing regime was designed to examine the underpinning treatment processes (i.e. coagulation and disinfection). The only exception was P&G Water Purifier (formerly known as PUR), as its formulation has been published elsewhere [23]. P&G Water Purifier [29] , Pureit [19], and Aquasure [20] have been previously tested with the same methodology used in this study, and these results were included in this study for comparative purposes.

2.3.2 Performance testing

Treatment efficiencies (i.e., bacterial log reductions (LRs), turbidity reductions, and FCR levels) were evaluated against current relevant (i.e., for development and humanitarian contexts) drinking water quality objectives. Specifically, products were evaluated in comparison to The SPHERE Handbook (SPHERE 2018) [10] and WHO Household Water Treatment Quality guidelines (Table 3) [9], [24]. The SPHERE Handbook (The Humanitarian Charter and Minimum Standards in Humanitarian Response) was developed for practitioners involved in planning, managing or implementing a humanitarian response by a group of humanitarian non-governmental organisations and the Red Cross and Red Crescent Movement [10].

Table 2 Summary of CDPs evaluated and corresponding product information

	Code	Form[1]	Coagulant Active Ingredient (stated)	Disinfectant Active Ingredient (stated)	Contact Time (min)	Volume treated (L)	Product weight (g)	Reported cost[2]	Shelf life (years)	Country of Origin	Peer-reviewed Studies (Lab)	Peer-reviewed Studies (Field)
Aquasure	AQS	PS	FS	NADCC	60	10	n/a	n/a	n/a	France	[20]	[26]
Aquafloc[3] + Aquatab	AFL	T	AS	NADCC	30	5	A + 0.067	A + 0.046	A + 5	Ireland	[25]	
Bishan Gari	BG	PS	AS	CH	22	20	2.5	0.055	3	Ethiopia		
Chlor-floc	CF	PS	AS	NADCC	11.5	1	0.6	0.333 to 0.667	3	USA	[27][16]	
Jar Nirmal	JN	PS	FS	CH	30	15	1.5	0.130	1	India		
P&G Purifier of Water	PUR	PS	FS	CH	30	10	4.0	0.035 to 0.114	3	USA	[17][8] [28][29] [30]	[23][31] [32][33]
Pureit	PIT	PS	FS	CH	22	10	2.5	n/a	n/a	India	[19]	
Watermaker	WM	PS	AS	NADCC	25	10	2.5	0.049	3	South Africa	[22]	

[1]P/S: Powder/Sachet, T: Tablet

[2] US$ per use, sachet, tablet, etc. Prices are taken as of 2012

[3] Aquafloc was a trial product developed to partner with the current chlorination product, Aquatab. However, this product was never released to market and therefore data is limited. Aquafloc is denoted at A in the table when data was unknown. Studies listed are a non-exhaustive list of tests completed on Aquatabs alone as there are no further known studies or evaluations of Aquafloc.

Table 3 Drinking water quality objectives used within the CDP evaluation

Water Parameters at Point of Delivery	SPHERE 2018	WHO 2017
E. coli	< 10 CFU/100ml	<1CFU /100mL
Turbidity	< 5NTU	< 5NTU
FCR	≥ 0.2–0.5mg/l at point of delivery	≥ 0.5mg/L after 30-minute contact time 0.2mg/L at point of delivery

While percent compliances will be assessed for turbidity and FCR within this study, a strong emphasis was placed on bacterial LRs given the link to the WHO Risk Assessment [34] and associated importance in emergency contexts. *Escherichia coli* (*E. coli*), a commonly used microbial quality criterion for water based bacterial removal was used as an indicator organism. Table 4 summarizes default bacterial LRs required to achieve "Interim," "Protective" and "Highly Protective" performance with regard to bacterial, viral and protozoan contamination.

Table 4 LRs performance requirements for POU technologies from WHO [9]

	Log Reduction Required		
Pathogen Class	**Interim**	**Protective**	**Highly Protective**
Bacteria	Achieves "protective" target for two classes of pathogens and results in health gains	≥ 2	≥ 4
Viruses		≥ 3	≥ 5
Protozoa		≥ 2	≥ 4

In addition to bacterial reductions and aesthetic metrics, the WHO [9] also recommends assessment of POU water treatment product performance with regards to viral and protozoan reductions. As only bacterial criteria were quantitatively evaluated in this study, FCR concentrations after prescribed treatment times were used to calculate Concentration-Time (CT) factors for each CDP. These values were then used to assess compliance with the USEPA [35] CT values to achieve given virus and protozoa log removal values by WHO [9].

2.3.3 Test waters

To determine the performance of the products, a 1:5 dilution of a primary settled wastewater (PSW) in dechlorinated tap water [9] was used as a test water to simulate a grossly polluted water source. These conditions were selected to see how the products performed in challenging conditions. The PSW was collected weekly from a local wastewater treatment plant (Québec, Canada) and had an average chemical oxygen demand of 116.8 mg/L, a suspended solids concentration of 45.4 mg/L, and a turbidity of 44.2NTU during the study period. Samples were stored in a cold room (< 4 °C) until use and kept for a maximum of one week.

Previous CDP testing revealed the parameters with the greatest influence on microbiological water quality were high pH (i.e. alkaline conditions) and low temperature (i.e. < 5 °C) as well as low pH (i.e. acidic conditions) from an aesthetic (i.e. turbidity reduction) perspective [29]. Through the information obtained from previous studies, test waters were prepared to illustrate the "reference", "acidic", "alkaline" and "cold" conditions (Table 5).

Table 5 Test water conditions for CDP evaluations

Condition	PSW dilution	Target turbidity (NTU)[1]	Target pH	Target temperature (°C)
"reference"	1:5	100	7	20
"acidic"	1:5	100	5	20
"alkaline"	1:5	100	9	20
"cold"	1:5	100	7	5

[1] A turbidity 100NTU was used except in the case of PIT of which used a turbidity of 50NTU for all test besides *"cold"* conditions for which it used 100NTU.

Turbidity was adjusted to bring test waters to 100NTU ±10% using a kaolin clay (Sigma-Aldrich, USA). Waters were then adapted to various test water conditions (pH and temperature); pH was adjusted to "acidic", "neutral" or "alkaline" conditions (target pH 5, 7, and 9, respectively) using appropriate solutions of either NaOH (Bio Basic Canada Inc., Canada) and H_2SO_4 (Fisher Chemical, USA) to test the CDP at neutral and extreme treatment pH. Except for cold temperature trials, all experiments were conducted at ambient room temperature (20°C). A crushed ice jacket around the mixing vessel kept the test water at 5 ± 1 °C for cold temperatures.

2.3.4 Experimental setup

Instructions for each CDP typically involved several steps, specifically: mixing (for the dispersion of the chemicals and floc formation); settling (for sedimentation of formed flocs); cloth filtration; and disinfection contact time (as specified by each product). Such steps were adapted to a laboratory setup according to each products' instructions and required treatment volume. A Kemwater Flocculator 2000 (Kemira, Sweden) stirring paddle was fixed above the mixing vessel to provide uniform mixing intensities throughout the study. The mixer was set to 250 rpm, as this was found to be the intensity at which flocs would remain in suspension without shearing (visually assessed in previous studies) and also selected to closely mimic field mixing time. Furthermore, initial tests showed no discrepancies with regard to turbidity reductions when compared to manual mixing. Consistent with the objective of testing the products under challenging conditions, a J-Cloth (Associated Brands, Canada) was used as a filtration material. This is a non-woven viscose fiber fabric chosen to simulate a worst-case scenario (highest porosity) with regard to the choice of filtration material. Ideally, a tightly knit filter material would be used to ensure the greatest level of physical filtration available; however, this is an unrealistic expectation for the field and would likely provide an overestimation of product performance. After filtration, the treated water was collected in sterile polypropylene containers. Between tests, the mixing apparatus setup was washed and rinsed then sterilized with methanol.

2.3.5 Treatment performance trials

Each CDP product was tested three times within each test water condition (Table 5), resulting in 12 tests per product. Tests were randomised and conducted in the pre-established order with the water sample that was available that week. With the exception of FCRs (sampled only after duration of specified treatment), turbidity, pH, and the faecal indicator bacteria reductions were measured based on concentrations before and after treatment for each CDP. Bacteriological sampling was conducted in triplicate using sterile autoclaved polypropylene bottles containing sodium thiosulfate (Sigma-Aldrich, USA) to quench any residual chlorine. This was to ensure that the microbiological results were representative of stated time of treatment, which varied based on product descriptions. As the testing between different products was not randomised, variance between source waters was assessed through use of statistical testing.

2.3.6 Analytical methods.

Turbidity, pH (and temperature), and FCRs were measured using a 2100 P turbidimeter (limit of detection 0.01-1000NTU) , HQ40d pH meter, and Pocket Colorimeter™, respectively, as specified by the manufacturer (HACH, USA). The Pocket Colorimeter™ low range procedure measured values from 0.02-2.0 mg/L, and the high range assessed values between 0.1-8.0 mg/L. The limit of detection was therefore 0.02mg/L and this value was used throughout testing, even if FCRs may have been below the limit of detection. The low range procedure was used as default, unless the FCR reached the upper limit, at which point the test was redone and the high range procedure was used to measure resulting FCR. Enumeration of naturally occurring faecal indicator bacteria was quantified through eithee the protocols of membrane filtration analysis method [9], or the Colilert test method. The membrane filtration method is based on physical filtration through a membrane filter and incubated onto a compact dry plate containing a dried agar growth medium which was rehydrated by the sample. After an incubation time of 24hrs, when E. coli is present, blue/green colonies are formed [36]. In contrast, if using the Colilert test method, sample test water is placed in a specific tray system (Quanti-Tray), sealed and incubated for 24hrs. Analysis is completed through counting coloured cells within the 96-well tray. Enumeration of naturally occurring faecal indicator bacteria are expressed as colony forming units (CFU) for thermotolerant (faecal) coliforms (based on membrane filtration analysis [37]) or as most probable number (MPN) for *E. coli* (based on Colilert test method) represented per 100 mL sample. Performance assessment of AFL, CF, PUR, WM and JN was expressed in MPN, while AQS, PIT and BG are represented in CFU. The variance was due to the availability of different techniques at different time periods. In short, laboratories and agencies worldwide use both MPN and CFU interchangeably and are considered comparable for following study. Given the viral and protozoan LRs were not evaluated in the laboratory settings, concentration time (CT) values were calculated for each product and water condition to evaluate product performance. CT values presented by the USEPA [35] standards were compared against the lab data to achieve "highly protective" and "protective" status for viruses and protozoa respectively.

2.3.7 Statistical Analysis

To assess statistical significance of the source waters used for testing of different products, normality testing was completed first. The Kruskal Wallis method was then used to determine statistical differences. An analysis of variance (ANOVA) was used on normalized data sets to compare different products and test water conditions (i.e. "Reference," "Acidic," "Alkaline," and "Cold" as defined in Table 5) with regards to bacterial LRs. Where significant differences were noted relative to test water conditions, *post-hoc* analysis with a Dunnett's test was performed in relation to the "Reference" (defined *a priori*). Such post-hoc comparison was not done between products, as no performance reference product was established. Arithmetic mean was utilized for analysis incorporating turbidity, FCR, temperature and pH. Standard deviation was used to quantify the variation. Geometric mean was used for microbiological analysis to ensure there was no disproportional representation of a single extreme value. For bacterial LR calculations when microbial concentrations were less than the method detection limit of 1, a value of 0.9 CFU/100 mL or 0.9 MPN/100 mL was used as a conservative assessment during the calculation of geometric means and statistically significant differences at a significance level of α = 0.05.

2.4 Results

2.4.1 Microbiological reductions

For all test water conditions, all but one CDP (JN) attained the default value of 4 bacterial LRs to be considered as "highly protective" as per WHO [9] criteria. As some bacterial levels were noted as below the limit of detection (<1 MPN or CFU) after treatment, it can be expected that these products may have been able to achieve greater removal as they were censored by initial bacteria concentrations. These results show that the bacterial LRs by those given products (denoted by an * in Figure 1) may be conservative with respect to microbial reductions. Initial bacteria concentrations of test waters ranged from an average of 1.00E+06 (95% CI 6.3E+05 to 1.4E+06) MPN /100mL for CF "Cold" conditions to 9.65E+04 (6.3E+05 to 1.4E+06) CFU/100mL for JN "Acidic" conditions.

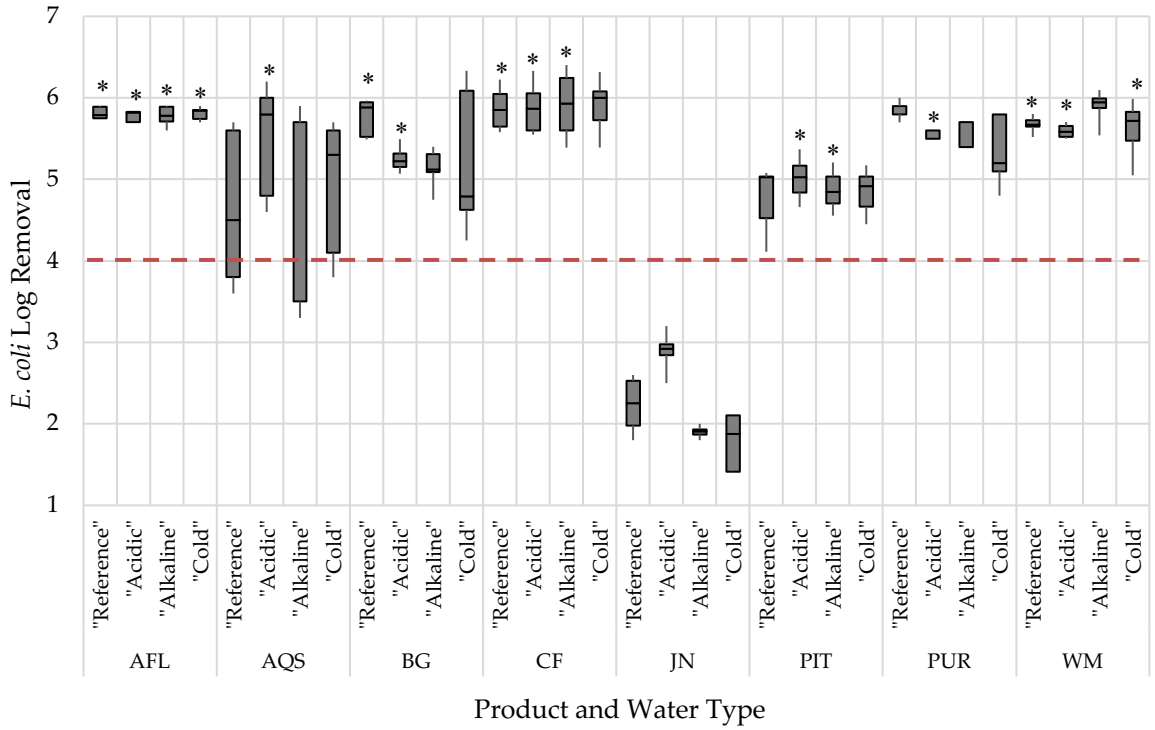

Figure 1. Resulting *E. coli* LRs post CDP treatment. Box-and-whisker plots (min/max, lower/upper quartiles, and median) of the *E. coli* Log Removal. The dashed line represents the default LR value to be considered "highly protective" by the WHO. The asterisk (*) indicates that the mean bacterial concentration after treatment is below the limit of detection (<1 MPN or CFU).

Because input water parameters were of significant difference (Kruskal Wallis test $p<0.01$), bacterial LRs were used for the basis of calculations and comparisons between products. Using the ANOVA assessment on bacterial LRs across all products and all the test conditions (i.e. "Reference," "Acidic," "Alkaline," and "Cold"), results did not show an overall significant difference ($P=0.538$). However, when investigating each product individually, results showed bacterial LRs that were statistically significant ($P < 0.05$) across the different treatment pH and temperature conditions for half of the CDPs (PUR, WM, JN and BG). However, these initial conditions did not generate a significant difference ($P >$

0.05) for the remaining four (AFL, AQS, CF and PIT). Post hoc comparisons (i.e. Dunnett's tests) between the "Acidic," "Alkaline," and "Cold" conditions in comparison to the "Reference" conditions were completed for each product for which a significant difference was observed.

Dunnett's test illustrated JN was significantly impacted by "Acidic" water conditions ($q > q_{crit}$; where $q_{crit} = 0.303$, $q=0.625$), and "Cold" water conditions ($q=0.666$), while PUR ($q > q\ q_{crit}$; $q_{crit} = 0.260$), and BG ($q > q_{crit}$; where $q_{crit} = 0.508$), experienced significant influence in log reduction from acidic and alkaline adjustments (PUR q=0.311,0.278, and BG q=0.522, 0.614 respectively,) and pH (PUR q=0.533 and BG q=0.614) on the test waters. While WM obtained a significant difference between test water conditions overall, Dunnett's testing did not find a significant difference between any of the test waters and the "Reference" conditions. ($q < q_{crit}$; $q_{crit} = 0.234$). While the results of these products and influence of pH and temperature on bacterial LRs vary greatly, Figure 2 illustrates that for a given CDPs, the test conditions can influence % compliance with the ranging categories of *E. coli*.

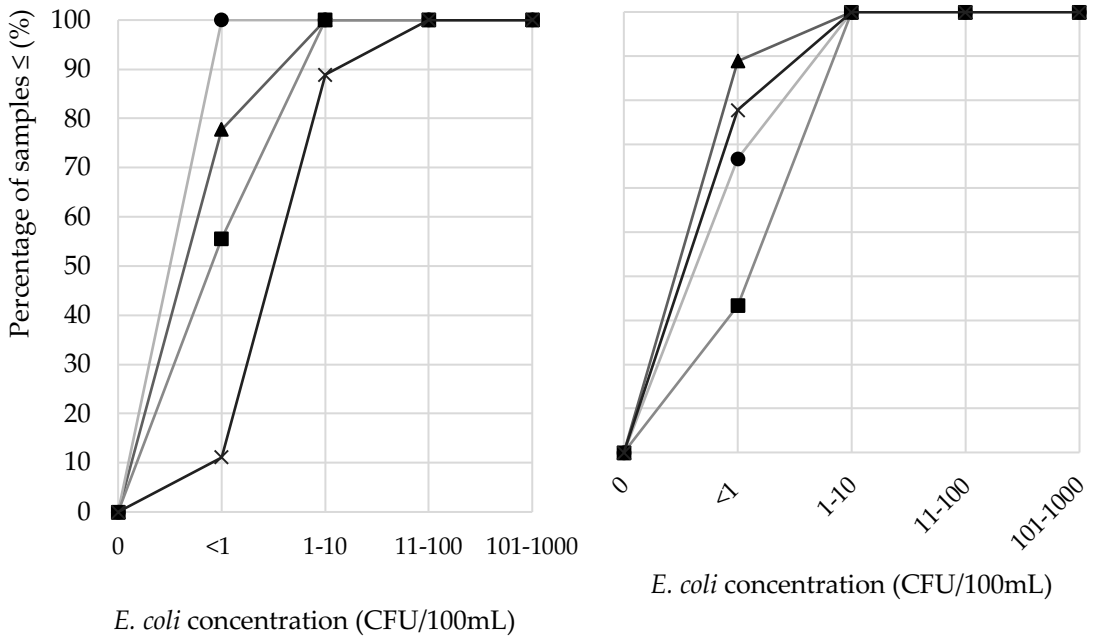

Figure 2 Cumulative percentage of all *E. Coli* counts within each bacterial concentration stratum after treatment for "Acidic" -●, "Reference" -▲, "Alkaline" - ■, and "Cold" - X treatment conditions, for PUR (left) and BG (right)

2.4.2 Free chlorine residuals

For all the FCR values sampled after the prescribed treatment time (varying from 11.5 - 60 minutes), none of the products was able to achieve the minimum recommended FCR level of 0.5 mg/L after at least 30 min contact time for all test water conditions (Figure 3). However, CF achieved a median value above the WHO2011b guides of 0.5 mg/L after at least 30 min contact time in "Alkaline" and "Cold" conditions.

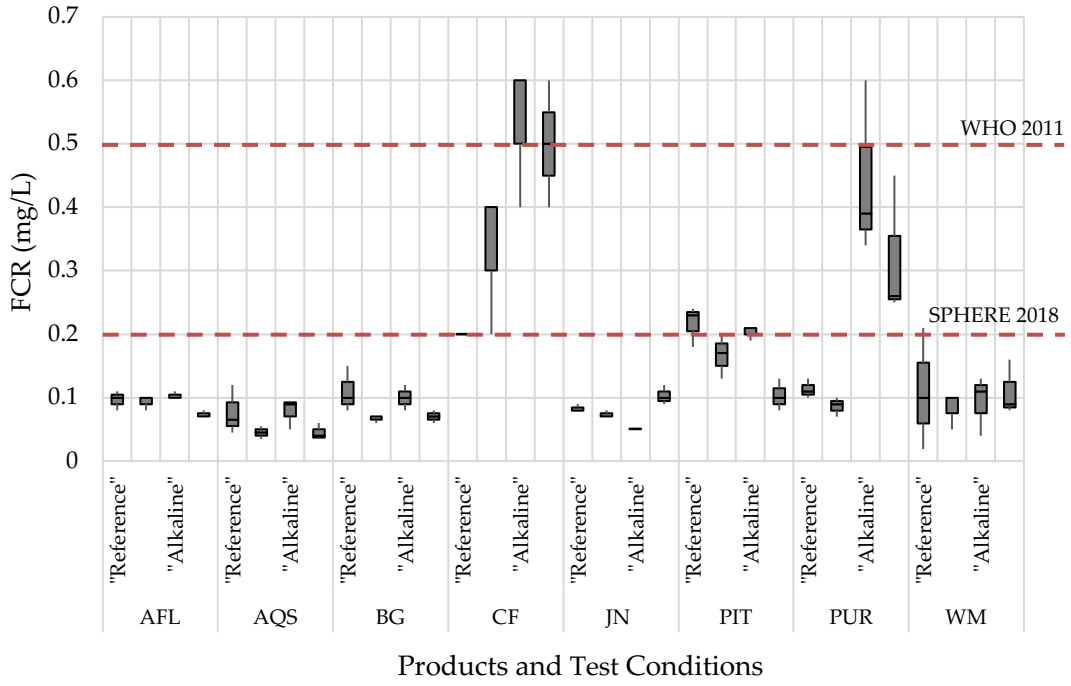

Figure 3 Resulting FCRs post CDP treatment. Box-and-whisker plots (min/max, lower/upper quartiles, and median) of the final treatment FCR for each CDP after prescribed treatment time.

The product with the greatest residual was CF which surpassed the 0.5mg/L requirement at the end of prescribed treatment time in "Alkaline" and "Cold" conditions, achieving 0.53 and 0.50 mg/L respectively. However, it is important to note that CF treatment time was 11.5 min based on manufacturing specifications, less than all other CDPs. PUR also performed well in "Alkaline" and "Cold" conditions, achieving 0.443 ± 0.113 mg/L, and 0.320 ± 0.092 mg/L respectively, and an average of 0.241 ± 0.148 mg/L across all test conditions. The products which generated the lowest FCR values were AQS and JN which only achieved an average of 0.06 and 0.08 mg/L across all test waters for all test conditions. PUR showed the largest deviation of 0.148 mg/L between test water conditions, while WM and AFL showed the lowest with a standard deviation of 0.011 mg/L.

Assessing the 0.2mg/L SPHERE 2018 [10] guideline, it is shown that three of the products (CF, PIT, and PUR) were able to achieve 0.2 mg/L at the point of delivery (upon completion of prescribed treatment time) for at least one of their test water conditions.

Dividing the products into disinfectant type revealed any variations in FCR based on disinfectant product, NADCC (0.161 ± 0.134 mg/L) and CH (0.144 ± 0.067 mg/L), but the results remained statistically insignificant (P=0.557). Results showed no significant influence of temperature (P=0.521), but pH showed an influence on FCR (P=0.049), with averages ranging from 0.126, 0.019, and 0.201 mg/L for pH 7, 5, and 9 respectively.

CT values are presented below (Table 6) and allow quantitative comparisons to the CT values presented by the USEPA [35] to achieve viral and protozoan LRs standards. Results found that overall, through calculating the averages across the test water conditions, PUR (7.23 ± 4.43 mg-min/L) and CF (7.84 ±2.68 mg-min/L) achieved the greatest CT values.

Table 6 CT values calculated from product specific treatment time and FCRs post-treatment

		CT in mg-min/L					
Product	**Disinfectant**	**"Reference"**	**"Acidic"**	**"Alkaline"**	**"Cold"**	**Average**	**Contact Time (min)**
AFL	NADCC	4.35	4.20	4.65	3.30	4.13	60
AQS	NADCC	2.30	1.35	2.35	1.35	1.84	30
BG	CH	2.42	1.47	2.20	1.54	1.91	22
CF	NADCC	4.00	6.67	10.67	10.00	7.84	11.5
JN	CH	2.50	2.20	1.50	3.10	2.33	30
PIT	CH	4.77	3.67	4.47	2.27	3.80	30
PUR	CH	3.40	2.60	13.30	9.60	7.23	22
WM	NADCC	2.74	2.08	2.33	2.75	2.48	25
(mg-min/L) value for 4-log viral removal (FCR <1mg/L)		3	3	3	8		
(mg-min/L) value for 2-log protozoan removal(FCR <1mg/L)		37	26	78	99		

Using this CT table in conjunction with Table E-7 in the same USEPA report [35], it was found that - to achieve a LR of 4 as per WHO guidelines and within the pH range of 6-9 - the CT values for inactivation of viruses by free chlorine are 8 mg-min/L for 5°C degrees and 3 mg-min/L for 20°C degrees. Following these viral LR guidelines, one of the products, CF, achieved the minimum required CT guideline for all test waters. In comparison AQS, BG, JN and WM did not achieve these targets for any of the given water. AFL and PIT achieved viral LRs of 4 for all conditions besides the "Cold" conditions, and PUR achieved all beyond the "Acidic" condition.

Tables E-2 and E-5 in the USEPA document recommend a CT value dependent on pH, temperature, and approximate chlorine concentration to achieve 2 LR of [35] the protozoa *Giardia lamblia* (*G. lamblia*). Given these conditions, none of the products achieved log inactivation to the recommended requirements, as none of the products achieved CT values greater than 13.30 mg-min/L.

2.4.3 Turbidity reductions

Averages of treated turbidity test water ranged from 3.27NTU to 28NTU across the CDPs. AFL (97±2%) and PUR (96±4%) achieved the greatest turbidity removal across all test waters, while BG and CF achieved the lowest turbidity removals and greatest standard deviations of 60±25% and 62±39% respectively.

Temperature generated a significant difference ($P<0.01$) in regard to turbidity removal as, for test waters with a temperature of 20°, the average removal was 91±11%, while products tested at a temperature of 5° produced an average of 70±11% removal. CF - which performed well on the reference and basic conditions - was the least temperature resilient of all the CDP, with an average of 96% decrease in performance from 20°C to 5°C. Additionally, WM, BG, PUR and JN also had a decrease in turbidity by

-9%, -19%, -8%, and -34%, respectively. The most temperature resilient products were AFL, PIT, and AQS, each of which generated only a 1% difference in turbidity removal at each temperature.

pH was also shown to generate a significant impact on turbidity removal (P<0.01); the averages for pH 7, 5 and 9 were 91%, 76% and 93% respectively. Across all products, pH 7 generated an average of 2±6% increase in turbidity removal, where pH 5 generated an approximate decrease of 15±16%. The product most resilient to both increase and decrease in pH was PUR (1% decrease performance for each) while BG experienced the greatest change in turbidity reduction with -47% decrease for pH 5 and 19% increase for pH 9.

Percent compliance was evaluated for each product in all water types to assess how the products aligned with categorized performance for achieving a final turbidity of <1NTU, <5NTU and <10NTU (Table 7). None of the products achieved <1NTU for any of the test water conditions. Under the <5NTU compliance, all but one test water condition was under compliance for AFL and PUR. PIT achieved 42% compliance and AQS achieved 8% compliance. For compliance of the <10NTU guidelines, PIT and AFL both achieved 100% compliance, while the remaining products obtained greater than 50% compliance except for BG and JN (0% and 8% respectively).

Table 7 Resulting turbidity removal and turbidity compliance post-treatment

		NTU Values (Averages)			All Water Types Turbidity Compliance		
	Coagulant Type	Initial Turbidity (With Clay)	Post Treatment	Average Removal (%)	<1NTU	<5NTU	<10NTU
AFL	AS	94 ± 2.1	2.0 ± 0.19	98%	0%	75%	100%
AQS	FS	95 ± 2.4	5.1 ± 0.65	95%	0%	8%	92%
BG	AS	104 ± 0.94	30 ± 20	72%	0%	0%	0%
CF	AS	111 ± 2.4	7.8 ± 0.53	93%	0%	0%	50%
JN	FS	101 ± 5.2	13 ± 1.6	87%	0%	0%	8%
PIT *	FS	56 ± 6.7	5.1 ± 0.79	91%	0%	42%	100%
PUR	FS	101 ± 9.2	1.7 ± 0.18	98%	0%	75%	92%
WM	AS	101 ± 4.8	8.2 ± 0.84	92%	0%	0%	58%

* denotes the PIT test of which was completed with 50NTU water for all tests except the cold test water settings.

When the products were divided by coagulant type, there was a significant difference (P=0.0178) in turbidity removal by AS 77±30% and FS 88%±13%; however, significance was not attributed to any one specific water condition.

2.4.4 pH Values

In general, finished water pH observed in the lab testing was typically lower than initial target pH. Figure 4 below illustrates the product specific capacity for buffering in each product.

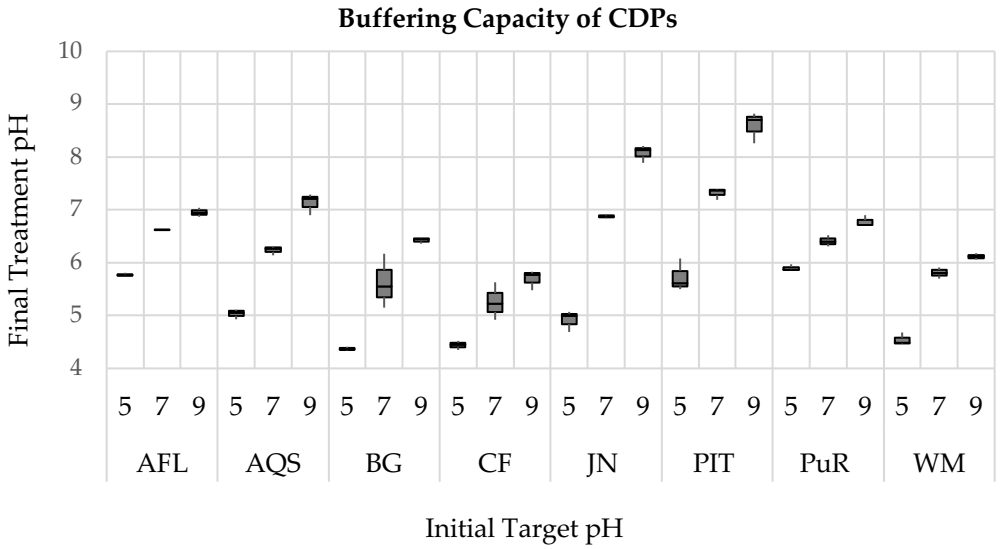

Figure 4 Initial and final pH values during CDP treatment. Box-and-whisker plots (min/max, lower/upper quartiles, and median) of the final treatment pH for each initial target pH tested divided by product.

Alongside the graphical representation in Figure 4, the slope of the final pH from test conditions over the original pH resulted in the values shown in Table 8. This slope value expresses the products' ability to control high pH test waters and was calculated by dividing the observed change in pH post treatment of the 5, 7, 9 test conditions by the change in initial pH values (before the product was added). A slope of one denotes a product with zero buffering capacity, expressing that when the product was added to the test water, there was no control of pH. In contrast, a low slope denotes that the product has a relatively strong buffering capacity to control the extreme pH values of the test water. The following table shows the ranges of values from 0.298 (relatively high buffering capacity in comparison to other tests) to 0.785 (relatively low buffering capacity).

Table 8 Slope of pH post-treatment for the various CDPs

	Slope of pH	Disinfectant	Coagulant
AFL	0.303	NADCC	AS
AQS	0.532	NADCC	FS
BG	0.528	CH	AS
CF	0.334	NADCC	AS
JN	0.785	CH	FS
PIT	0.783	CH	FS
PUR	0.206	CH	FS
WM	0.422	NADCC	AS

Results shown in Table 8 were further investigated by coagulant type and disinfectant type. However, prior to this investigation, it is important to note that there may be buffering agents in these product formulations of which information was not available. The analysis showed that for NADCC (0.398±0.103), a slightly greater buffering capacity was observed than CH (0.576±0.238). However,

similar results were shown between AS (0.397±0.101), and FS (0.577±0.274), making it difficult to determine which variation of formulation generated this variation.

2.5 Discussion

Results found that no single product was able to achieve all water treatment guidelines (≥4 bacterial LRs, <5NTU, FCR > 0.2 mg/L (SPHERE) and FCR > 0.5 mg/L (WHO)) for all water conditions. However, seven of the eight CDPs (AQS, AFL, BG, CF, PUR, PIT, WM) achieved bacterial LRs ≥ 4 for all test waters, which is the minimum default value to be considered a "highly protective". PUR, PIT, CF and AFL achieved higher performance in accordance to water quality guidelines overall, while JN was the lowest performing of the CDPs and did not achieve any of the drinking water guidelines. Table 9 outlines the summary of the CDPs evaluation and compliance.

FCRs act as a tool to examine the prolonged protection of drinking water via chemical disinfection residual. This is of high importance in emergency contexts, as risk of post-treatment recontamination increases [5]. Overall, FCR levels and compliance of the CDPs to both the WHO and SPHERE guidelines were low, which has also been exhibited in existing studies [30]. These results may be caused by the high organic content (i.e., high chlorine demand) of the test waters used [14, 31], and suggest that - with naturally occurring test waters - the results may have obtained higher FCR values. When assessing and revaluating these products to achieve higher FCRs, increasing the initial dose of chlorine in the formulation is often the first course of action. However, this may result in excessively high disinfectant doses that could compromise taste acceptability for users [38]. In addition to acceptability for users, inadequate chlorine dosing also leads to an increased health risk of disinfectant by-products (DBPs). DBPs are formed upon the reaction of chemical disinfectants with natural organic material [40] which can generate public health concern during the chlorination process. Some studies have suggested that long-term exposure to consistently high levels of DBPs might increase the risk of cancer [41]. Specific to emergency contexts, sub-chronic exposure risks are relatively under-explored and warrant further investigation [42]. To develop a "one size fits all" solution for the formulation of CDPs to increase FCR, minimize DBPs, and maintain acceptability, optimizing the coagulant formulation may be a viable alternative to reduce the impacts of improper disinfection doses. Additionally, research has illustrated that turbidity should not be used as an accurate indicator for chlorine demand as 90%, of the demand still remains in the filtrate [43]. This has the potential to shift and motivate research surrounding CDPs to be driven towards NOM removal, beyond the turbidity-based coagulant doses.

CF was able to achieve the highest FCR after the prescribed treatment time; however, this may have been influenced by the relatively short treatment time (11.5 minutes) and therefore low time available for chlorine decay. When developing and altering CDPs, it is important to note that the benefit of this short treatment time not only applies to the perceived efficacy, but it also simplifies the operation for the consumer as it is a less time intensive procedure. In contrast, to account for the influence that cold temperature has on the coagulation phase of the product, some of the products recommended an increased treatment time (i.e. AQS 30 minutes; CF 19.5 minutes) based on the temperature of the source water. Increasing the treatment times or increasing the complexity of the treatment process may have a detrimental impact on adherence to consistent use.

Studies show that high adherence and consistent use are essential to realize potential health gains from household water treatment interventions, as adherence-related costs can often outweigh their benefits [44]. One of the key trade-offs within POU water treatment is between maximum efficacy and

Table 9 Overall CDPs compliance summary

		≥4 Log Removal	<5NTU	FCR > 0.2mg/L	FCR > 0.5mg/L
AFL	"Reference"	✓	✓		
	"Acidic"	✓			
	"Alkaline"	✓	✓		
	"Cold"	✓	✓		
AQS	"Reference"	✓			
	"Acidic"	✓			
	"Alkaline"	✓			
	"Cold"	✓			
BG	"Reference"	✓			
	"Acidic"	✓			
	"Alkaline"	✓			
	"Cold"	✓			
CF	"Reference"	✓			
	"Acidic"	✓		✓	
	"Alkaline"	✓		✓	✓
	"Cold"	✓		✓	
JN	"Reference"				
	"Acidic"				
	"Alkaline"				
	"Cold"				
PIT	"Reference"	✓	✓	✓	
	"Acidic"	✓			
	"Alkaline"	✓		✓	
	"Cold"	✓			
PUR	"Reference"	✓	✓		
	"Acidic"	✓	✓		
	"Alkaline"	✓	✓	✓	
	"Cold"	✓		✓	
WM	"Reference"	✓			
	"Acidic"	✓			
	"Alkaline"	✓			
	"Cold"	✓			

user adherence. While maximizing efficacy is of great importance, to ensure any POU water treatment technology is effective, it must be used consistently, correctly, and over long periods of time (i.e., high adherence)[45]. Low adherence, or inconsistent use, can be caused by complexity or uncertainty of use [46], malfunction of the technology [47], or taste acceptability [39]. Simplifying the procedures of CDPs is critical for increased effectiveness.

The turbidity analysis of the different CDPs found a prominent variation between compliance of the <5NTU and <10NTU levels. For example, WM did not adhere to the <5NTU compliance for "reference" conditions, yet still provided "highly protective water" and a slightly above average FCR. From this standpoint, the turbidity standard of <5NTU can be considered as a limiting parameter that should be evaluated for extension to <10NTU, if other parameters and conditions are still adequately met. Turbidity results also illustrated that there was a significantly greater turbidity removal performance (P=0.0178) by FS 88±13% over AS 77±30%, unspecific to any one given condition. This result is consistent with other studies of which have evaluated the efficacy of aluminum versus iron-based coagulants on turbidity removal [48]. While turbidity removal is an important water quality parameter associated with coagulant type, it is also of interest to consider the pH of these products. Data has found that ferric-based coagulants can be consistently more acidic than alum [49] and therefore will not only have an impact on coagulation, but on the effectiveness of disinfectant in conjunction with the need for a buffer. These results warrant further investigation specific to CDPs and coagulant types used.

Comparing the trends of this CDP overview to the individual product studies yielded relatively consistent results. Given AFL was a two-part product, and not yet on market, studies were only found regarding the chlorination component (Aquatabs) resulting in lack of relevant and comparable data. Similarly, no existing literature was found surrounding JN and BG. PIT studies found similar microbiological and FCR results, but also extended the study to assess free chlorine decay experiments. With initial FCR levels well above the 0.5 mg/l guideline, no residual in these PIT trials were achieved at 24hrs [18]. WM laboratory evaluations indicated variations in the commercially-available product, but similar to other evaluations, found FCR values highly dependent on source waters [50]. AQS achieved microbiological guidelines but target FCR was not attained [20]. Additionally, CF met requirements for bacterial LRs [16][27]. PUR was by far the most widely researched product of those selected, providing insight into effectiveness of CDPs in many field conditions. It is expected that the ability of this product to decrease the incidence of diarrhea [23] may also be applicable to similarly performing CDPs. Further studies found PUR to be effective in removing arsenic from test water and achieving capacity for >4-log viral and >3-log parasite reductions across a variety of water types [17]. This last finding highlighted the limitations of using strictly CT as a removal indicator within this study as previously mentioned. Consistently across these independent studies, products often struggled to reliably produce residuals for safe storage after POU treatment [28], but managed to achieve LRs which achieved "highly protective" status. Many times, studies illustrated the performance envelopes and the CDPs under challenging conditions [20].

Relationships observed in this study were consistent with previously determined associations made between temperature and coagulation [51]. Cold temperatures were shown to decrease bacterial LRs and turbidity for some of the products, indicating that differences were likely attributed to coagulation-related processes (i.e., coagulation, flocculation, sedimentation, and filtration). These results draw attention to the fact that CDP performance can be further compromised in field applications based on the environmental conditions.

Using "Reference", "Acidic" and "Alkaline" test waters allowed an evaluation of pH on the CDPs assessed. JN, PUR and BG specifically were significantly impacted by "Acidic" water conditions which may be attributed to relatively low buffering capacity and therefore impact on turbidity removal under these specific conditions. pH and buffering capacity of CDPs plays a key role in the functionality and

efficacy of many of the chemicals that make up the basis of the CDPs. Notably, coagulants' efficacy is greatly impacted by pH, but pH is also affected by the strength of the selected disinfectant. Chlorine is known to lose its disinfection effectiveness at higher levels of pH due to the dissociation of HOCl [52]. While 78% of chlorine exists in the active HOCl at neutral pH 7, at pH 8 the level drops to 26% [25]. As previously mentioned, there was no significant difference in the FCR produced by either NADCC or CH in this study, while other studies have found that NADCC can continue to release significant amounts of HOCl over a wider pH range [25];[53]. Both CH and NADCC are basic in nature and have the tendency to increase the pH of the solution, so must be carefully balanced with the formulation.

While this study provided a series of tests to evaluate the base mechanisms of the products (chlorination and coagulation), without further formulation of the products, evaluation is limited by their mode of use and factors. Therefore, these findings provide a comparison between select products but should not be generalized for other CDPs, as their performance may vary with different instructions for use and formulations. This study exhibits how CDPs were able to achieve "highly protective" bacterial LR status at the end of the prescribed treatment time; however , formulations should be altered to improve the FCR after the point of treatment time and ability to protect and enhance and safe storage options.

2.6 Limitations

The authors acknowledge that not all products have been assessed for effectiveness in reduction of diarrhoeal diseases. However, one of the guidelines of this paper - the SPHERE guidelines - state that adequate water quantity and quality is the underlying cause of most public health problems in crisis situations [10]. Because this study focused on diarrhoeal disease in emergency contexts, and that the diluted wastewater would not have been an accurate representation of DBPs formed, the study's laboratory element did not address disinfectant DBPs. However, the authors acknowledge the importance of monitoring and understanding DBPs. Outside of this study, previous laboratory investigations have evaluated AQS on the basis of two DBPs - total trihalomethanes (THMs) and haloacetic acids (HAAs) [20]. These results showed that DBPs were below the USEPA maximum contaminant limits for THMs (0.080 mg/L) and HAAs (0.060 mg/L) . THMs were also shown to be below the WHO [24] additive toxicity guideline value (i.e., sum of the values of the four THMs divided by their respective guideline values should be < 1) [20]. Other studies of PUR have investigated DBPs associated with chlorination alone. These studies found that by using DBPs in CDPs in comparison to chlorination alone, produced THM levels were 26.1% lower at 1 hour after treatment, 65.0% lower at 8 hours, and 73.1% lower at 24 hours [26]. It is speculated that these results may be consistent with other CDPs, but it is also important to acknowledge that - based on the different products components (NADCC vs. CH) - DBPs may vary. This is an important area of research to be further investigated. Further work is needed to develop a full and clear understanding of the role that DBPs play in CDPs.

The overall efficacy of the CDPs to remove viruses and protozoa were not evaluated in the lab and therefore the products' overall treatment ability is outside the scope of this study. However, through CT values and comparisons to USEPA[35] standards, all products achieved high levels of viral reductions, while none of the products achieved log inactivation to the recommended requirements for the protozoa. This can be expected, as chlorine is known to have a poor performance against some protozoa inclusive of cryptosporidium oocysts [24]. These findings highlight the benefits of a CDP specifically surrounding the coagulation component. While CT was a method that was able to give a general comparison between the two products, it is important to understand the nature of the products themselves and that through the understanding of CT, this does not capture or consider viral and protozoan reductions that take place in coagulation, sedimentation and filtration procedures where CDPs can outperform the products containing chlorine alone.

2.7 Conclusions

This study identified the treatment performance of eight CDPs under challenging test water conditions. The study determined general influences of test water conditions (pH and temperature), but also acknowledged the variety between products and those with greater resilience to varying conditions. Recommendations are made to improve and motivate research surrounding CDPs and important considerations to be included in the alterations of their formulations.

2.8 Acknowledgements

The author acknowledges support from SNC-Lavalin and suppliers of the trial products; Oxfam GB (PIT), GlobalMedic (PUR), and additional suppliers (Bishan Gari, Watermaker, Aquafloc). Jean-Thomas Marois-Fiset and Alain Marcoux are also acknowledged for their contributions to the laboratory work

3. Model-based evaluation of coagulant disinfectant emergency water treatment products using principles of enhanced coagulation

3.1 Abstract

Point-of-use (POU) water treatment systems can aid in improving water quality [12] in humanitarian emergencies, as sanitary conditions deteriorate, and risk of diarrheal disease outbreak increases [5]. Coagulant disinfectant products (CDPs) are a POU water treatment technology that uses a chemical based, pre-mixed formulation consisting of a coagulant and disinfectant. Unfortunately, current pre-mixed CDPs on the market are found to be ineffective at maintaining adequate levels of free chlorine residuals (FCRs) [29], [18], [54] a key guarantee of microbiological safety. Optimizing the coagulant formulation of CDPs may be key to developing a solution suited to a broad range of contamination scenarios. Applying the approach of enhanced coagulation, an excel based computational model (referred to as the *CDP model)* was developed and executed with simulated test waters and two CDPs identified as Watermaker (WM) and Proctor and Gamble Purifier of Water (PG). Results were evaluated based on overall FCR performance and in relation to two guidelines set out by enhanced coagulation recommendations and relevant studies; the Point of Diminishing Return (PODR) and Universal NOM Removal Dosage (UNRD). The model suggests that WM exhibited a greater FCR after treatment, associated with the initially high chlorine doses, while PG appeared to remove a higher amount of natural organic matter in the form of dissolved organic matter (DOC). Both CDPs surpassed the guidelines of coagulant dosing to achieve the PODR and UNRD outlined through the principles of enhanced coagulation. This study also highlighted the influence of pH on coagulation ability. This study serves as a baseline evaluation to motivate further computational modelling and laboratory analysis of CDPs. Recommendations are made to motivate future research and limitations of the model are discussed.

3.2 Introduction

In humanitarian emergencies, water quality becomes progressively more important as sanitary conditions deteriorate and risk of diarrheal disease outbreak increases [5]. POU systems are key for treating water in these contexts as they are considered to be user-friendly, low cost, low maintenance, and grid-independent [55]. Importantly, they can aid in improving water quality and decreasing diarrheal disease incidence [12]. CDPs are a chemical based POU water treatment method which use a pre-mixed formulation to help aid in the reduction of these risks associated with humanitarian emergencies.

CDPs pre-mixed formulation consists of a coagulant (for turbidity and NOM removal), and a disinfectant (to meet safe microbiological limits). Unfortunately, the current pre-mixed CDPs on the market were found to be ineffective in lab based evaluations at maintaining adequate levels of FCRs [29], [18] [54], a key guarantee of microbiological safety. One of these comparative studies [54] found that the waters tested had an organic demand that exceeded reasonable test conditions. In this case, having a tool to predict approximate performance of these products prior to laboratory analysis, may have generated more operational results. Analysis of CDPs performance in all studies supported the need for further investigation.

The presence of FCRs in water post-treatment provides an indication that disinfection has been effective and ensures continued disinfection ability during storage of the treated water. When CDPs fail to produce adequate FCRs, a feasible solution might be to increase the initial dose of chlorine in the formulation. However, this may result in excessively high disinfectant doses that could compromise taste (and therefore acceptance) for users, in addition to increased health risks of DBPs. DBPs are

formed upon the reaction of chemical disinfectants with NOM (often referred to as DBP precursors) [40] which can generate public health concern during the chlorination process. Some studies have suggested that long-term exposure to consistent high levels of DBPs might increase the risk of cancer [41]. NOM/DBP precursors can be removed from drinking water by several treatment options, of which the most common and economically feasible processes are considered to be coagulation and flocculation [56]. Reducing NOM in test water will consequently reduce the waters chlorine demand [43].

In conventional water treatment systems, the term "enhanced coagulation" refers to the process of improving the removal of NOM/DBP precursors in a conventional water treatment plant [57]. The process essentially highlights the use of optimizing coagulation dose for the removal of NOM as the motivating metric of the dosing. Studies have also shown that using this technique may result in an improved higher maintenance of FCRs post-treatment [59].

Two applications of the principle "enhanced coagulation" are the Point of Diminishing Return (PODR) as outlined by the USEPA Enhanced Coagulation and Enhanced Precipitative Softening Guidance Manual [57], and the Universal NOM Removal Dosage (UNRD) as outlined in Beauchamp et al. [58].

The PODR is defined as the point on the NOM vs. coagulant dose plot, where the slope drops below 0.03, (unitless, as slope is calculated from mg/L TOC over mg/L aluminum sulfate), which reflects the optimal removal of DBPs precursors obtained per coagulant dose. The purpose of this PODR guideline is to reduce exposure to these DBPs in drinking water. Similarly, the UNRD is a constant stoichiometric ratio of aluminum sulphate dose (coagulant agent) to initial water NOM values (measured in UV254) that was found to exhibit a NOM removal plateau (DOC removal ratio) in waters of diverse origins and characteristics [58].

A "one-size-fits-all" solution that can effectively treat a broad range of contamination scenarios is crucial in emergency contexts. In order to develop this "one size fits all" solution for CDPs, optimizing the coagulant formulation through application and comparison to both the PODR and UNRD may be a useful evaluation to ensure 24-hour FCRs targets are achieved, providing safe water where POU interventions are of high importance. While an existing study by Dorea and Borrett [54] has critically analyzed the formulations of CDPs, there has been minimal research surrounding computational modelling of CDPs to screen product performance and identify hypotheses to be experimentally tested. The objective of this work is to generate a mathematical and computational based model (referred to as the *CDP model* from henceforth) to increase understanding of CDPs in regard to NOM removal through specific comparisons to the PODR and the UNRD. Additionally, this *CDP model* can be used as a tool by policy makers, researchers, manufacturers and aid agencies to predict how CDPs will perform in given test water conditions and in what contexts they may be best applied.

3.3 Materials and Methods

3.3.1 Coagulant Disinfectant Products

Two commercially-available CDPs were selected for testing in the *CDP model*. Table 10 summarizes the characteristics of the surveyed products. Although the specific formulation of these products is undisclosed or proprietary, the two significant active ingredients are known: the coagulant is aluminum sulphate (AS) or ferric sulphate (FS) and the disinfectant is sodium dichloroisocyanurate (NADCC for short) or calcium hypochlorite.

Table 10 Product information for CDPs input into the *CDP model*.

Product Name	Disinfectant	Coagulant	Total Weight (g)	Volume Treated (L)	Laboratory Evaluations
Watermaker (WM)	NADCC	Aluminum Sulphate	2.5	10	[22]
Purifier of Water (PG)	$Ca(ClO)_2$	Ferric Sulphate	4	10	[17][8][28][29]

3.3.2 Test Waters

Test water parameters run through the *CDP model* were extracted from three different sources in water supply locations of Quebec, Canada as shown in Table 11. Averages for the St. Lawrence and St. Charles were obtained from published data sources, while Charny data was taken from June-October routine monitoring at the University of Laval.

Table 11 Test water conditions input into the *CDP model*

Name	UV_{254} (cm^{-1})	DOC (mg/L)	Data Source	Data Points (n=)
Charny River	0.3290	8.1	Laval (Unpublished)	18
St. Lawrence River	0.1805	4.7	[60],[61]	21
St. Charles River	0.2775	6.5	[60],[61]	27

3.3.3 Construction of the Model

The *CDP model* was constructed through the consolidation of two predictive water treatment models and one lab relationship (Figure 5). The model was compiled and statistically analyzed using Microsoft Excel.

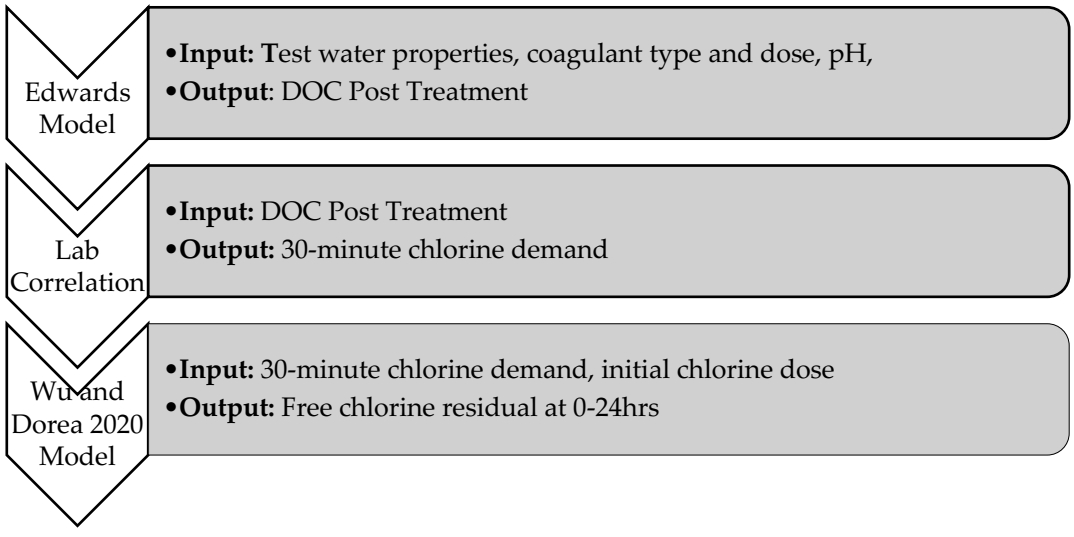

Figure 5 Overview of the *CDP model*

The coagulation component of the model uses the Langmuir-based semi-empirical model described by Edwards in "*Predicting DOC removal during enhanced coagulation*" [49] (referred to as the Edwards model from henceforth). This model predicts the DOC removal during aluminum sulphate and ferric sulphate coagulation and was developed from 21 water sources coagulated with ferric salts (250 jar tests) and aluminum sulphate (608 jar tests). The model accepts raw water properties (pH, initial DOC, initial UV254), coagulation traits (dose, type) as input variables and breaks down the DOC into absorbable and nonabsorbable fractions. The model's output is the DOC remaining after treatment.

The chlorination element of this model was extracted from Wu and Dorea 2020 which investigated the challenges of adequate chlorine dosing in humanitarian contexts through the development of a predictive tool to rapidly and accurately estimate chlorine decay kinetics [62]. Through use of the Feben and Tara model [63], Wu and Dorea calibrated a dose specific decay constant and relationship from test waters 30-minute chlorine demand. Wu and Dorea recommended that 30-minute chlorine demand be used as an indicator for chlorine dose design given its testing simplicity and ability to encapsulate many of the water's parameters. The model estimates chlorine decay rate at integral doses only and therefore, chlorine doses of 4mg/L and 2mg/L, which aligned with the values of the CDPs, were used. Equations used in the modelling procedures were as follows:

For initial chlorine dose = 4 mg/L:

$$C_t = C_0 - (1.8119x + 0.1319)t^n,$$

For initial chlorine dose = 2 mg/L:

$$C_t = C_0 - (1.2101x + 0.3585)t^n,$$

Where Ct= Chlorine at time t, C0= Chlorine at time 0, n = power term determined from regression analysis (0.22 for this study), and x = 30-minute chlorine demand.

The relationship between DOC and 30-minute chlorine demand provided a link between the Edwards and Wu and Dorea Models, resulting in the formulation of the *CDP model*. To connect the outputs of the Edwards model and the inputs of the Wu and Dorea Model, a relationship was methodically collected from source waters in the same region as water used in the trial runs of the *CDP model*. UV254 (HACH DR6000), DOC (Sievers 5310C Lab TOC Analyzer) and 30-minute chlorine demand values (HACH pocket chlorometer) were obtained. Data was then plotted to determine the relationship between DOC and 30-minute chlorine demand.

3.3.4 Determining Approximate Product Composition

In order to test the selected products in the model, approximation of the coagulation and disinfectant doses were required. To obtain coagulant doses, Safety Data Sheets (SDSs) of the given products were first assessed to give an approximate percent range. For PG, the coagulant dose was labelled on the product, while for WM, this value was determined through the Equivalent Dose Method.

The Equivalent Dose Method is a two-step protocol that requires laboratory equipment and a minimum of 40L of test water. The first step of this protocol was to determine the NOM removal ability (measured in UV254 removal) of the CDP in a full 10L batch. In order to isolate the NOM removal ability of the coagulant, a predetermined dose of chlorine quencher (sodium sulphite) was used to avoid any oxidation reactions or interference by the chlorine. The pH is controlled to provide consistent test water conditions (through the predetermined doses of hydroxide and sulfuric acid). NOM was then measured

using the UV254 spectrometer (HACH DR6000) before and after prescribed treatment time, to determine the CDPs NOM removal ability. Using the same test water, the next stage was to complete a jar test, a laboratory procedure that simulates coagulation/flocculation with differing chemical doses to estimate the minimum coagulant dose required to achieve certain water quality goals. The jar test generated a coagulant dose (mg/L) vs. % NOM removal (UV254 removal) plot for the given test water used in part 1. The NOM removal achieved by the 10L full-scale CDP batch is then plotted as an horizontal line across the graph, overlaying the jar test results. The x-value at the intersect between the jar test graph and 10L batch data was determined graphically. This intersect represents the approximate equivalent dose of coagulant in the CDPs. This test was completed on a test water with a UV254 value of 1.050cm-1, generated through a mixture of distilled water and humic acid (Sigma Aldrich, United States). The resulting coagulant doses were expressed in both mg/L and moles of active metal.

Initial chlorine doses of the CDPs were determined through laboratory testing in distilled water. The product sachets were mixed in to the standardized batch (10L as specified for each product) of distilled water and stirred for one minute. After thorough mixing, FCR readings were taken using the Pocket Chlorometer (HACH). Ten 10L tests were completed for each product and the standard mean was taken across each of the CDPs. Results were rounded to the greatest whole number.

3.3.5 Evaluation of the Products and Model

Prior to commencing product specific analysis, a sensitivity analysis was completed on the model to understand any uncertainty. The model input water parameter values (UV254, DOC, pH) were adjusted independently and impacts on 30-min FCR were graphically represented.

CDPs were evaluated on the basis of FCR outputs at 0-24hrs, coagulation ability (% DOC removal) and influence of pH on resulting FCR. The coagulation component of the model was compared to the PODR as defined by the USEPA and tested against the UNRD.

The PODR for the given test waters was determined by calculating the slope of each segment (change in DOC per dose of coagulant). The point where the slope of 0.03 was achieved and sustained was then aligned to the corresponding dose. Dissolved organic carbon (DOC) was used in this study in place of TOC as completed in existing studies [58]. This dose, and corresponding DOC removal, was labelled as PODR. Variances between the PODR for each test water and the CDP doses were numerically evaluated.

The CDPs coagulant doses were also evaluated against the UNRD (aluminum sulphate/UV254 stoichiometric dose) of 180 ± 25 mg cm/L that is shown to represent a point of diminishing return (i.e. it maximizes DBP precursor removal). Additionally, to gain further understanding of the limitations of this *CDP model*, specifically the coagulation component, the results generated from the Edwards model were compared to the data sets in the Beauchamp et al. [58]. Comparisons were made through visual inspection and the calculation of correlation coefficients. The UNRD has only be proven through the use of aluminum sulphate-based products and therefore WM was the only CDP assessed against the UNRD.

To complete the second step, data was extracted from Beauchamp et al. [58] using WebPlotDigitilizer for four selected test waters in the paper (Charny, Nord Autumn, Nord Summer Dry and Sacacomie). These test water input values were then run through the Edwards Model to illustrate graphical deviation between the UNRD in the model and laboratory settings. The relationship between laboratory and model results were evaluated through visual inspection and statistical analysis.

3.3.6 Statistical Analysis and Product Comparison

Standard deviation and arithmetic means were taken across the three test waters for the analysis of the impacts of pH on FCRs, whereas all other parameters were evaluated for each test water independently. The relationship between laboratory and model results were graphically evaluated and resulting FCRs from the *CDP model* were compared against existing CDP evaluations. While test waters varied from those selected in this study, they provided a general comparison of patterns observed.

3.4 Results

3.4.1 Approximation of the product doses

The coagulant dose for WM was determined through the Equivalent Dose Method. Laboratory analysis found the intersection between the 10L full-scale batch and 1L jar test results to be 100mg/L at a UV254 removal of 99%, as shown in Figure 6.

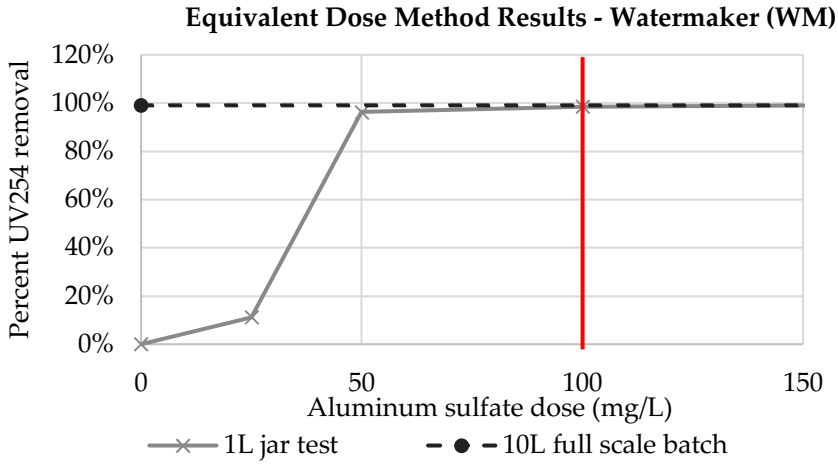

Figure 6 Graphical representation of the equivalent dose method used for WM. The red line denotes the intersection between the 1L jar test results and the percent UV254 removal obtained by the 10L full-scale batch of WM. Both tests were completed at pH 7 with test water initial UV254=1.050.

After the Equivalent Dose Method was used to graphically extract an approximate aluminum sulphate dose for WM, the value was compared against the range given by the SDS. Using the SDS coagulant percentage of 30-50% of the 2.5g packet, the value was determined to be between 75-125 mg/L. Given that the data extracted from the Equivalent Dose Method fit well within this range, the value of 100 mg/L was accepted. For PG, the Equivalent Dose Method was not required as the packet states that it contains 35.2mg/L of iron (as per manufacturer). In order to find the iron sulfate dose specifically, the molar mass relationship was used and resulted in an equivalent dose of 125.7 mg/L. Verifying this value with the product's SDS, the range is set to 30-40% of the 4g packet, with a range between 120-160 mg/L. These results, in conjunction with the FCRs obtained in the lab, are shown in Table 12.

Table 12 Equivalent doses of coagulant and disinfectant input into the *CDP model*

Product	SDS Coagulant Range	Equivalent Dose Methods Results	Coagulant Dose used in Edwards (mg/L)	Moles of Active Metal	FCRs ± SD (mg/L) as determined in the lab	Rounded value to be used in Wu and Dorea 2020 Model (mg/L)
PG	Iron (III) Sulphate Hydrate 30-40%	n/a	125.7	6.29×10^{-4} mols Fe	2.11 ± 0.35	2
WM	Aluminum Sulphate 30-50%	100mg/L	100.0	5.85×10^{-4} mols Al	3.97 ± 0.19	4

3.4.2 DOC and Chlorine Demand Association

Lab evaluations of four different test waters in the Quebec region exhibited a relationship with a strong correlation (r = 0.953) between DOC and 30min chlorine demand. Results extracted from tests waters with UV254 values of 0.224, 0.122, 0.379 and 0.026 cm^{-1} illustrated the following relationship.

$$DOC = 2.744 * (30\ Minute\ Chlorine\ Demand) + 1.3688$$

3.4.3 Sensitivity Analysis

The sensitivity analysis (Figure 7) was completed through independent variation of the input parameters (DOC, UV254 and pH), while other parameters remained at fixed values. The analysis found that DOC had the greatest influence on resulting 30-minute FCR, generating an average of 0.3 mg/L FCR decrease per 1.0 mg/L of DOC increase between the bounds of 3.0-7.0mg/L DOC. pH showed the most significant influence on resulting 30-min FCR between pH values of 6 and 10, with the lowest resulting FCR at pH 7. UV254 was shown to have minor influence on resulting FCR with a resulting increase of 0.65 mg/L 30-min FCR at 30 minutes between the extreme values of UV254.

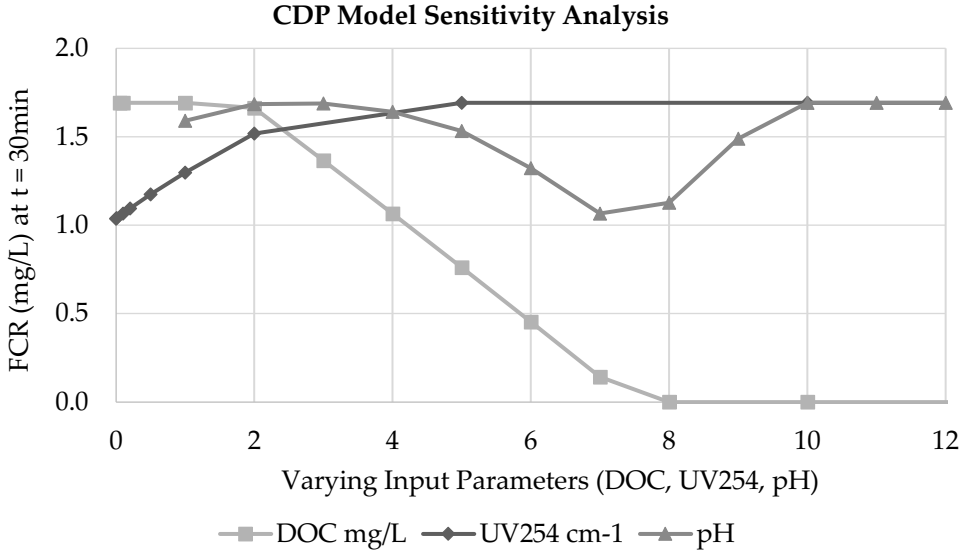

Figure 7 Sensitivity analysis of the *CDP model* through the variation of DOC, UV254 and pH

3.4.4 Product Evaluation

FCR values and decay behaviour was evaluated for the three test waters from a timespan of 0-24hrs (Figure 8). WM achieved a greater average 24-hr FCR of 2.63 ± 0.63 mg/L across the three test waters for pH 6, while PG obtained an average of 0.73 ± 0.39 mg/L. Given the initial dose variation between WM and PG (4 mg/L and 2mg/L respectively), assessing a 4mg/L dose across both products illustrated that the coagulation ability of PG generated similar but slightly higher 24-hr FCR over WM, 2.92 ± 0.59 and 2.63 ± 0.63 mg/L respectively.

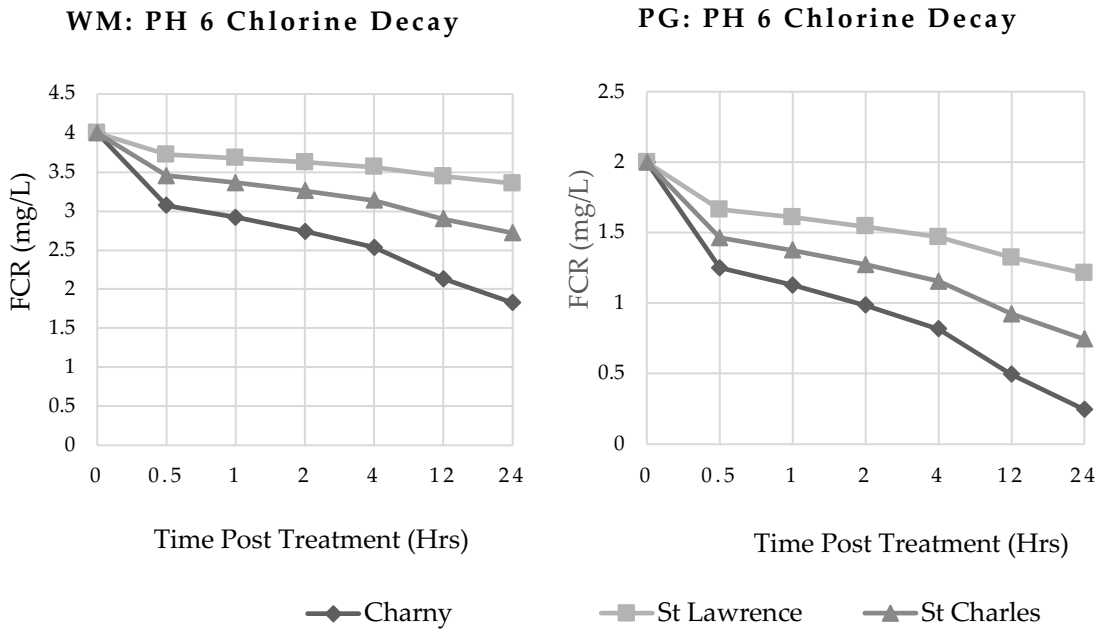

Figure 8 Chlorine decay for all test waters for time post treatment (0-24hrs)

pH was shown to influence the rate of FCR decay across both products, as the higher pH values generated an increased deviation across the three test waters (Figure 9). Adjusting the pH inputs of this model revealed that WM experienced a greater drop of FCR with an average variation of FCR at 30minutes of 0.43 ± 0.11 mg/L in comparison to PG which experienced a similar variation but slightly lower 0.40 ± 0.10 mg/L when changing from pH 6 to 7.

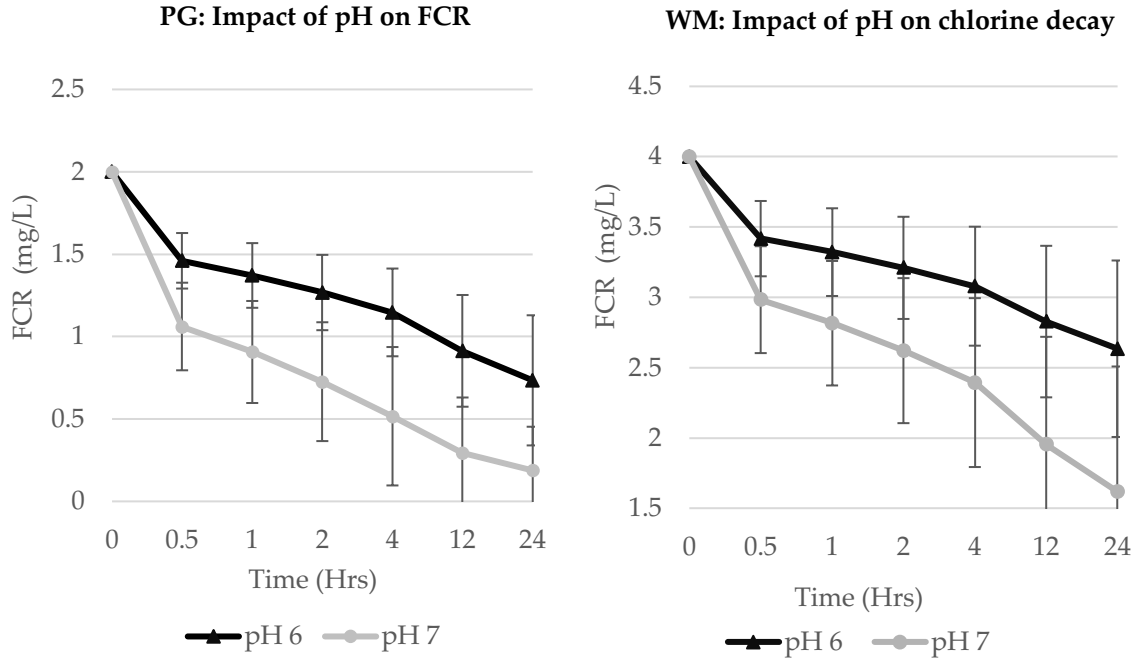

Figure 9 Average influence of pH on resulting FCRs of the three test waters. The vertical error bars denote the standard deviation between the three test water results.

Isolating the coagulation abilities of the products for pH 6, PG demonstrated a greater % DOC removal, likely caused by a higher dose of coagulant (WM 5.85 x 10^{-4} moles aluminum, vs. PG 6.29 x 10^{-4} moles iron). PG achieved a percent DOC removal of 69% ± 0.5% in comparison to WM that achieved 66% ± 1.0%. However, when testing a 100mg/L dose in the model for both coagulant types (WM 5.85 x 10^{-4} moles aluminum sulphate, vs. PG 5.00 x 10^{-4} moles ferric sulphate) the aluminum sulphate based product (WM) achieved only a slightly higher removal of 66% ± 1.0% in comparison to 65% ± 0.5% the model generated for the iron-based product (PG).

3.4.5 Analysis of Products in relation to the PODR

The coagulation dose corresponding to the PODR (slope below 0.03) was calculated for each of the given test waters at pH 6. Resulting values ranged from a dose of 40-80mg/L of ferric sulphate for PG and 20-40mg/L of aluminum sulphate for WM (Figure 10).

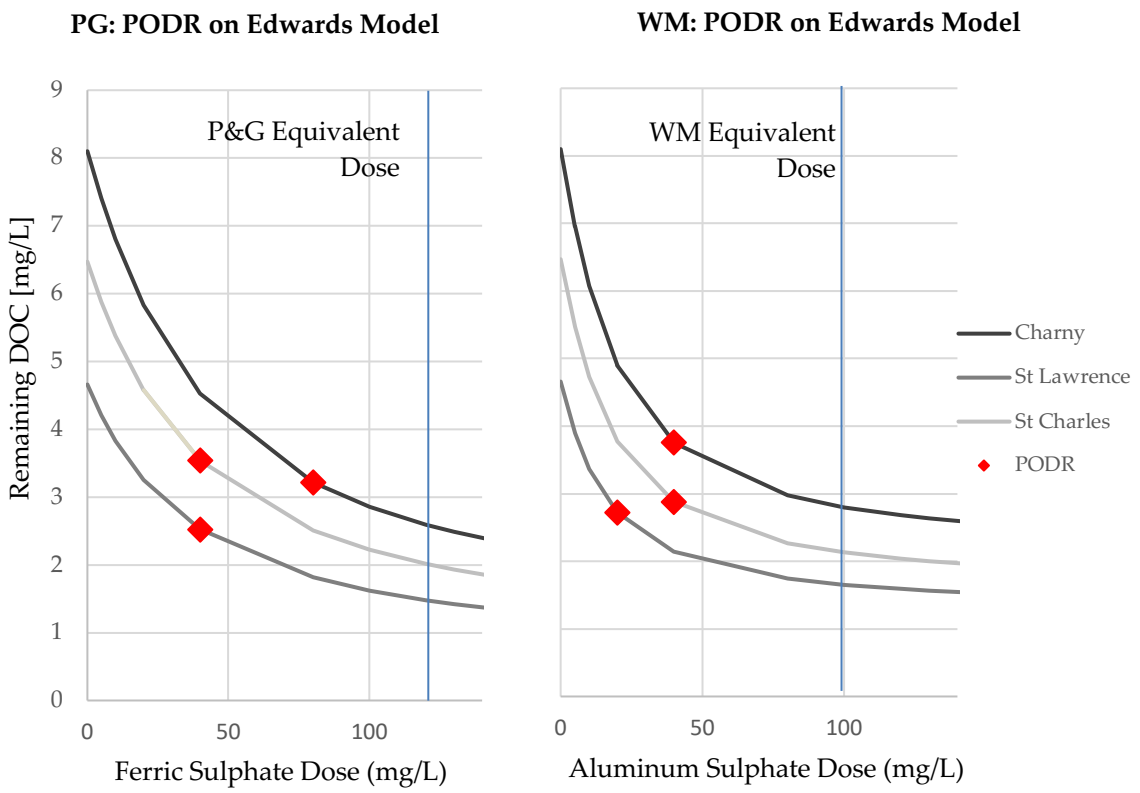

Figure 10 Graphical representation of the PODR (red points) denote where the slope of the remaining DOC slope drops below 0.03 for each product and water combination at pH 6.

The model illustrated that in all test waters, CDPs coagulant doses surpassed the PODR for the given test waters. On average, for pH 6, the estimated doses of the products were an average of 72 mg/L and 67 mg/L greater than the PODR for PG and WM respectively. These products coagulant doses were also graphically compared against other test waters as completed in the original USEPA guidelines [57]. Results showed similar patterns as those exhibited in this study, with the equivalent doses surpassing the PODR.

In conjunction with the PODR, the results of this modelling exercise were also compared against a relationship determined from the Beauchamp et al. paper [58], which found that for the wide range of waters tested, an aluminum sulphate/UV254 stoichiometric dose ratio of 180 ± 25 mg cm/L represented a point of diminishing return (i.e. it maximizes DBP precursor removal). This relationship was investigated for the use of aluminum sulphate and therefore was only compared against the WM product. Results indicated that the equivalent aluminum sulphate dose/original water UV254 ratios of the evaluated CDPs surpassed that of the UNRD given by the Beauchamp et al. paper (Figure 11).

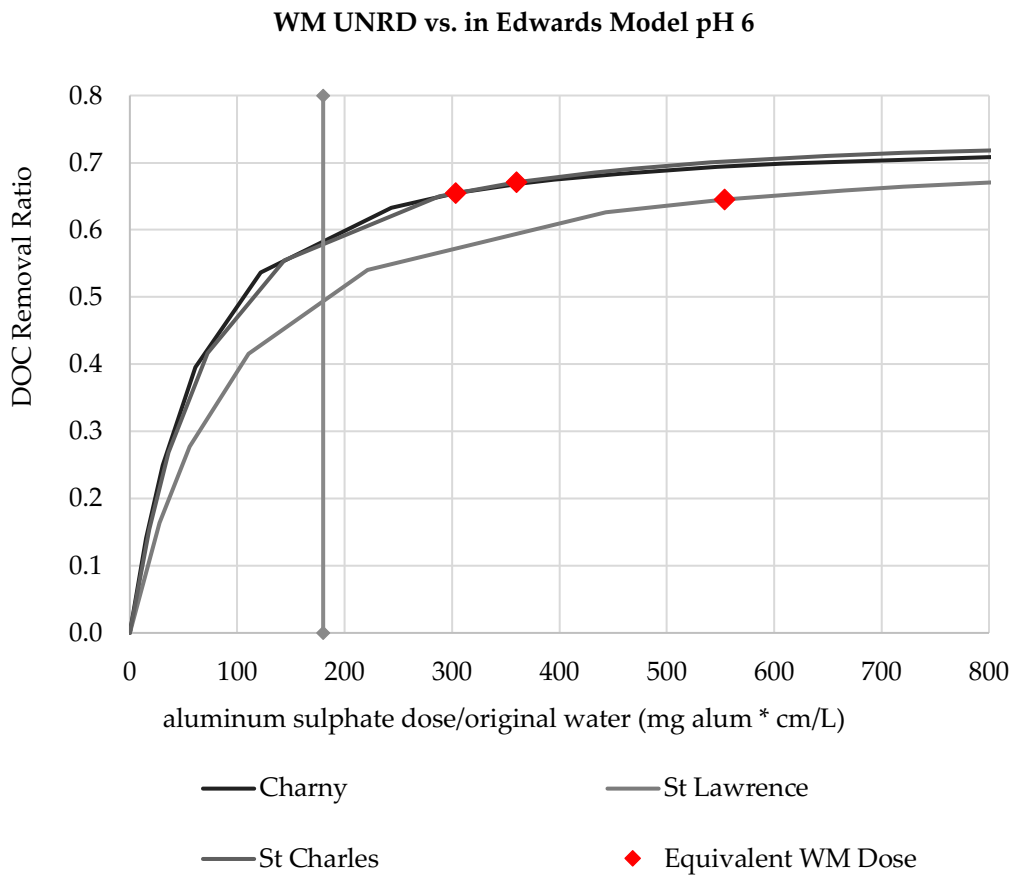

Figure 11 DOC removal plotted against aluminum sulphate dose/original water UV254for given source waters. The vertical line represents the UNRD determined by Beauchamp et al. of 180 ± 25 mg cm/L [58]

Results show that all of the product equivalent doses and aluminum sulphate dose/original water UV254 ratios of the CDPs surpass the value given by the Beauchamp et al. paper. On average, WM surpassed the UNRD by 406 ± 107 mg * cm/L.

3.4.6 Lab and Model Results Comparison

Running the Beauchamp et al. data [58] within the Edwards model provided visual display of the variances between the graphical results generated from laboratory and model data (Figure 12).

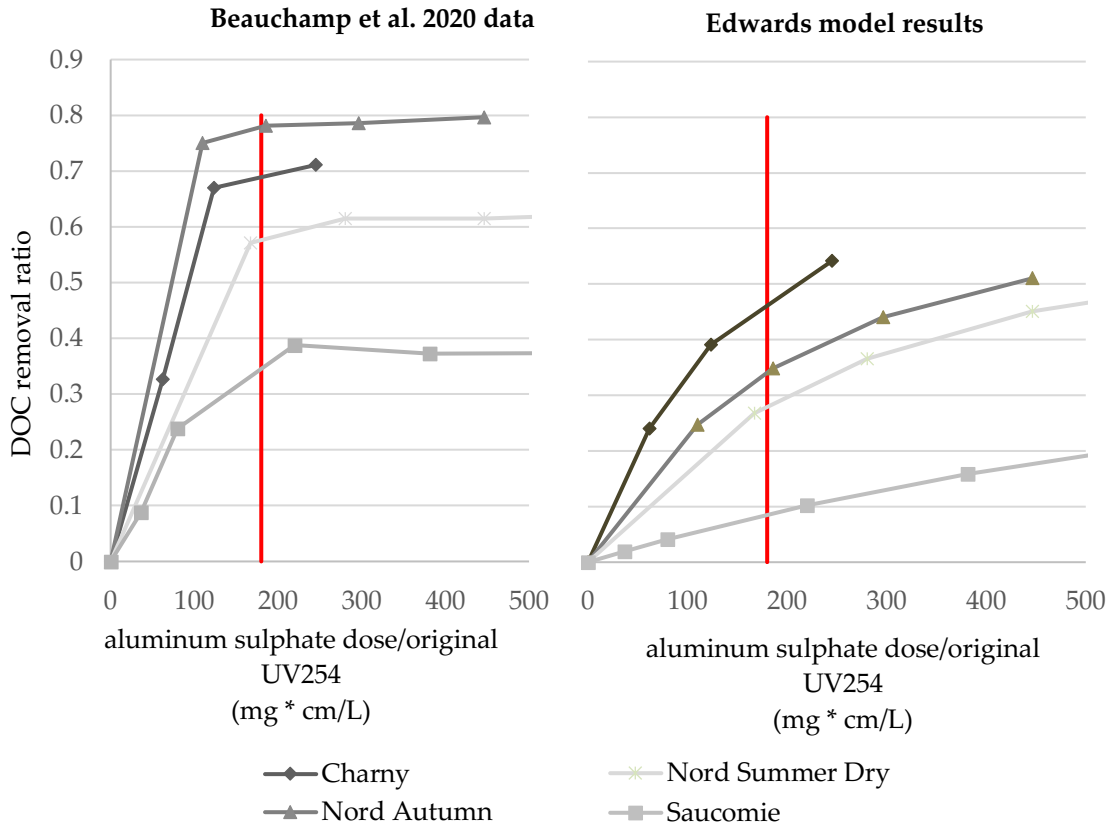

Figure 12 Lab data extracted from Beauchamp et al 2020 vs. Edwards model data

Numerically, results showed that for the given test waters, lab conditions exhibited a higher DOC removal ratio. At the set aluminum sulphate dose/original UV254 ratio across the two methods, the average increase in DOC removal ratio in the Beauchamp et al. lab data over the Edwards model ranged from 0.13 ± .10 for Charny (UV254 0.490 cm^{-1}), 0.32 ± 0.17 for Nord Autumn Raid (UV254 0.268 cm^{-1}), 0.17 ± 0.11 for Nord Summer Dry (UV 0.179 cm^{-1}) and 0.15 ± 0.09 for Sacacomie (UV0.040 cm^{-1}).

Graphically, it is shown that the laboratory results reached a point of stable equilibrium at a certain aluminum sulphate dose/original UV254 ratio. This asymptotic behavior at the maximum DOC removal ratio was at a significantly lower aluminum sulphate dose/original UV254 ratio than the model. Within the aluminum sulphate dose/original UV254 ratio range explored in the model, this behavior was not observed.

3.5 Discussion

The results above illustrate key findings regarding the comparative performance of two CDPs, similar to the laboratory work done in Chapter 2, but completed within the *CDP model*. Findings above also provided an appraisal of the functions, patterns and limitations of the model as a whole. First, the patterns exhibited by the *CDP model* were consistent with many relationships found in conventional water treatment practices. Specifically, the model reinforced the influence of low pH on coagulation ability [64], as test waters at pH 6 were shown to achieve a greater DOC removal than pH 7 in both CDPs. Given the linear association between DOC and 30-minute chlorine demand, greater pH directly produced a greater FCR. Lower pH is not only key in the ability to generate higher NOM removal, but also in the context of disinfectant strength, as chlorine is known to lose its disinfection effectiveness at

higher levels of pH, due to the dissociation of HOCl [52]. While the relationship between pH and coagulation is well-known, it highlights the importance of buffering capacity beyond conventional water treatment and within CDPs. Existing studies have shown the ability of CDPs to withstand changes in pH due to their buffering capacity [29] [54], and this is to be kept at the forefront when altering and optimizing their formulations.

Additionally, the *CDP model* contributed to the ongoing comparison between iron and aluminum sulphate based coagulants, and their ability to remove NOM. Other laboratory evaluations [65] have determined that iron coagulants such as ferric sulphate, are generally more effective at removing NOM, while conclusions of the Edwards paper find that results vary, depending on the test water [49]. The results from this study displayed a marginally higher removal through the use of aluminum sulphate. In some contexts, this can be contributed to the differing acidity of the coagulants, however given the pH was controlled in this study, this relationship is directly due to the coagulant specific input parameters, obtained within the Edwards model.

The sensitivity analysis within this study highlighted another common water treatment relationship regarding the influence of specific ultraviolet absorbance (SUVA), (UV254/DOC *100) on coagulation ability. The sensitivity analysis showed that with an increase in UV254, and no alteration in the DOC, there was an increase in FCR. This in turn supports the association that a higher SUVA makes the NOM in the water more amendable to coagulation, due to the lower fraction of non-absorbable DOC. Other studies have further analyzed these relationships to show the ability of SUVA to predict the reactivity of test water with coagulants and chlorine [66][67]. This further supports the use of SUVA to define appropriate treatment strategies for removing NOM from drinking water and lowering the corresponding DBPs.

Beyond confirming conventional water treatment relationships and patterns, the model provided a performance evaluation between the two CDPs. For both CDPs, modelling results exhibited an overestimation of the FCRs compared with existing studies [22], [54]. Individually, results found that WM achieved a greater FCR after treatment due to a higher initial chlorine dose, but PG achieved a greater DOC removal percentage based on a higher initial dose of coagulant. This evaluation highlighted the simplicity of the model, but also illuminated and potentially amplified the weight that initial chlorine dose had on the resulting FCR.

Focusing on coagulation evaluation, specific to the PODR and UNRD (for WM), the CDPs coagulation doses both surpassed guidelines outlined by enhanced coagulation principles. What the model is displaying, is that these products have surpassed the point of optimal return and reducing coagulation dose would have minimal influence on DOC removal ration, and therefore potential FCR outcomes. It is also important to acknowledge discrepancies between lab data [58] and Edwards data. Analysis determined significant differences between the data sets produced in the laboratory vs through the model. As Charny was the only water that did not exhibit a significant difference between the laboratory and model results and was also noted as the water with the highest SUVA, it is expected that the model produces a more accurate DOC removal prediction for waters with higher SUVA values.

In comparison to other studies, the results of the *CDP model* are shown to overestimate the FCR remaining in the test waters post-treatment. The *CDP model* outputs for WM at 0.5hr were 3.73 mg/L and 3.44 mg/L for pH 6 and pH 7 respectively. An existing study [22] evaluating WM in a low organic test waters (completed in the same St. Lawrence test water as listed in Table 11) detected a value of 2.16 mg/L at 0.5hr, at a starting pH of 7.5 (finishing pH of 6.5) in laboratory conditions. The 24hr residual was noted as 1.27 mg/L in the study, in comparison to the *CDP model* results of 3.36 and 2.68 mg/L for pH 6 and pH 7 respectively. Similarly, when evaluating the studies on PG [54], [8], [17], [28], [29], FCRs were shown to be lower than the 0.73 ± 0.39 mg/L exhibited by this modelling exercise.

3.6 Limitations

The *CDP model* presents several limitations. The *CDP model* does not consider all components in CDPs as it overlooks the interplay of clay, buffers, polymers and flocculant enhancers. Another limitation reflects that the model operates under the assumption that the coagulation and disinfection reactions occurring independently, while in reality, they occur in parallel, which may influence the amount of NOM available to react with chlorine during disinfection. Additionally, the chlorination component of the model is generated through laboratory trials of sodium hypochlorite [62], while the CDPs in the *CDP model* contain CH and NADCC as their disinfecting component. Studies have shown variance in these chlorination products regarding pH and disinfection strength[25], while little evidence has shown any variance in the resulting FCR [54]. However, accounting for the variance in chlorination products may be a positive adjustment to the model and motivate further research. The *CDP model* also disregards the interaction between coagulated/ non-coagulated NOM and the influence on chlorine demand. Existing studies have shown a higher degradation rate of chlorine in a coagulated solution over an aqueous solution[68]. This likely plays a role in the final FCRs produced post treatment.

This study provided efficacy testing of given CDPs to predict FCRs after treatment. While this level of evaluation is needed to ensure products are performing as desired, it is also important to acknowledge that in order for any POU intervention to be effective, it is required that technology is used consistently, correctly, and over long periods (i.e., high adherence). This is to be considered throughout the design and alteration phases of these products [45].

3.7 Recommendations

Results from the *CDP model* found that CDPs surpassed guidelines (PODR [57], and UNRD [58]) for enhanced coagulation. However, this computation modelling approach illustrated a variety of limitations, and is acknowledged as a starting point and motivation for further research in addition to laboratory validation. Additional work is recommended to disentangle complexities in coagulation and disinfection interactions, in addition to further understanding the kinetics of these two reactions in parallel. Further work may also include adding an estimate of resulting DBPs to the model to highlight secondary health concerns. Given the variance between the plateau shown in Beauchamp et al. lab observations and Edwards modelling results, trialling alternate calibrations of the Edwards model may also prove to be beneficial. This study has illustrated important findings in the understanding of the improvement of CDPs and recommends the careful consideration of buffering capacity and SUVA be considered for further improvements of CDP formulas.

4. Discussion

This thesis addressed the research objective of invoking conversation surrounding effective emergency response, specifically through developing solutions to provide clean drinking water in at-risk communities during complex humanitarian emergencies. The approach to achieving this research objective is expressed within this discussion as a three-step process inclusive of evaluation, improvement and the field application of CDPs. In Chapter 2, I addressed evaluation through a laboratory assessment of eight CDPs. Using these findings, I approached possible methods of CDP improvements through a computation model, as shown in Chapter 3. Finally, through part three of this discussion, I addressed the field application of these products to the larger scale elements of global health. The importance of each of these elements, and their interconnected capacity is highlighted in the discussion below.

4.1 Evaluation

The research encompassed in this thesis was built on the foundation of a thorough laboratory evaluation of CDPs, as literature surrounding CDPs was lacking an overarching, simplistic comparison of commercially available products. Chapter 2 reflected on the how these products perform in laboratory conditions. These results were able to generate a tool that illustrated how CDPs are predicted to meet different water treatment goals for varying test conditions.

Results within this evaluation found that no single product was able to achieve all household water treatment guidelines as outlined by WHO and SPHERE (≥4 bacterial LRs, <5NTU, FCR > 0.2 mg/L (SPHERE), and FCR > 0.5 mg/L (WHO)) for all test water conditions (accounting for varying pH and temperature). This association illustrated that some products performed to a higher compliance with certain guidelines over others. Specific to the microbiological performance of the products, all but one product achieved "highly protective" standards for microbiological LRs. Regarding turbidity, none of the products achieved <1NTU for any of the test water conditions while half of the products achieved <5NTU for at least one of their test waters. None of the products were able to achieve the minimum recommended FCRs of 0.5 mg/L after at least 30 min contact time for all test water conditions. The average FCR across all products was 0.15 ± 0.12 mg/L. While this may have been caused by the high organic demand of the test water, this evaluation is still of great importance when considering the challenging waters that may be treated in emergency contexts.

Alongside the specific results that this evaluation provided for each CDP independently, it also highlighted generic trends across the performance of CDPs. Results found that ferric sulphate-based products generated a greater turbidity removal and that there was minimal influence of disinfectant type (NADCC or CH) on resulting FCR. Cold temperatures were shown to influence LRs and turbidity for some of the products, while others exhibited resilience to changing conditions. As a generic trend, the study found that while products were able to achieve adequate log and turbidity removals, they were limited in their capacity to provide adequate FCRs, critical to emergency field applications.

While DBPs were not addressed in this study, the author acknowledges the importance of monitoring and understanding their relevance in CDPs. The evaluation also disregarded the overall efficacy of CDPs to remove viruses and protozoa beyond a simplified CT calculation. This research and evaluation would have benefited from further lab trials to address these factors. Overall, FCR levels, and compliance of the CDPs to both the WHO and SPHERE guidelines were low. Once these evaluations and overarching themes were determined, I progressed to the improvement phase of my research.

4.2 Improvements

Following the evaluation of the selected CDPs and after gathering an understanding of these products' performance, I was led to the secondary questions of my research. This question addressed; how can CDPs be improved, and what tools can we develop to improve them? As highlighted in Chapter 2, FCR performance was low across nearly all CDPs.

The computational model (the *CDP model*) was developed as a tool to be used to further evaluate and simultaneously advance the formulations of CDPs. The *CDP model* works by partnering the two underlying mechanisms in CDPs (coagulation and disinfection) to determine the resulting FCR performance. The model provided the ability to break down these mechanisms and investigate them independently while still accounting for the direct impact these mechanisms have on one another.

The results in this study exhibited that the patterns shown in the *CDP model* were consistent with many relationships found in conventional water treatment practices. Specifically, this model reinforced the positive influence low pH (pH 6 over pH 7) has on coagulation [4] and exhibited slightly stronger NOM removal by aluminum sulphate-based coagulants. Comparing the model results against existing studies [54], [18], [50] found the *CDP model* consistently overestimated the FCR.

Coagulation doses in the *CDP model* were compared to enhanced coagulation principles, UNRD (only for WM) and PODR. Through analysis, both WM and PG surpassed optimal coagulation doses set out by these principles for all test waters. These results could suggest that these products could be achieving the same NOM removal, with a lower coagulant dose. If these products were to utilize a reduced coagulation dose, this could potentially in turn reduce the cost of the products, making them more widely available.

The suggestions illustrated above are under the assumption that results produced by the model are an ideal representation of the products performance in laboratory conditions. However, it is also of high importance to acknowledge the limitation originated through the use of a simplistic model, leading to discrepancies between lab data [58] and model results. While the model allows for an understanding of the baseline functions, it does not consider all components in these products, as it overlooks the interplay of clay, buffers, polymers and flocculant enhancers. The CDP model also disregards the interaction between coagulated/non-coagulated NOM and the influence on chlorine demand [68]. Additionally, the *CDP model* operates under the assumption that the coagulation and disinfection reactions occur independently, while in reality, they occur in parallel. Despite the limitations of these studies, the *CDP model* produces a novel evaluation of these products and can generate discussion acting as a foundation to encourage further improvements.

4.3 Application

Chapters 2 and 3 of this thesis were primarily based on a laboratory-based approach and evaluation. While this type of evaluation is important, I was often pulled into the minutiae of laboratory work and became disconnected from the context of its application. However, throughout my program I was fortunate to be involved in many public health courses where I was exposed to the field of global health. The discussion below illustrates my projects relation to what I consider the "bigger picture" and the applications of the CDPs extensively evaluated in this thesis.

Global health is defined as "an area for study, research, and practice that places a priority on improving health and achieving health equity for all people worldwide" [69]. While the academic discipline of global health did not exist only a couple of decades ago in the capacity it does today, initiatives to promote global health research programs are growing quickly [70]. Furthermore, the global spending on health research in 2002 exceeded US$60 billion with less than 10% of those funds addressing the diseases and conditions that account for 90% of the global disease burden[71]. This statistic highlights inequities in the global flow of information and findings [69]. As the discipline grows and the world strives to move beyond a "charity model" of global health and its colonial roots [70], various initiatives are being taken to incorporate health equity in all elements of research. The *Canadian Coalition of Global Health Research (CCGHR)* aims to break underlying biases and inequalities of global health research as a "knowledge network for global health equity." I was privileged to work with this organization throughout the duration of my masters.

Through my involvement with CCGHR, I was exposed to the *Principles for Global Health Research* which encourage researchers to adopt more ethical and equitable analyses of global health. By being involved with this organization and completing public health courses, I was able to apply my research to the "bigger picture" through a global equity lens. Specifically, I was able to link my work to six principles: *Authentic Partnering, Inclusion, Shared Benefits, Commitment to the Future, Responsiveness to Causes of Inequities,* and *Humility* [72].

The principle of *humility* encourages researchers to ask, "*Who am I in this research context?"* which prompted me to think of the disconnect between myself and the local cultures where this technology is to be applied. As a researcher from the global north I have limited experience in field applications and acknowledge that my strengths are based in scientifically improving these products. That being said, I was extremely fortunate to be mentored by Mustafa Kamal of a Bangladesh non-for-profit JSKS (Jhanjira Samaj Kallyan Sangstha) alongside with Dr. Uddin at the Asian University of Women in Bangladesh, who have a deep understanding of the local application of these products. Understanding the context of application through field practitioners and local insight, allowed me to realistically centre myself and my strengths appropriately.

When we ask ourselves "How does this research contribute to a more equitable future?" we make an ethical *commitment to the future.* If CDPs are intended to be a sustainable water treatment solution, the research completed in the previous chapters of this thesis must be partnered with a commitment to equitable education interventions. Studies have shown there is a vast inequity in how these products are used, as barriers exist even for inexpensive water treatment technologies among the less educated [73]. For these products to be successful, they must be implemented with a strong educational plan and an eagerness of the selected communities to learn about the given technologies. To increase the potential for health gains from these products, programs will need to increase uptake of the product, particularly among the poorest households, and focus on strategies to ensure correct, consistent, and sustained use [6] [73]. There is a scarcity of research on behavior changes with respect to POU water treatment technologies, suggesting that this field is underdeveloped [74]. The efficacy of CDPs to treat water is only as good as its use; we must determine how to ensure water is treated effectively and acknowledge that more research is required in this field.

While the principle of *inclusion* within the *Principles for Global Health Research* specifically reflects an involvement of all populations, my research calls for an assessment of the inclusion of processes in regard to water quality. This must be prefaced with an understanding that within emergency water response, quantity can be of greater importance over quality [75] as transmission of water-related diseases in emergencies can be caused by the lack of sufficient quantities for hygiene [76]. However, when considering the laboratory efficacy of CDPs (and therefore focusing on water quality), one has to raise the question of why the modern goals of conventional water treatment practices are not present

in low resource contexts or humanitarian aid discussions. Specifically, as previously mentioned, enhanced coagulation refers to the process of increasing the NOM removal rate by increasing coagulant dose and optimizing pH in conventional water treatment [77]. The main goal of enhanced coagulation is reducing DBP pre-cursors as well as DBPs. While only a few studies have evaluated the DBPs produced by CDPs [20], I believe there is room for scientific literature to challenge these emergency response technologies in regard to conventional water treatment. Using conventional water treatment parameters as a metric in emergency response literature will facilitate discussions of inclusivity across multiple contexts.

My research also reflects on the principles of *shared benefits* and *authentic partnering*. As part of my master's degree, I had an opportunity to partake in the *University of North Carolina's* conference on Water and Health. In one of the first panel discussions of the conference, I became aware of the disconnect between the work completed in the field by practitioners and the research done by academics. In response, I was motivated by the idea that to make an impact, research must be made available and useful to the people it affects. By connecting with field practitioners (such as Oxfam and Doctors Without Borders) I engaged in intriguing dialogue focused on how the research I was doing could be an authentic partnering experience with those in the field. This led to the question "how can organizations and companies work effectively to provide products that are useful and applicable?" Feedback received reinforced a focus on the importance of communication, community participation, and continual feedback.

In closing, I address the principle of *responsiveness to the causes in equities* by asking, "what are the causes (and the roots of these causes) of inequities related to the research issue?" For emergency water treatments, I believe the root causes of these inequities come from the "charity model" of global health. This model holds that the organization, person, or funding structure has hierarchy over the region or community of implementation. I hope that through the preceding paragraphs I have been able to counter the antiquated charity model of global health with an appreciation of all there is to gain and learn from affected communities on any type of global health issue. The initial aim of this thesis was to evaluate and assess CDPs, but I believe this goes hand in hand with the consideration of equity in these products applications and all aspects of research if we strive for CDPs to have any impact at all.

4.4 In summary

This thesis addresses the lab-based assessment of a POU water treatment product while also linking results to the "bigger picture" of global health. My work focused on one of the many technologies that exists in the realm of emergency water treatment. While representing a relatively small share of all possible interventions, this work may aid further conversation, research and investigation into to any effective emergency response technology. I believe that this research can feed into the knowledge and understanding needed to make responsible, equitable, and effective decisions in humanitarian emergency response contexts.

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Appendix A Chapter 2 Raw Data (Turbidity, FCR, pH and Temp.)

	Test Water Condtions	Turbidty		FCR	pH		Temperature	
		Initial	After	After	Initial	Final	Initial	Final
AQS	"Reference"	96 ± 2.4	5.1 ± 0.65	0.08 ± 0.03	7.0 ± 0.1	6.2 ± 0.1	17.8 ± 1.4	19.2 ± 2.0
	"Acidic"	98 ± 7.2	6.4 ± 0.40	0.05 ± 0.01	5.0 ± 0.0	5.0 ± 0.1	16.9 ± 0.5	18.1 ± 0.6
	"Alkaline"	97 ± 1.8	7.9 ± 2.9	0.08 ± 0.02	9.0 ± 0.0	7.1 ± 0.2	17.7 ± 1.3	19.2 ± 1.7
	"Cold"	101 ± 5.2	6.8 ± 2.1	0.05 ± 0.01	7.0 ± 0.0	6.1 ± 0.1	5.6 ± 0.3	8.5 ± 0.8
AT	"Reference"	95 ± 2.1	2.0 ± 0.19	0.10 ± 0.01	7.4 ± 0.1	6.6 ± 0.0	18.8 ± 0.1	19.7 ± 0.1
	"Acidic"	97 ± 1.4	6.5 ± 0.95	0.09 ± 0.01	5.0 ± 0.0	5.8 ± 0.0	19.1 ± 0.1	20.1 ± 0.1
	"Alkaline"	99 ± 3.3	2.0 ± 0.19	0.10 ± 0.01	9.0 ± 0.0	7.0 ± 0.1	18.8 ± 0.1	19.4 ± 0.2
	"Cold"	96 ± 2.9	2.65 ± 0.79	0.07 ± 0.01	7.2 ± 0.0	6.6 ± 0.0	6.4 ± 0.1	6.2 ± 0.1
BG	"Reference"	105 ± 0.9	30 ± 20.8	0.11 ± 0.03	7.3 ± 0.0	5.6 ± 0.4	21.9 ± 0.3	22.6 ± 0.2
	"Acidic"	98 ± 4.3	74 ± 2.6	0.07 ± 0.01	5.0 ± 0.0	4.4 ± 0.0	22.1 ± 0.5	22.6 ± 0.5
	"Alkaline"	103 ± 2.2	10 ± 0.3	0.10 ± 0.02	9.0 ± 0.0	6.4 ± 0.1	22.6 ± 0.6	23.2 ± 0.5
	"Cold"	98 ± 2.1	47 ± 3.0	0.07 ± 0.01	7.2 ± 0.0	6.0 ± 0.0	6.1 ± 0.3	6.1 ± 0.2
CF	"Reference"	112 ± 2.4	7.8 ± 0.5	0.20 ± 0.00	7.1 ± 0.1	5.3 ± 0.3	20.9 ± 0.7	21.6 ± 0.7
	"Acidic"	96 ± 1.6	33 ± 9.0	0.33 ± 0.09	5.0 ± 0.1	4.4 ± 0.1	21.0 ± 1.3	21.4 ± 1.1
	"Alkaline"	108 ± 9.5	6.3 ± 0.8	0.53 ± 0.00	9.0 ± 0.0	5.7± 0.2	20.2 ± 0.8	20.8 ± 0.7
	"Cold"	105 ± 2.8	108 ± 14	0.50 ± 0.10	7.5 ± 0.1	4.8 ± 0.1	5.6 ± 0.1	6.8 ± 1.0
JN	"Reference"	101 ± 5.2	13 ± 1.6	0.08 ± 0.01	7.4 ± 0.1	6.9 ± 0.0	20.3 ± 0.1	21.2 ± 0.1
	"Acidic"	98 ± 1.7	41 ± 2.5	0.07 ± 0.01	5.0 ± 0.1	4.9 ± 0.2	20.8 ± 0.2	21.5 ± 0.2
	"Alkaline"	95 ± 2.0	11 ± 0.9	0.05 ± 0.00	9.0 ± 0.0	8.1 ± 0.1	21.1 ± 0.5	21.9 ± 0.5
	"Cold"	105 ± 4.1	49 ± 4.7	0.10 ± 0.01	7.1 ± 0.3	6.5 ± 0.0	5.7 ± 0.1	6.0 ± 0.1
PIT	"Reference"	96 ± 2.1	4.6 ± 0.7	0.20 ± 0.01	7.4 ± 0.1	7.3 ± 0.1	21.9 ± 0.5	22.5 ± 0.2
	"Acidic"	94 ± 2.2	6.6 ± 0.6	0.12 ± 0.02	5.0 ± 0.0	5.7 ± 0.3	21.8 ± 0.5	22.6 ± 0.2
	"Alkaline"	101 ± 7.9	6.8 ± 0.2	0.22 ± 0.03	9.0 ± 0.0	8.6 ± 0.2	21.9 ± 0.7	22.5 ± 0.4
	"Cold"	106 ± 4.3	6.8 ± 0.2	0.10 ± 0.03	7.2 ± 0.1	6.7 ± 0.1	5.6 ± 0.1	5.5 ± 0.3
PUR	"Reference"	102 ± 9.2	1.7 ± 0.2	0.11 ± 0.01	7.2 ± 0.0	6.4 ± 0.1	21.0 ± 0.3	21.4 ± 0.3
	"Acidic"	104 ± 1.3	2.4 ± 0.4	0.09 ± 0.01	5.0 ± 0.0	5.9 ± 0.1	22.0 ± 0.1	22.8 ± 0.1
	"Alkaline"	101 ± 7.6	2.5 ± 0.9	0.44 ± 0.11	9.0 ± 0.1	6.8 ± 0.1	20.8 ± 0.1	21.2 ± 0.1
	"Cold"	97 ± 5.3	9.2 ± 3.1	0.32 ± 0.09	7.2 ± 0.0	6.4 ± 0.1	6.0 ± 0.5	6.6 ± 0.3
WM	"Reference"	102 ± 4.8	8.2 ± 0.8	0.11 ± 0.08	7.2 ± 0.1	5.8 ± 0.1	18.5 ± 1.1	19.5 ± 0.9
	"Acidic"	101 ± 3.4	13 ± 2.6	0.08 ± 0.02	5.1 ± 0.0	4.5 ± 0.1	18.8 ± 0.8	19.9 ± 0.5
	"Alkaline"	104 ± 8.8	7.2 ± 0.5	0.09 ± 0.04	9.0 ± 0.0	6.1 ± 0.1	19.5 ± 0.6	20.1 ± 0.4
	"Cold"	101 ± 1.8	17 ± 3.0	0.11 ± 0.04	7.3 ± 0.1	5.7 ± 0.0	5.6 ± 0.3	7.2 ± 0.9

Appendix B Chapter 2 Raw Log Reduction Data

		Before Treatment CFU/100mL	After Treatment MPN or CFU/100mL
AT	"Reference"	5.8E+05 ± 5.9E+04	< 1
	"Acidic"	5.4E+05 ± 4.5E+04	< 1
	"Alkaline"	5.3E+05 ± 8.8E+04	< 1
	"Cold"	5.9E+05 ± 4.2E+04	< 1
AQS	"Reference"	3.1E+05 ± 1.4E+05	6.6 ± 12.2
	"Acidic"	1.7E+05 ± 1.8E+05	< 1
	"Alkaline"	2.4E+05 ± 4.7E+04	2.7 ± 24.4
	"Cold"	1.1E+05 ± 5.8E+04	1.1 ± 2.0
BG	"Reference"	5.4E+05 ± 1.4E+05	< 1
	"Acidic"	1.7E+05 ± 4.0E+04	< 1
	"Alkaline"	2.6E+05 ± 6.3E+04	1.8 ± 1.4
	"Cold"	1.3E+05 ± 4.7E+05	< 1
CF	"Reference"	6.6E+05 ± 2.6E+05	< 1
	"Acidic"	6.9E+05 ± 3.4E+05	< 1
	"Alkaline"	7.5E+05 ± 4.3E+05	< 1
	"Cold"	8.0E+05 ± 3.7E+05	1.0 ± 0.2
JN	"Reference"	1.1E+05 ± 5.70E+04	762.4 ± 90.8
	"Acidic"	9.1E+04 ± 2.18E+04	116.7 ± 14.4
	"Alkaline"	2.1E+05 ± 2.26E+04	2619.7 ± 545.7
	"Cold"	1.4E+05 ± 4.91E+04	3494.8 ± 1950.8
PIT	"Reference"	1.3E+05 ± 5.05E+04	< 1
	"Acidic"	1.4E+05 ± 5.12E+04	< 1
	"Alkaline"	1.3E+05 ±4.59E+04	1.0 ± 0.2
	"Cold"	1.5E+05 ± 6.59E+04	1.9 ± 2.3
PUR	"Reference"	7.3E+05 ± 1.02E+05	1.0 ± 0.3
	"Acidic"	3.6E+05 ± 3.04E+04	< 1
	"Alkaline"	4.6E+05 ± 7.37E+04	1.2 ± 0.5
	"Cold"	7.3E+05 ± 1.08E+05	3.3 ± 2.9
WM	"Reference"	4.4E+05 ± 5.13E+04	< 1
	"Acidic"	3.5E+05 ± 4.03E+04	< 1
	"Alkaline"	8.2E+05 ± 1.05E+05	1.0 ± 0.2
	"Cold"	3.7E+05 ± 1.57E+05	< 1

** <1 MPN or CFU denote lower limit of detection