Improving the Understanding of Factors Influencing *Cryptosporidium* Removals Reported for Granular Media Filtration

by

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Author's Declaration

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

Cryptosporidium is an important waterborne protozoan pathogen which has been implicated in several large gastrointestinal disease outbreaks attributable to inadequate treatment of drinking water. Unfortunately, *Cryptosporidium* oocysts, the life cycle phase found in water, are highly resistant to conventional disinfectants such as chlorine and chloramines. As such, rapid granular filtration (preceded by adequate coagulation) serves as an important barrier against the passage of *Cryptosporidium* oocysts. However, a wide range of *Cryptosporidium* removals, from 1.4 log to 5.8 log, have been reported from various pilot- and full-scale filtration investigations (with or without removals by clarification), with the reasons behind the substantial variability not well understood. The disparity in published data leads to uncertainty in developing expectations for the removals that can be reasonably achieved by filtration processes. To further complicate the interpretation of these studies, there is still some uncertainty involved with accurate oocyst enumeration. The objective of this research is to investigate reasons behind the substantial variability in oocyst removals reported in the literature by attempting to link them to differences in raw water characteristics, coagulant conditions, filter design, filter operation, and analytical and experimental methods. This research included two components: (1) a thorough review of the literature, and (2) the development, distribution, and analysis of a questionnaire to access industry knowledge and insights that might not necessarily be reflected in the peer-reviewed literature.

An up-to-date review of published studies was conducted with the intent of identifying the potential effects of a variety of factors as they relate to the determination of *Cryptosporidium* oocyst removals by granular media filtration. However, the amount of detail contained in published studies is still somewhat limited and the current data pool is not sufficiently extensive to definitively identify reasons behind the substantial variability in removal data. As an outcome of the review, it was felt that views from drinking water professionals on the factors which may have an impact on reported *Cryptosporidium* removals by granular media filters would enhance research into this important topic. In developing the questionnaire,

thirty-three influencing factors were identified, and these fall into six groups. In total, 39 completed questionnaires were returned, representing a response rate of 35%. In addition, 260 open-ended comments were collected. Statistics from the background survey revealed that the majority of respondents could be considered to be sufficiently knowledgeable to be able to provide valuable input (with more than 70% of respondents having direct involvement in research on *Cryptosporidium* or/and surrogate removals through filtration).

From the questionnaire, consensus was reached that the most influential factors were optimized coagulant dose (95% of respondents rated it as having a strong influence) and filter effluent turbidity (81% rated it as having a strong influence), while the least influential were *Cryptosporidium* species and the use of chlorinated backwash water (0% rated them as being strongly influential). A weighting system was developed to evaluate the overall influence of an identified factor on *Cryptosporidium* removal through filtration and a sensitivity analysis was conducted to evaluate the robustness of the weighting system. The weighting system ranked the importance of optimized coagulant dose, filter effluent turbidity, *Cryptosporidium* oocyst detection limit, *Cryptosporidium* recovery adjustment, and *Cryptosporidium* spike concentration as the five most influential factors (in that order). For most findings, the questionnaire results demonstrated consistency with literature results.

This research narrowed down the factors contributing to uncertainty in developing expectations for *Cryptosporidium* removals in a given situation, by ranking the influence of each of a number of factors. It also identified some potentially important issues/factors whose effects have not yet been assessed, and provided useful information and some speculation which may not have been reflected in published studies. However, it may not be possible to single out any one factor which accounts for a substantial portion of the variability; in fact, the reported differences may not be attributable to any single factor, but rather a group of factors.

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List of Acronyms

CFE: combined filter effluent

CT: Product of C and T (C refers to the residual concentration in mg/L; T refers to the contact time of disinfectant with water in minutes)

DAF: dissolved air flotation

DAPI: 4’,6-diamidino-2-phenylindole

DALY: Disability-Adjusted Life Year

DBP: disinfection by-product

DLVO: Derjaguin-Landau-Verwey-Overbeek

DNA: deoxyribonucleic acid

FACS: fluorescently activated cell sorting

FI: Filter influent

ft: feet

GAC: granular activated carbon

US gpm: US gallons per minute

HLR: hydraulic loading rate

IFA: immunofluorescence assay

IMS: immunomagnetic separation

L/D: length (depth) of a granular media filter bed by the weighted effective diameter of the filter media

LT2ESWTR: Long Term 2 Enhanced Surface Water Treatment Rule

MAC: maximum acceptable concentration

MCLG: maximum contaminant level goal

MECs: microorganism elimination credits

MDL: method detection limit

MOECC: Ministry of the Environment and Climate Change

MWD: Metropolitan Water District

NOM: natural organic matter

NTU: Nephelometric Turbidity Unit

PACl: polyaluminum chloride

PCR: polymerase chain reaction

TOC: total organic carbon

USEPA: United States Environmental Protection Agency

UV: ultraviolet light

WHO: World Health Organization

Chapter 1
Introduction

1.1 Introduction

Cryptosporidium parvum, a single-celled protozoan parasite which is present in water in oocyst form with a diameter of 4-6 µm, is commonly found in Canadian surface water samples in the range of 1 to 100 oocysts/100 L (Health Canada, 2012a). In the 1990's, oocysts were occasionally found in treated drinking water with one study reporting that oocysts were found in 3.5% of treated water samples (Wallis *et al*., 1996). This parasite can cause gastrointestinal illness at very low concentrations and has been responsible for some large outbreaks attributable to public drinking water supplies such as those which occurred in North Battleford, Saskatchewan, and Milwaukee, Wisconsin (Health Canada, 2001; MacKenzie *et al*., 1994).

Adequate treatment of oocysts in drinking water facilities is essential to protect public health. Unfortunately, *Cryptosporidium* oocysts are highly resistant to conventional disinfectants such as chlorine and chloramines (Korich *et al*., 1990; Gyürék *et al*., 1997). Despite recent developments in membrane technologies and innovative disinfection methods (e.g. UV), which have demonstrated adequate removal/inactivation of oocysts, such processes are costly and require operators with advanced education and skills. As such, *Cryptosporidium* removal continues to rely on physicochemical removal processes (coagulation/flocculation/(clarification)/rapid granular filtration processes) as the major treatment barrier.

1.2 Problem Statement

Substantial variability in oocyst removals from 1.4 to 5.8 log have been reported from various pilot- and full-scale experiments (with or without removals by clarification) during stable filtration operation and normal coagulation. These experiments tested different water sources and had various filter design and operational configurations (e.g. filter media type, coagulant type, filtration rate), with variations in analytical methods and experimental

configurations (i.e., detection limit, type of oocyst inactivation, seeding protocol). To further complicate the interpretation of these studies, there is no single reliable parameter that universally correlates well with oocyst log removal, and despite advances in current analytical methodologies, there is still some uncertainty in accurate oocyst enumeration. The wide range in reported removal results pose uncertainties in developing expectations for the removal capability that can reasonably be achieved by filtration in a given location. Few literature studies have attempted to explain the substantial variability in reported log removals in past studies and a valid conclusion upon which a variable can most significantly influence oocyst removals reported from various filtration studies has not been drawn. Being able to improve the understanding of expected removals would assist greatly in developing treatment strategies and guiding potential studies to quantify removals in a specific plant.

1.3 Objective

The objective of this research is to investigate reasons behind the substantial variability in oocyst removals reported in the literature by attempting to link them to differences in six groups of factors including aspects of raw water quality, coagulation conditions, filter design, filter operation, experimental differences, and analytical differences. The specific objectives of this research were to:

- Prepare a comprehensive up-to-date review of *Cryptosporidium* removal by filtration.
- Evaluate the effect of influencing factors through review of published studies and comparison of available data.
- Prepare a structured list of potentially influencing factors.
- Develop and distribute a questionnaire to document industry knowledge from professionals with involvement in *Cryptosporidium* research and/or real world applications.
- Code the data from questionnaire responses to identify the most and least influential factors for *Cryptosporidium* removal by filtration.

- Compare published findings to those acquired through the questionnaire to ascertain if there are differences.

1.4 Approach

This research project involved two components: (1) a thorough review of the literature and (2) the development and distribution of a questionnaire to access industry knowledge and insights that might not necessarily be reflected in the peer-reviewed literature. The review focused on the role of granular media filtration in removing *Cryptosporidium* oocysts and the assessment of some process and experimental factors affecting the oocyst removal results reported. A questionnaire on the assessment of the list of identified factors was established and distributed to document industry knowledge on the relevance of the factors identified from the up-to-date literature review. Drinking water professionals with involvement in *Cryptosporidium* research and real world applications were identified and contacted. The responses from the questionnaire were analyzed to again identify and compare the most and least influential factors on *Cryptosporidium* removals by filtration processes. The differences are identified and discussed, as are the comments provided by questionnaire participants.

1.5 Thesis Structure

Chapter 2 includes a literature review of *Cryptosporidium* oocyst removal by granular filtration, followed by identification and assessment of factors potentially influencing oocyst removals. Chapter 3 describes the development of the questionnaire, identification of appropriate water professionals to contact, limited pre-questionnaire release testing, and revisions to the questionnaire in response to test participant comments. Chapter 4 presents an overview of responses from the surveyed professionals and analyzes their responses by coding the data according to different response choices and bases for these choices. Chapters 5 and 6 summarize the research findings and present recommendations for treatment systems and future research. Published *Cryptosporidium* removal data are summarized in Appendix A.

The cover letter, original questionnaire for pilot testing, and the final version of the questionnaire as circulated are provided in Appendix B.

Chapter 2

Cryptosporidium Oocyst Removal by Granular Media Filtration and Potential Influencing Factors: A Review

2.1 Summary

Rapid granular filtration processes (preceded by adequate coagulation) serve as an important barrier against the passage of *Cryptosporidium* oocysts. However, a wide range of *Cryptosporidium* removals, from 1.5 log to 5.5 log (Hijnen and Medema, 2010), has been reported from various pilot- and full-scale filtration investigations (with or without removals by clarification) during stable filtration operation and normal coagulation. These studies were conducted using different water sources and various filter design and operational configurations (e.g. filter media type, coagulant type, hydraulic loading rate), with variations in analytical methods and experimental configurations (i.e. detection limit, type of oocyst inactivation, seeding protocol). The reasons behind the substantial variability in reported log removals are still not fully understood despite the passage of time since initial awareness of this problem.

This chapter includes a review of *Cryptosporidium* oocysts removal within water treatment plants and illustrates how chemically assisted granular filtration processes serve as an efficient barrier. It is followed by the identification of potential factors influencing *Cryptosporidium* removals by granular media filtration and further discussion examined by reviewing published filtration studies.

2.2 *Cryptosporidium* Removal in Water Treatment Plants

2.2.1 *Cryptosporidium*—An Important Waterborne Pathogen

Cryptosporidium is an intracellular gastrointestinal protozoan parasite (Health Canada, 2012a). It is found in water following direct or indirect contamination with human or animal

feces. For several decades, *Cryptosporidium* was considered to be an animal disease (Tyzzer, 1907), until 1976 when the first human case was reported in a three-year-old child who developed acute enterocolitis, which is an inflammation of the digestive tract (Nime *et al*., 1976). At present, twenty *Cryptosporidium* species have been recognized and more than forty genotypes have been proposed, with *Cryptosporidium hominis* (*C. hominis*) and *Cryptosporidium parvum* (*C. parvum*) being the two major species responsible for human cryptosporidiosis (Health Canada, 2012a). The dormant form of *Cryptosporidium* in its life cycle is known as an oocyst, and is round with a diameter of 4-6 µm, protected by a thick wall resistant to various environmental stresses. Contact with livestock or contaminated water are common transmission routes for this disease. Theoretically, a single oocyst can potentially lead to infection although the infective dosage is generally reported to be in the 10 to 100 oocysts range (Meinhardt *et al*., 1996; Health Canada, 2012a). Infection with *Cryptosporidium* can exert acute or chronic health effects, with common symptoms including vomiting, nausea, dehydration, and diarrhea (Pitlik, 1983). The severity of infection depends on the host's immune system, the infectivity of oocysts, and the exposure duration. The immunocompromised are particularly prone and their symptoms can be prolonged and life threatening. Cases of human infections have been reported in many countries including Canada, with many cases related to public drinking water; major outbreaks include the North Battleford outbreak in Canada and the Milwaukee outbreak in US (MacKenzie *et al*., 1994; Health Canada, 2001). Investigations revealed that high oocyst concentrations in source water and inadequate removal by drinking water treatment processes were potential causes (Schuster *et al*., 2005).

2.2.2 Occurrence of *Cryptosporidium* Oocysts in Surface Water

Cryptosporidium is excreted in animal feces and is typically found as a contaminant in surface waters but outbreaks have also been associated with groundwater under the influence of surface water. As oocysts are highly resistant to a variety of physicochemical stresses commonly encountered in water and sediments, they can survive for extended periods of time

(Health Canada, 2012a). Extensive surveys have been conducted to investigate the occurrence of *Cryptosporidium* oocysts in surface water sources as well as treated water. Oocysts are frequently detected in Canadian surface waters with typical concentrations ranging from 1-100 oocysts/100L (Health Canada, 2012a). In the western US, 77% of surface waters sampled contained oocysts with a geometric mean of 94 oocysts/100L (Ross, 1988). In another study across Canada and US, 60.2% of surface water samples tested oocyst-positive with a mean concentration of 240 oocysts/100L (LeChevallier and Norton, 1995). Oocyst concentrations in Ontario water have also been reported. Average concentrations in the Ottawa River have been reported to be 6.2 oocysts/100L while in the Grand River a median concentration of 15 oocysts/100L have been reported (Van Dyke *et al*., 2006; Douglas, 2009). High concentrations of oocysts are somewhat infrequent and are often associated with severe runoff. In 1997, during heavy spring runoff, oocyst concentrations in the raw water of Edmonton drinking water treatment plants were reported to be as high as 10,300 oocysts/100L. Although multi-stage physico-chemical treatment processes efficiently eliminate oocysts, they are still occasionally detectable at low levels in filtered or treated water samples, with their viability and infectivity unknown (USEPA, 2009a). In a survey of 66 surface water plants across the US and Canada, *Cryptosporidium* oocysts were detected in 26.8% of filtered water samples with a geometric mean of 1.52 oocysts/100L (LeChevallier *et al*., 1991). An early Canadian survey found that 3.5% of treated water samples were oocyst-positive in 72 municipalities (Wallis et al., 1996). Even being in strict compliance with current regulations, the absence of oocysts in treated water of conventional water plants cannot be guaranteed.

2.2.3 Physical-chemical Properties

Cryptosporidium oocysts are spherical to oval in shape. Depending on the species type, the dimensions of oocysts fall in the range of 3.8-6.3 µm by 4.6-8.4 µm (Dumètre *et al*., 2012). *Cryptosporidium* oocysts are larger than viruses and bacteria, but smaller than *Giardia* cysts (another waterborne protozoan parasite). The oocysts are negatively charged in most natural

environments and respond to chemical coagulants in a similar manner as other particles which are typically present in water (Ongerth and Pecoraro, 1996). The zeta potential of oocysts, measured as electrophoretic mobility, was reported to be -25 mV in distilled water at neutral pH and is subject to changes in pH, natural organic matter concentration/composition, and ionic strength of the surrounding water (Engeset and Dewalle, 1979, Ongerth and Pecoraro, 1996., Tufenkji *et al*., 2006). The surface structure of oocysts has received attention from researchers as it plays an important role in parasite-particle interactions and thus potentially impacts its physico-chemical removal. Oocyst surface roughness and macromolecule coverage affects adhesion by creating potential repulsive and attractive forces in parasite-particle interactions (Dumètre *et al*., 2012). The oocyst wall consists of three layers: an inner layer of glycoproteins, a central layer of lipid protein, and an outer layer of glucose-rich glycocalyx (Dumètre *et al*., 2012). The glycocalyx in the outer layer is exposed to the surrounding environment, providing immunogenicity and attachment potential (Jenkins *et al*., 2010). It is delicate and highly prone to chemicals such as disinfectants and preservation agents (Gao and Chorover, 2009; Harris and Petry, 1999). Inactivating oocysts by formalin or heat, as is normally done, potentially affects the oocyst-sand interaction performance compared to that of naturally present oocysts.

2.2.4 Detection Methods

U.S. Environmental Protection Agency (EPA) Method 1623 (USEPA, 2005) is the most widely used method to evaluate the occurrence of both *Cryptosporidium* and *Giardia* in water (Health Canada, 2012a). Compared with other detection methods, this method has higher recoveries and less variance (Quintero-Betancourt *et al*., 2002). The method can be summarized as follows: 1) sample collection, 2) sample filtration and elution, 3) sample concentration and separation, and 4) oocyst detection. The details are described below. Despite advances in current analytical methodologies, there is still uncertainty in accurately enumerating oocysts, and recovery efficiency varies from sample to sample, subject to

various substances present. This poses difficulties in accurately measuring oocyst removals through a process and comparing oocyst removal results from different studies.

Water samples are collected either as bulk samples or filtered on site and then shipped for laboratory processing. The water sample volume depends on the expected oocyst concentration and typically ranges between 10 to 1,000 L.

As the oocyst concentration is very low in most waters, samples need to be filtered to concentrate oocysts to detectable levels. A variety of filter types can be utilized, including membrane filters, wound filters, and hollow fiber filters. The differences among various types of filters contribute to the wide range of recovery efficiencies reported in literature (Ferguson *et al*., 2004). When filtration is complete, eluting solution is added, and the oocysts retained on filters are released in filter eluate.

The filtered water samples are then centrifuged to produce a pellet (re-suspended in buffer solutions). To minimize the effect of other particulates on oocyst detection, oocysts are separated through immunomagnetic separation (IMS)/immunocapture. The pellet is mixed with oocyst-specific monoclonal antibodies attached to immunomagnetic beads and a magnetic field is applied. As the beads attach to oocysts selectively, oocyst-bead mixtures are separated from other particulates that may interfere with oocyst detection.

Once oocysts are concentrated and extraneous particulates are removed, oocyst detection can be achieved by commonly applied techniques, including three primary techniques: immunofluorescence assay (IFA), flow cytometry, and molecular methods. IFA is the most commonly applied approach where the oocysts are stained on well slides with fluorescently labeled monoclonal antibodies and specific antigens. Potential oocysts can then be located as fluorescing bodies by direct immunofluorescence microscopy. Additional staining and microscopy are required in the final oocyst identification because some autofluorescent algae

are very similar to oocysts and may be misidentified as potential oocysts. Given that 4',6-diamidino-2-phenylindole (DAPI) can bind to deoxyribonucleic acid (DNA) and highlight oocyst nuclei, DAPI stains are applied to discern from oocyst from other autofluorescent algae. Flow cytometry is based on light scattering to enumerate microscopic *Cryptosporidium*. The flow cytometry technique for examining *Cryptosporidium* is fluorescently activated cell sorting (FACS) where immunofluorescent antibodies are first added into oocyst suspension. The suspension then passes through a beam of light so that oocyst fluorescence can be measured and counted. However, as the accuracy of this procedure can also be impacted by the autofluorescent algae and antibody cross-reactivity with other organisms; confirmation of oocysts by microscopy is required. FACS is still in the development phase and is not routinely applied. At present, no molecular methods are validated for detecting oocysts in water samples. Polymerase Chain Reaction (PCR) is the most widely used molecular method. This technique releases DNA from the oocyst by lysing *Cryptosporidium* cells and then primers are introduced which target specific *Cryptosporidium* coding regions. PCR has advantages such as being specific and sensitive, however, PCR can be problematic, in that this technique may be inhibited by some divalent cations, and humic and fulvic acids (Sluter *et al*., 1997). Samples should be purified to remove the inhibitors. In addition, inefficient oocyst lysis may not release all DNA from oocyst cells, leading to fewer detected oocysts than are actually present.

The existing analytical methods provide limited information on the viability and infectivity of oocysts, which is important for assessing their health impact. Although oocyst viability can be analyzed easily and rapidly, the analysis of infectivity is much more complicated. Due to the required availability of qualified personnel and costly procedures, viability and infectivity are not typically applied in oocyst assessment.

An important component in *Cryptosporidium* detection is to determine recovery efficiencies. As mentioned previously, concentration and separation during oocyst detection processes can

lead to significant losses of oocysts. As well, the presence of suspended solids or algae can also interfere with the oocyst detection. As a result, only a proportion of oocysts can be detected (Health Canada, 2012a). The recovery efficiency is the ratio of the measured number of oocysts to the known oocyst number, usually measured by spiking a known number of oocysts into water samples before the analysis. The actual oocyst concentration can then be calculated by dividing the measured concentration by the recovery efficiency (Ongerth, 2013). Recovery efficiencies vary substantially and are influenced by variations in raw water quality, and internal control of recoveries for each water sample is important to assure accuracy (Health Canada, 2012a). As recovery efficiency is affected by background water characteristics, it varies from study to study, and also changes within one study throughout different treatment stages (i.e. raw water, settled water, filtered water).

2.2.5 Regulations and Guidelines

Based on research verified oocyst removals, a *Cryptosporidium* removal credit of 2 to 3 log has been assigned to conventional and direct filtration processes which are in compliance with regulated filter effluent turbidity values (USEPA, 2006; Ministry of the Environment and Climate Change, 2006; Health Canada, 2012b). The removal credits assigned in the United States and Canada are summarized in Table 2.1. Detailed information associated with each regulation/guideline is described below.

Table 2.1 *Cryptosporidium* removal credits in United States and Canada

Country	Documents	Conventional Filtration	Direct Filtration
United States	LT2ESWTR	3 log	2.5 log
Canada	Guidelines for Canadian Drinking Water Quality	3 log	2.5 log
	Procedure for Disinfection of Drinking Water in Ontario	2 log	2 log

United States Environmental Protection Agency

The USEPA has set a maximum contaminant level goal (MCLG) for *Cryptosporidium* in drinking water to be zero (USEPA, 2009b). The Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) promulgated in 2006 is designed for public health protection by lowering infectious *Cryptosporidium* to a level of less than 1 oocyst/10,000 L in drinking water (USEPA, 2006). Two years of source water *Cryptosporidium* monitoring for all filtered and unfiltered systems has been conducted using USEPA 1622/1623. Depending on the average *Cryptosporidium* concentration measured (<0.075 oocysts/L; 0.075-1 oocysts/L; 1-3 oocysts/L; ≥3 oocyst/L), filtered water treatment systems were slotted into four treatment bins requiring 3, 4, 5, and 5.5 log removals to be in compliance. Thus plants with higher source water oocyst concentrations required additional treatment technologies.

The USEPA defines conventional filtration as a combination of coagulation, flocculation, clarification, and granular media filtration. Because plants employing alternative clarification methods (e.g., dissolved air flotation) have demonstrated equivalent oocyst removal capability compared to those using sedimentation (Gregory and Zabel 1990, Plummer *et al*. 1995, Edzwald and Kelley, 1998), the USEPA does not differentiate between the alternative clarification methods. Based on a review of key published studies, conventional treatment has been assigned a 3 log oocyst removal credit (McTigue *et al*., 1998; Patania *et al*., 1999; Dugan *et al*., 2001; Emelko *et al*., 2000; Huck *et al*., 2000; Nieminski and Bellamy, 2000; Harrington *et al*., 2001). Direct filtration, which omits a sedimentation basin or other alternative clarification methods, are assigned an oocyst removal credit of 2.5 log, which is 0.5 log less than the removal credit given to conventional treatment. The rationale for this was based on studies revealing that sedimentation processes typically achieve 0.5 log or greater oocyst removals (Payment and Franco, 1993; Kelly *et al*., 1995; Patania *et al*., 1995; States *et al*., 1997; Edzwald and Kelly, 1998; Dugan *et al*., 2001). In order to receive the

removal credit, filtration systems must be in compliance with specified filter effluent turbidity and is worded as follows: “the combined filter effluent (CFE) at least every four hours using approved methods, although States may reduce this frequency to once per day for public water systems (PWSs) serving 500 people or fewer (40 CFR 141.74(a) and (c)). For PWSs using conventional or direct filtration, at least 95 percent of the CFE turbidity measurements must be less than or equal to 0.3 NTU, and the turbidity must never exceed 1 NTU” (USEPA, 2006).

Health Canada

Unlike the USEPA, Health Canada (2014) does not set a maximum acceptable concentration (MAC) for *Cryptosporidium* due to the limitations in current detection methods in reliably detecting oocysts. Health Canada sets a health-based treatment goal of 3 log oocyst removal based on the following procedure (Health Canada, 2012a). The risk level can be measured by DALYs as the unit, which incorporates the probability of illness and injury as well as the extent of health effects (Murray and Lopez, 1996; Havelaar and Melse, 2003). The World Health Organization (WHO) (2011) has proposed an acceptable level of risk for oocyst of 10^{-6} DALY/person per year. A 3 log oocyst reduction is required to achieve the reference level of 10^{-6} DALY/person per year assuming 1 L water/day is consumed and 13 oocysts/100L are present in source water (Health Canada, 2012a). For source water with higher oocyst concentration (more than 13 oocysts/100L), additional log reduction is needed to meet the reference risk level. The 3-log oocyst removal/inactivation through drinking water plants is thus adopted as the minimum treatment requirement; the guideline also indicates that higher oocyst reductions may be required depending on source water quality (Health Canada, 2014)

In 2012, Health Canada (2012b) conducted its own review, and agreed with and subsequently adopted the assumptions for *Cryptosporidium* log removal credits of 3 log and 2.5 log, respectively, to conventional and direct filtration processes in compliance with specified turbidity requirement, similar to those of USEPA. The guideline states that: “For

conventional and direct filtration, less than or equal to 0.3 NTU in at least 95% of measurements either per filter cycle or per month and never exceed 1.0 NTU". It also states that where possible, the design and operation of filtration systems should be optimized to reduce turbidity and strive to achieve a treated water target of less than 0.1 NTU from individual filters" (Health Canada, 2014). Health Canada (2012b) did not assign additional *Cryptosporidium* credit for systems achieving turbidity of less than 0.1 NTU due to uncertainty in the literature with regard to the magnitude of additional removal credit.

Ontario Ministry of the Environment and Climate Change (MOECC)

The Ministry of the Environment and Climate Change (2006) assigned 2 log oocyst removal credits for both conventional and direct filtration processes in compliance with a filter effluent turbidity requirement, which states that filtered water turbidity should be less than or equal to 0.3 NTU in 95% of the measurements each month. The standard also states that the design and operation of filtration systems should be optimized to reduce turbidity to as low as possible, with a goal of less than 0.1 NTU in treated water at all times. The document also emphasizes the maintenance of continuous coagulant application, appropriate adjustment of coagulant dosage in response to variation in raw water quality, effective backwashing, and continuous monitoring of filtered turbidity from each filter in order to receive the 2 log removal credit.

2.2.6 Oocyst Removal Technologies in Water Treatment Plants

Cryptosporidium oocysts are removed within conventional water treatment plants through a series of processes including coagulation, flocculation, clarification, filtration, and potentially, disinfection. Depending on raw water quality and plant design, other processes may be substituted for some of those listed above. In some instances, direct filtration replaces clarification, and inline filtration can replace both the flocculation and clarification processes (LeChevallier and Au, 2004). Alternative technologies such as membrane filtration, UV

radiation, slow sand filtration, and diatomaceous earth filtration are also able to effectively remove or inactivate oocysts. The section below summarizes the mechanisms of oocyst removal/inactivation within a variety of drinking water treatment technologies.

Coagulation and Flocculation

Coagulants (e.g. aluminum sulfate/chloride (alum), ferric salts, polyaluminum chloride [PACl]) are added at the rapid mix stage to destabilize particles through mechanisms of double layer compression, charge neutralization, enmeshment in precipitate, adsorption, and inter-particle bridging (Crittenden *et al*., 2012). Coagulant dose is dependent on raw water quality and is commonly determined using a jar test. Flocculation processes enable the flocs formed during coagulation to aggregate together and form larger flocs. Coagulation and flocculation aids are applied in some plants to facilitate floc formation. Oocyst removals do not occur directly during coagulation and flocculation but they do in subsequent sedimentation and filtration steps. However, oocysts cannot be effectively removed unless adequate coagulant is applied to change the negatively-charged surface of the oocysts. The negatively-charged oocysts respond to coagulants similarly to naturally occurring particles. Adequate coagulation and flocculation are crucial to ensure removals by clarification and filtration. Coagulation failure or suboptimal coagulation has been reported to lead to substantial deterioration in oocyst removals in subsequent clarification and filtration processes in several published studies. A mean oocyst removal of 0.2 log was reported for a sedimentation process being operated under suboptimal coagulation conditions compared to a 1.3 log removal achieved under optimal coagulation conditions (Dugan *et al*., 2001). Little if any oocyst removal by filtration has been reported in the absence of coagulants (Patania *et al*., 1995; Huck *et al*., 2001). Substantially lower oocyst removals (by at least one log) were reported when suboptimal coagulant dosages were applied prior to filtration (Ongerth and Pecoraro, 1995; Dugan *et al*., 2001; Huck *et al*., 2001; Dugan and Williams, 2004; Brown and Emelko, 2009). Coagulation and flocculation processes vary from plant to plant as it pertains to mixing energy, coagulant type, coagulant dose, the application of coagulant or

flocculant aids, and pH. The effects of all combinations of the above variables on oocyst removals by subsequent clarification and filtration have not yet been fully been documented in literature.

Clarification

Destabilized particles and oocysts are physically removed through clarification as the first reduction barrier. The oocyst removal efficacy of clarification explains the additional oocyst removal credit (0.5 log) that has been assigned to conventional filtration (coagulation, flocculation, clarification, and filtration) compared to direct filtration processes where there is no clarification tank by USEPA (2006) and Health Canada (2012b). Clarification methods include sedimentation and dissolved air flotation (DAF) (Crittenden *et al*., 2012).

Sedimentation

In a sedimentation basin, settable particles are removed by gravity settling. Various bench- and pilot-scale experiments have reported oocyst removals from 0.61 to 1.6 log under a variety of treatment conditions (Plummer *et al*., 1995; Edzwald *et al*., 2000; Cornwell and Macphee, 2001; Dugan *et al*., 2001). Two full-scale plants reported a 0.5-0.8 log oocyst removal by sedimentation processes (Kelley *et al*., 1995). Through data analysis, sedimentation oocyst removals were found to be correlated to various operational and raw water parameters. Haas *et al*., (2000) found that oocyst log removals were correlated with coagulant concentration, process pH, and polymer concentration using data from four bench- and pilot-scale coagulation, flocculation, and sedimentation studies ($R^2 = 0.94$). Dugan *et al* (2001) observed a statistically significant correlation between oocyst removal and turbidity reduction during sedimentation (correlation coefficient of 0.88).

Dissolved Air Floatation

As an alternative to sedimentation, DAF removes fragile or light flocs by flotation. Air bubbles are introduced, which become attached to particulate matter and floc particles when moving upward through the water. Higher oocyst removals by DAF compared to reductions achieved by sedimentation have been reported (Plummer *et al*., 1995; Edzwald and Kelley, 1998; Edzwald *et al*., 2000; Harrington *et al*., 2001). Full-scale DAF data are scarce while bench- and pilot-scale studies have reported better oocyst removals than sedimentation. Bench-scale experiments demonstrated more than 2 log removals of oocysts under various treatment conditions compared to a log reduction of only 0.81 by sedimentation (Plummer *et al*., 1995). One pilot-scale DAF study reported oocyst removals of 3.1 log and 2 log with ferric chloride and alum coagulation, respectively (Edzwald and Kelley, 1998). Another demonstrated 1.7 log and 2.5 log oocyst removals in the winter and late spring, respectively (Edzwald *et al*., 2000). DAF oocyst removals were found to be correlated with raw water quality and other parameters. Plummer *et al* (1995) observed correlations between DAF oocyst removals and percent reduction of turbidity, UV_{254}, and dissolved organic carbon. French *et al* (2000) found DAF removal of oocysts was positively correlated with recirculation ratio of recycle water, coagulant dose, temperature, flocculation time, and negatively correlated with pH and turbidity. Dissolved air flotation is not widely practiced in drinking water treatment plants.

Rapid Granular Media Filtration

Rapid media filtration consists of a filter bed of granular material more uniform in size than commonly present in nature, is pretreated with coagulants, and employs mechanical and hydraulic systems that effectively remove particles retained on the filter media (Crittenden *et al*., 2012). The oocyst-media interactions include physical straining, physicochemical filtration, and steric hindrance.

Previous filtration experiments (bench-, pilot-, and full-scale) have reported effective oocyst removals when preceded by adequate chemical pretreatment. Suboptimal coagulation studies

have shown that log removals can drop by 1 or more log compared to experiments under adequate coagulation conditions (Ongerth and Pecoraro, 1995; Dugan *et al*., 2001; Huck *et al*., 2001; Dugan and Williams, 2004; Brown and Emelko, 2009). The end-of-run, early breakthrough, and late breakthrough are vulnerable periods with oocyst removals compromised by up to 2 log compared to those achieved during stable operation (Emelko *et al*., 2003). In their experiments, oocyst removals deteriorated substantially when filter effluent turbidity had just begun to rise (but was still less than 0.1 NTU) under end of run operating conditions. Filter ripening was also associated with a decline in oocyst removals although somewhat less than the other conditions (0.5-1 log) (Emelko *et al*., 2005).

Currently, there is no single reliable parameter that universally correlates well with oocyst log removals by filters. Though three studies have reported statistical correlations between log removals of turbidity and oocysts (LeChevallier *et al.*, 1991; LeChevallier and Norton, 1992; Nieminski and Ongerth, 1995), the bulk of the available data indicate the relationship may be site-specific and may not be a one-to-one correlation. Despite the proven efficacy of granular media filters for oocyst removal, a wide range of oocyst log removals has been reported from different filtration studies, with no clear explanation for the substantial variability (Hijnen and Medema, 2010).

Disinfection-activation

Disinfectants are applied to inactivate pathogens. The ability of chlorine, chloramine, chlorine dioxide, ozone, and UV radiation to inactivate oocysts is discussed below.

Disinfection efficacy can be described through the CT concept (the product of C and T): C refers to the residual concentration in mg/L; T refers to the contact time of disinfectant with water in minutes (Crittenden *et al*., 2012). CT tables have been developed for given disinfectants to achieve a certain log inactivation of specified microorganisms under various pH and temperature conditions. The efficacy of chemical disinfectants for protozoa (*Giardia*

and *Cryptosporidium*) in decreasing order is ozone > chlorine dioxide > chlorine > chloramines, because increasingly higher CT values are required for these four disinfectants (in order) to achieve the same degree of oocyst inactivation (Crittenden *et al*., 2012). In general, *Cryptosporidium* is more resistant to chemical disinfectants than *Giardia* partly due to its thick walls protecting oocysts (Health Canada, 2012a). Chlorine is the most widely used because it is readily available, relatively inexpensive, and can provide a residual to maintain disinfection in distribution systems. However, *Cryptosporidiu*m is highly resistant to chlorine and requires a prohibitively high chlorine concentration and contact time for inactivation to occur (Korich *et al*., 1990, Health Canada, 2012a). Monochloramine requires even higher contact times and concentrations to inactivate oocysts (Kirmeyer, 2004). As such, the reliance on chlorine or chloramine alone to achieve significant oocyst removals is impractical. Chlorine dioxide and ozone are stronger oxidants that are effective against *Cryptosporidium* oocysts at practical doses (Korich *et al*., 1990). However, these two disinfectants require more capital and skilled operators, which can limit their more widespread application, especially in small systems.

Ultraviolet (UV) radiation is rapidly becoming the technology of choice for utilities that can afford to install, operate, and maintain such systems. When UV radiation penetrates the microorganism cells, it is absorbed and photochemical reactions occur which lead to alterations in molecular structure resulting in the inability of oocysts to be infectious (USEPA, 1999). UV is particularly attractive for *Cryptosporidium* inactivation as relatively low UV doses are quite effective (Clancy *et al*., 1998; Craik *et al*., 2001). A UV dose of 12 mJ/cm^2 is required to receive a 3 log oocyst inactivation/removal credit by USEPA (2006). In Canada, UV doses of at least 20 mJ/cm^2 are commonly applied (Ontario Ministry of the Environment and Climate Change, 2006). Although promising, UV technology has not been widely applied in small systems, those which could most arguably benefit from this technology.

Other Treatment Methods

Slow sand filtration

Commonly applied in small systems with low-turbidity water at hydraulic loading rates about 100 times slower than rapid media filtration, slow sand filtration removes particles physically and biologically without coagulation pretreatment (Crittenden *et al*., 2012). The USEPA (2006) reviewed published studies and subsequently concluded that a well-designed and operated slow sand filter can obtain 3 log oocyst removals (Fogel *et al*., 1993; Hall *et al*., 1994; Schuler and Ghosh, 1991; Timms *et al*., 1995). Hijnen and Medema (2010) calculated an average microorganism elimination credit of 4.8 log oocyst removal from slow sand filtration for multiple studies (Hijnen and Medema, 2010).

Diatomaceous earth filtration

Diatomaceous earth filtration, also referred to as precoat filtration, retains particles at the surface of filter material, with straining as the predominant removal mechanism (Crittenden *et al*., 2012). The precoat filter material is initially deposited onto a support membrane which is called septum, and additional filter medium is applied throughout the filter operation to prevent filter clogging and rapid headloss development. Diatomaceous earth filtration has demonstrated better oocyst removal performance than granular media filtration. Several studies have reported 3 to 6 log oocyst removal through well-designed and operated diatomaceous earth filters (Schuler and Ghosh, 1990; Ongerth and Hutton, 1997; Ongerth and Hutton, 2001).

Membrane filtration

Since the middle of the twentieth century when the first membrane was developed, there has been an increasing trend in membrane research and application as an alternative to conventional treatment methods, owing to its increasingly affordable cost and advantages such as DBPs control and removal of fine particles. Both low pressure membrane (microfiltration and ultrafiltration) and high pressure membrane (nanofiltration and reverse osmosis) have demonstrated promising performance in reducing *Cryptosporidium*. For example, microfiltration and ultrafiltration have been reported to remove more than 4 log of oocysts (Jacangelo *et al*., 1995).

2.2.7 *Cryptosporidium* Removal by Granular Media Filtration

In water treatment plants relying on chlorine-based disinfectants and not employing UV, granular media filtration with adequate chemical pretreatment serves as an effective barrier against *Cryptosporidium*. It is employed in the form of either direct filtration or downstream from a clarification process. Oocyst removal mechanisms by granular media filters are discussed below. Results from published pilot- and full-scale studies illustrate a wide variation in reported oocyst removals.

Cryptosporidium-media Interactions

Oocysts, similarly to naturally occurring particles, are negatively charged in natural environments and respond to coagulation with metal salts (Ongerth and Pecoraro, 1996). The zeta potential of oocysts, measured as electrophoretic mobility, was reported to be -25 mV in distilled water at neutral pH and is subject to changes in pH, NOM composition/concentration, and ionic strength (Engeset and Dewalle, 1979; Ongerth and Pecoraro, 1996; Tufenkji *et al*., 2006). The negatively charged surface results in electrostatic repulsion between oocysts and the filter media, which hinders the attraction of oocysts to media surfaces. Chemical coagulation raises the zeta potential on the oocyst surface (becoming less negatively charged) and therefore decreases the electrostatic repulsion which facilitates the attachment of oocysts onto filter media. This oocyst/surface interaction

(physicochemical filtration) is commonly predicted by Derjaguin-Landau-Verwey-Overbeek (DLVO) theory which incorporates the electrical properties of oocysts and media particles (Derjaguin and Landau, 1941; Verwey and Overbeek, 1948). In addition to physicochemical filtration, physical straining which occurs when the media pore size is too small to allow oocyst passage, also contributes to oocyst reduction through media of different size (Tufenkji *et al*., 2004; Bradford *et al*., 2005; Hijnen *et al*., 2005). Another oocyst-media interaction is steric hindrance between oocysts and media in separation distances of less than 35 nm, due to the chemical structure of the oocyst surface. The macromolecules on the oocyst's surface were associated with additional electrosteric repulsive forces that cannot be explained by classic DLVO theory (Kuznar and Elimelech, 2006). When comparing the filtration behavior of surrogate particles such as inactivated oocysts or microspheres with that of viable oocysts, the differences in steric interaction and surface charge may affect oocyst removal prediction.

Cryptosporidium Removal in Pilot- and Full-scale Studies

To better understand filtration efficacy for *Cryptosporidiu*m removal, a number of full-scale and pilot-scale filtration experiments have been conducted. The number of all publications reviewed in this research with respect to the year of publication is shown in Figure 2.1. The peak of published filtration studies on *Cryptosporidium* removal occurred in the period 2000 to 2004, and a decreasing trend in number of publications was observed after that time. Pilot-scale studies with data for filtration processes and full-scale studies with oocyst removals through the entire plant were summarized (Appendix Tables A1 and A2). These full- and pilot-scale experiments have reported variable *Cryptosporidium* removals averaging from 1.4 log (96% reduction) to 5.8 log (>99.999% reduction) by granular media filters only (blue bars) or including removals due to clarification (grey bars) with coagulation pretreatment. The wide variation is evident in Figure 2.2 where *Cryptosporidium* removals in various studies are shown in descending order. The oocyst removal results in Figure 2.2 do not include trials where suboptimal coagulation condition was applied.

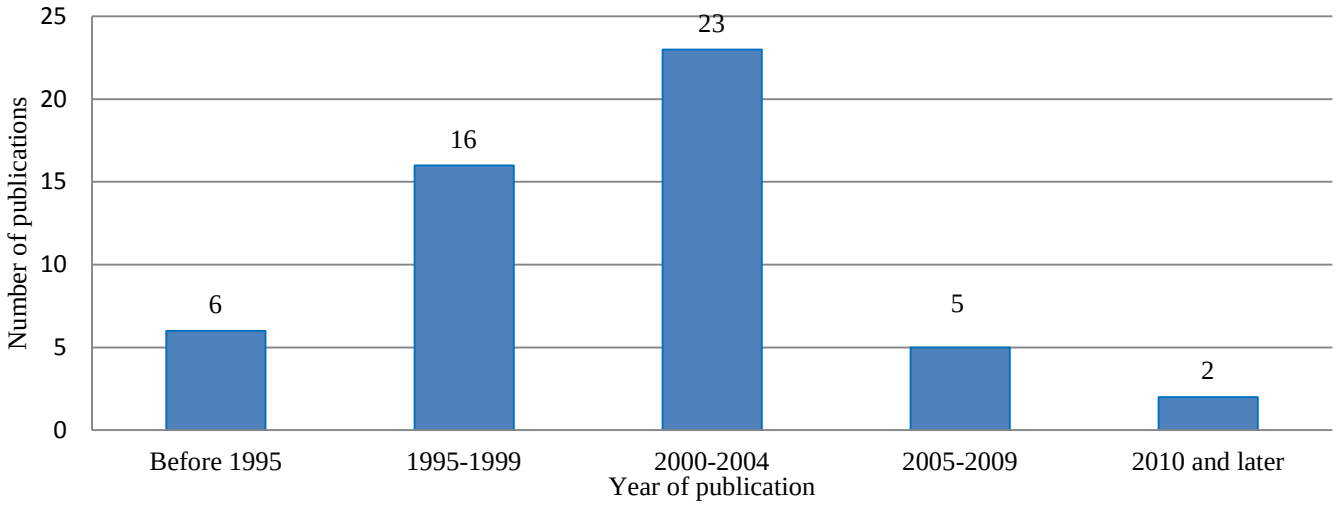


Figure 2.1 Number of publications on *Cryptosporidium* removal through granular media filtration in 5 year increments

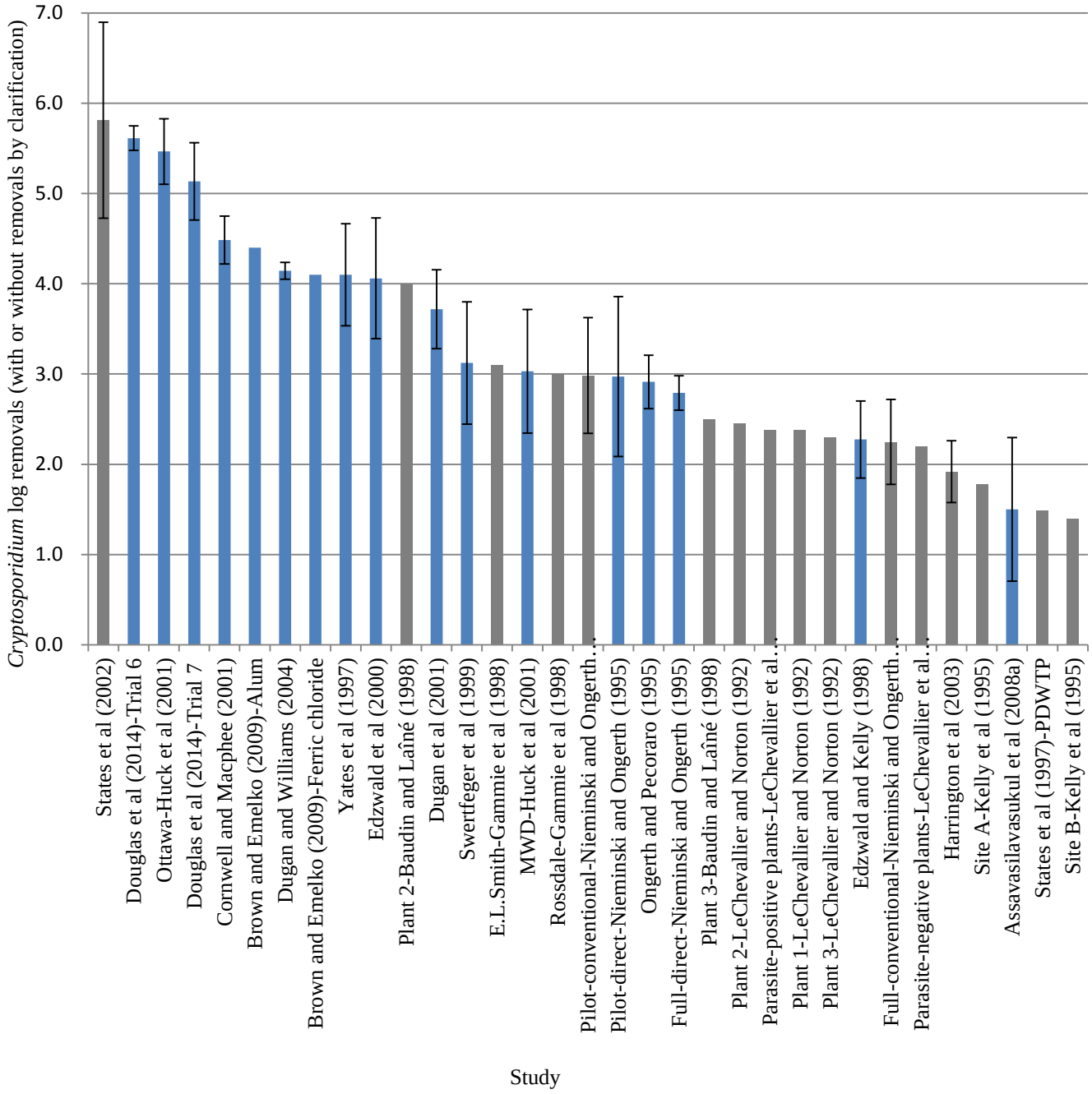

Cryptosporidium log removals (with or without removals by clarification)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
States et al (2002)
Douglas et al (2014)-Trial 6
Ottawa-Huck et al (2001)
Douglas et al (2014)-Trial 7
Cornwell and Macphee (2001)
Brown and Emelko (2009)-Alum
Dugan and Williams (2004)
Brown and Emelko (2009)-Ferric chloride
Yates et al (1997)
Edzwald et al (2000)
Plant 2-Baudin and Laîné (1998)
Dugan et al (2001)
Swertfeger et al (1999)
E.L.Smith-Gammie et al (1998)
MWD-Huck et al (2001)
Rossdale-Gammie et al (1998)
Pilot-conventional-Nieminski and Ongerth…
Pilot-direct-Nieminski and Ongerth (1995)
Ongerth and Pecoraro (1995)
Full-direct-Nieminski and Ongerth (1995)
Plant 3-Baudin and Laîné (1998)
Plant 2-LeChevallier and Norton (1992)
Parasite-positive plants-LeChevallier et al…
Plant 1-LeChevallier and Norton (1992)
Plant 3-LeChevallier and Norton (1992)
Edzwald and Kelly (1998)
Full-conventional-Nieminski and Ongerth…
Parasite-negative plants-LeChevallier et al…
Harrington et al (2003)
Site A-Kelly et al (1995)
Assavasilavasukul et al (2008a)
States et al (1997)-PDWTP
Site B-Kelly et al (1995)
Study

Figure 2.2 Average *Cryptosporidium* log removals reported in published studies (blue bars refers to removals by granular media filters only; grey bars include additional removals by clarification)

Although a wide range from low (1-2 log) to high (above 5 log) removals has been reported, few studies have compared and examined published oocyst removal data to determine how much can be confidently and reliably achieved by a filtration plant under normal coagulation conditions. A review by Emelko *et al* (2005) compared removal results from several studies, suggesting that a 3 log *Cryptosporidium* removal can be typically obtained through filtration processes under optimal or near-optimal conditions. Based on a review of several published studies (Dugan *et al*., 2001; Nieminski and Bellamy, 2000; McTigue *et al*., 1998; Patania *et al*., 1999; Huck *et al*., 2000; Emelko *et al*., 2000; Harrington *et al*., 2001), the USEPA (2006) assigned a 3 log oocyst removal credit to conventional filtration processes (preceded by coagulation, flocculation, and sedimentation) and a 2.5 log removal credit to direct filtration processes. Health Canada (2012b) reviewed the USEPA (2006) document and conducted its own review, and subsequently adopted similar log removal credits for granular media filtration processes. Hijnen and Medema (2010) summarized existing oocyst removal data by filtration studies. By weighting published data according to the scale of experiments (full-scale, pilot-scale, and bench-scale), type of microorganisms used (environmental organisms, lab-cultured organisms, or surrogates), and quality of each study, microorganism elimination credits (MECs) of 2.6 to 3.0 log for rapid granular filters preceded with coagulation and flocculation, and with direct in-line coagulation were calculated.

Currently, few studies have provided explanations for the substantial variability among studies, or identified significant factors that could influence removal results during stable operation and adequate coagulation conditions. Huck *et al* (2002) speculated that differences in analytical reliabilities, sample volumes processed, detection limits, and influent microorganism concentrations may all contribute to the reported differences. Assavasilavasukul *et al* (2008a) demonstrated that *Cryptosporidium* removals by a

conventional treatment plant were dependent on raw water turbidity and influent oocyst spike concentrations. In a critical review conducted by Hijnen and Medema (2010), it was speculated that the variability may be due to the differences in microorganism type (environmental vs. pre-cultured), raw water characteristics, temperature, and process set-up and operations.

As discussed above, the wide range in reported removal results poses uncertainties in developing expectations for the removal capability that can be reasonably achieved by filtration. The published filtration studies differ in aspects of filter design and operation, raw water characteristics, chemical pretreatment, and experimental and analytical configurations. Whether the reported variability is attributed to an above variable or combination of variables is not well understood. No universally applicable (or accepted) variable has been identified which can account for the substantially different oocyst removals reported in various filtration studies. An updated and comprehensive review on published data to help interpret *Cryptosporidium* log removal data and identify factors that might have an influence follows below.

2.3 Factors Affecting *Cryptosporidium* Removals by Granular Media Filtration

2.3.1 Potentially Influencing Factors

Previous investigators have attributed the wide ranges in reported oocyst removals through filtration to raw water quality, treatment operational differences, influent microorganism concentrations, microorganism type (environmental vs. inactivated), temperature, process set-up and operations, analytical reliabilities, processed sample volumes, and detection limits (Huck *et al*., 2002; Assavasilavasukul *et al*., 2008a; Hijnen and Medema, 2010). Two categories of potentially influencing factors are identified including process factors and experimental factors (Table 2.2). Process factors include aspects of raw water quality,

coagulation conditions, and filter design and operation, while experimental factors represent differences in experimental and analytical methods used to assess log removal.

Later in this section, the effect of each factor on *Cryptosporidium* results reported for granular media filtration is discussed by comparing published studies and examining published data. These factors are selected for detailed discussion, owing to the availability of published findings and data on their effect on *Cryptosporidium* removals.

Table 2.2 Potential factors influencing *Cryptosporidium* removals by filtration

Category	Potential influencing factors
Process factors	Temperature
	Coagulant type
	Coagulation pH
	Filter media type
	Hydraulic loading rate
	Filter effluent turbidity
Experimental factors	*Cryptosporidium* spike concentration
	Cryptosporidium condition
	Seeding location
	Detection limit
	Recovery efficiency

2.3.2 Data Collection

Published studies which have investigated *Cryptosporidium* removals through granular media filtration experiments are reviewed below. Effort was made to find the available studies from published journals, books, and conference proceedings. The process and experimental conditions for each filtration experiment have been compiled. Only pilot- and full-scale filtration studies were included, as they better represent real-world filtration application than bench-scale experiments. To avoid too much confounding, oocyst removals through clarification processes have been subtracted from combined clarification/filtration data when possible and data for the use of surrogates (including microspheres) were excluded.

To focus on variability in oocyst removals among filtration experiments under optimized or near-optimized coagulation conditions, only filtration trials which do not indicate suboptimal coagulation conditions were included. Published filtration experiments for spiked seeding studies are compiled in Appendix Table A1 including process and experimental conditions for which information was commonly available.

- Influent water turbidity and temperature are recorded under raw water quality characteristics.
- Information regarding coagulation type and dosage, coagulation pH, and coagulation aids were collected to represent coagulation conditions.
- In terms of filter design and filter operation, the type of filtration, filter media and depth, hydraulic loading rate, filter effluent turbidity, and filter aids are listed.
- As for experimental and analytical differences, oocyst spike concentration, *Cryptosporidium* condition, seeding location, detection methods, detection limits, recovery efficiency, and occurrence and handling of non-detects are provided.

Cryptosporidium removals through full-scale plants with naturally occurring oocyst concentration are also summarized in Appendix Table A2.

2.3.3 Discussion

Cryptosporidium Oocyst Removals Reported in Spiked Seeding Filtration Studies

Filtration experiments commonly apply oocyst spiked concentrations of 6-8 orders of magnitude higher than those generally present in natural water to get detectable oocyst levels in filter effluent, which facilitates accurate removal calculation. *Cryptosporidium* removals achieved in spiked seeding filtration studies are demonstrated as a whisker-and-box plot (Figure 2.3). Data in Appendix A Table A1 were used to create this figure. The top whisker represents the maximum removal and the bottom whisker represents the minimum removal in

the given study. The box bottom, line across the box, and box top illustrate the 25th percentile, median, and 75th percentile of the oocyst removal data in that study.

The 'n' in this case represents the number of oocyst removal data reported in published studies. There is concern in treating n as the reported number of removal values from all studies as studies did not report their removal results in consistent ways. Some studies reported one oocyst removal result for each experimental run, with or without identifying the value as an average or median removal, while other studies took multiple paired influent and treated water samples and calculated several removal results for each experimental run. The approach of defining n as the number of removals reported in the publication can be argued; however, to avoid introducing error and potentially misinterpreting reported data by recalculating removal results and in some way standardizing n in all studies.

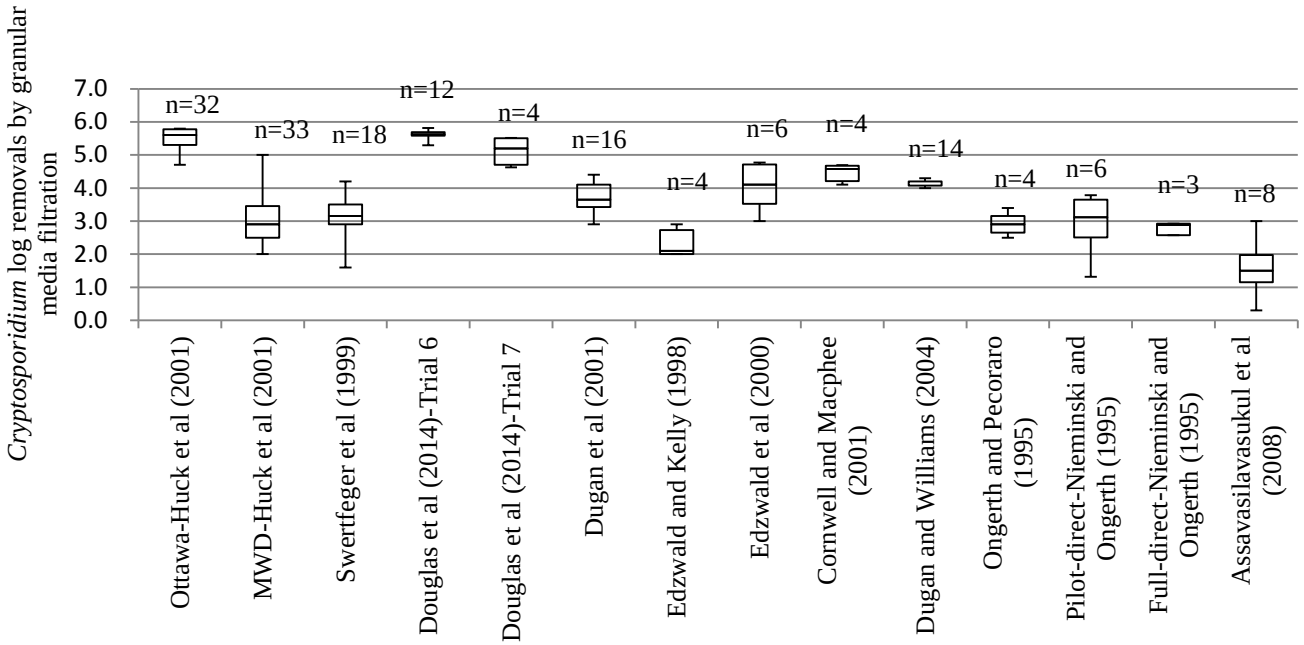


Figure 2.3 Box-and-whisker plot for oocyst removals in spiked seeding studies

It is apparent that reported *Cryptosporidium* removals through granular media filters vary substantially among different filtration studies, with median oocyst removals ranging from

1.5 log to 5.6 log. The removals can also vary considerably within a given study among different trials. For example, a pilot-scale filtration study conducted by the Metropolitan Water District of Southern California (MWD) reported a wide range of 2-5 log oocyst removals under stable filter operation, with only small variations in seeding concentration, filter influent turbidity, and temperature among trials (Huck *et al*., 2001). From Figure 2.3, it can be seen that nine out of fifteen spiked seeding studies reported more than 3 log removals as median removals while a few studies reported median removals in the lower range. As mentioned in the previous regulation section, 3 log and 2.5 log oocyst removals have been assigned by USEPA and Health Canada to conventional and direct filtration processes respectively, while the Ontario Ministry of the Environment and Climate Change (MOECC) has assigned only a 2 log removal credit to both processes. The oocyst removals in the lower range (1-3 log) in some studies demonstrate that there is still uncertainty in achieving 3 log oocyst removals in all conditions, and this may help explain why the Ontario Ministry of the Environment and Climate Change (MOECC) has assigned a lower credit.

Cryptosporidium Oocyst Removals Reported in Full-scale Plants with Naturally Occurring Oocysts

Fewer studies have been conducted on *Cryptosporidium* removals by full-scale plants where naturally occurring oocysts were present in raw water. Removal data in Appendix B were used to construct a bar chart where oocyst removals by full-scale plants are illustrated (Figure 2.4). The bars in blue represent plants where detectable oocysts were found in the filter effluent, while bars in grey are plants with non-detects in the filter effluent and oocyst removals are reported as ‘greater than’ the value calculated.

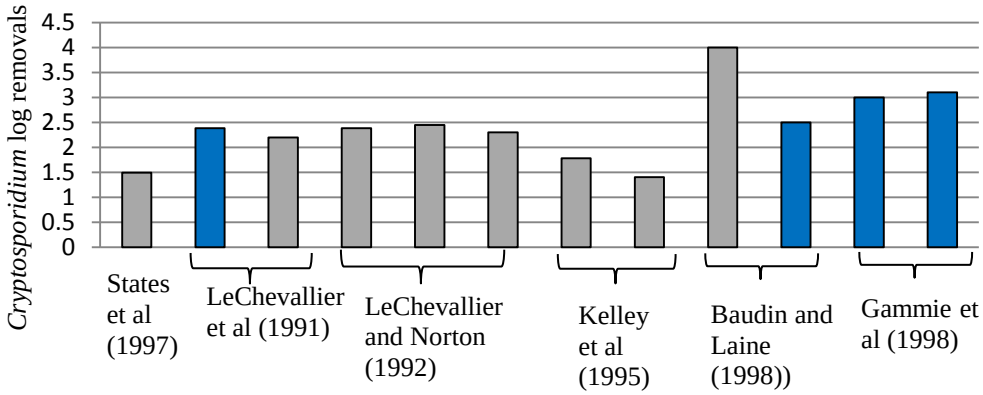


Figure 2.4 *Cryptosporidium* removals in full-scale plants with naturally occurring oocysts (grey bars are plants with non-detects in filter effluent; blue bars are plants where detectable oocysts were reported in filter effluent)

Compared to Figure 2.3 where greater than 3 log oocyst removals by filtration were achieved by the majority of spiked seeding studies, full-scale studies with naturally occurring oocyst concentrations have reported much lower removals through coagulation, clarification, and filtration; typically in the range of 1.5-3 log. Naturally occurring oocysts in raw water frequently lead to extremely low oocyst concentration or even non-detects in filtered water, which poses difficulty in accurately enumerating oocysts. When no oocysts are detected in filtered water, which is commonly the case for such plants, the method detection limit (MDL) is used to calculate the oocyst removal and the removal is prefixed with a ">". Focusing only on plants with detectable oocysts in filter effluent, oocyst removals of 2.38, 2.5, 3.0, and 3.1 log (blue bars) have been observed. These values better describe removals that full-scale filtration plants can typically be expected to achieve and approach what spiked seeding studies have reported. The effect of spiked concentration on oocyst removal will be discussed in detail later.

Effect of Identified Factors in Influencing *Cryptosporidium* Removal

The effects of the identified eleven factors on the removal of *Cryptosporidium* by filtration are examined in this section. Critical reviews of individual studies, as well as comparisons with removal data from all published studies are applied to investigate whether there is an apparent relationship between an identified factor and oocyst removals by filtration.

Temperature

The effect of temperature on oocyst removal by filtration is not easily elucidated since temperature changes may be associated with variations in other factors. For example, seasonal changes not only affect water temperature, but also can lead to very different raw water qualities. Ives and Sholji (1965) reported substantial decreases in particle removals under cold water conditions when other factors remained the same. However, based on filtration models for particle removal, temperature has very little effect on microorganisms larger than 1 μm and *Cryptosporidium* oocysts fall in the range of 4 to 6 μm (Rajagopalan and Tien, 1976).

Published filtration studies have reported little effect of temperature on oocyst removals. Swertfeger *et al* (1999) demonstrated no statistically significant difference in oocyst removals between summer and winter runs for three types of filter media (mono-media, fine dual and deep dual). Filtration studies conducted in Ottawa, Canada experienced a wide range of temperature from 1 to 27℃ and no significant variations in oocyst removals were observed throughout this temperature range, as shown in Appendix A (Huck *et al*., 2001). States *et al* (2002) conducted a series of filtration experiments with cold and warm water preceded by ferric chloride coagulation. Comparable oocyst removals through coagulation, sedimentation, and filtration were reported under cold and warm water conditions at various pH levels.

Coagulant type

Previous studies commonly applied alum, ferric compounds, and polyaluminum chloride (PACl) as coagulants (Appendix Table A1 and A2). No substantial effect of coagulant type

on oocyst removal through subsequent filtration under optimized operation has been reported to-date (Table 2.3). Dugan *et al* (2001) conducted two pairs of pilot-scale experiments to compare the performance of filters using different coagulants (alum versus ferric chloride, alum versus polyaluminum hydroxychlorosulfate). No significant impact of alternative coagulant types on *Cryptosporidium* removal was observed. In another pilot-scale study, comparable median oocyst removals of 4.4 log, 4.1 log, and 4.2 log were observed for alum, $FeCl_3$, and chitosan coagulation, respectively, while yielding similar effluent turbidity (Brown and Emelko, 2009). Despite comparable removals among the three coagulants, the authors reported that ferric chloride application produced consistently lower removals of oocysts and a surrogate, oocyst-sized microspheres, compared with trials with alum coagulation. This phenomenon is not fully understood and needs to be further investigated to determine whether this difference is applicable under other operational conditions (Brown and Emelko, 2009). However, a single conflicting observation was reported in one direct filtration pilot-scale study where slightly higher removals of oocysts, turbidity, particles, and spores occurred in trials with ferric chloride vs. those conducted with alum (Yates *et al*., 1997). During stable operation, 4.5 log removal of oocysts was reported when using ferric chloride, compared to 3.7 log removals achieved for filtration trials preceded with alum coagulation. The authors also reported greater headloss accumulation and shortened filter runs associated with ferric chloride trials, which led to more frequent backwashing.

Table 2.3 Studies investigating the effect of coagulant type on the removal of *Cryptosporidium* oocysts in downstream filters

Studies	Coagulant type	*Cryptosporidium* removals by filtration
Brown and Emelko (2009)	Alum (5mg/L)	4.4 log
	Ferric chloride (3mg/L)	4.1 log
	Chitosan (3mg/L)	4.2 log
States et al (2002)	Polyaluminum chloride (PACl)	5.9 log[1]
	Ferric chloride	6.1 log[1]

	Alum	5.4 log [1]
Dugan et al (2001)	Alum (40 mg/L) vs. ferric chloride (30 mg/L)	>3.6 vs. >3.3
	Alum (15 mg/L) vs. polymer (14 mg/L)	>4.3 vs. >4.4
Yates et al (1997)	Alum (5 mg/L)	3.7 log
	Ferric chloride (3 mg/L)	4.5 log

Note: [1]*Cryptosporidium* removals reported include the effect of clarification

Coagulation pH

The surface of *Cryptosporidium* oocysts is negatively charged in distilled water with an electrophoretic mobility of -25 mV at neutral pH (Engeset and Dewalle, 1979; Ongerth and Pecoraro, 1996), resulting in an electrostatic repulsion between *Cryptosporidium* and granular material. Theoretically, pH can affect oocyst surface charge, which plays an important role in coagulation and filtration processes (Lytle and Fox, 1994). As pH increases, the oocyst surface becomes more negatively charged and results in higher electrostatic repulsion at the oocyst- sand interface (Hijnen and Medema, 2010).

Enhanced coagulation processes, which include reducing pH levels to 5-6, have been examined to understand the effects of lower pH on oocyst removals. A pilot-scale study by States *et al* (2002) tested the effects of various pH levels on oocyst removals with three coagulants (alum, ferric chloride, and polyaluminum chloride). The series of experiments resulted in a mean log oocyst removal of 5.8 through coagulation, sedimentation, and filtration, at pH levels of 5-8, with no reported deterioration in oocyst removals due to pH reduction. Harrington *et al* (2003) evaluated the effect of pH on oocyst removal performance of coagulation, sedimentation and filtration by operating three filters (i.e. mono-media, dual-media and tri-media) in two parallel trains. The same coagulant doses were applied while the pH of the two treatment trains was set at 5.7 and 7, respectively, by adding sulfuric acid. The

mono-media filter achieved a significantly higher oocyst removal at pH 5.7 than at pH 7, while dual-media and tri-media filters demonstrated comparable oocyst removals at the two pH levels.

Filter media type

No systematic effects of filter media type on oocyst removals during stable operation have been observed in published studies comparing media simultaneously using the same source water (Table 2.4). Hall *et al* (1995) did not find performance differences between sand, dual-media, and GAC filters given similar filtrate quality. Similar oocyst reductions by sand and dual (anthracite/sand) media were reported by Dugan *et al* (2001), with removals of 3.5 log and more than 3.6 log, respectively. However, the sand filter encountered quicker headloss built-up and was more vulnerable to breakthrough compared with dual media filters, but this effect can be minimized by optimizing the backwash scheme (Dugan *et al.*, 2001). Swertfeger *et al* (1999) compared oocyst removals by sand, fine dual (anthracite/sand) media filters, and deep dual (anthracite/sand) filters. Though the average oocyst log removal by deep dual media was nearly 1 log higher than those by the other two media, an ANOVA revealed that there was no statistical difference among these three media at the 5% significance level. Dual and tri-media filters were also reported to achieve comparable oocyst removals in bench-scale experiments (Emelko, 2003). As well, anthracite/sand and GAC/sand filters resulted in comparable oocyst removals in six trials (Douglas *et al*, 2014).

Table 2.4 Oocyst removal performance by different filter media

Studies		Filter performance	
Hall et al (1995)	Filter type	Filter effluent turbidity (NTU)	Oocyst/L in filter effluent
	GAC	0.20	0.04
	Dual media	0.30	<0.02
	Single media sand	0.27	<0.05
Dugan et al (2001)	Filter type	Average filter effluent turbidity (NTU)	Oocyst removals
	Dual media	0.06	3.5 log

	Sand	0.06		>3.6 log	
Swertfeger et al (1999)	Filter type	Turbidity removals		Oocyst removals	
		winter	summer	winter	summer
	Sand (75cm)	1.45 log	1.11 log	2.8 log	2.7 log
	Dual media (90cm anthracite/30cm sand)	1.45 log	1.08 log	3.2 log	2.7 log
	Deep dual (150 cm anthracite/30cm sand)	1.5 log	1.03 log	3.6 log	3.9 log
Emelko (2003)	Dual media	Comparable oocyst removals achieved by dual media and multimedia filters during stable operation, ripening, and breakthrough; marginally higher median removals by tri-media filters			
	Tri-media				
Douglas et al (2014)	Filter type	Average oocyst removals			
	Anthracite/sand	5.62 log			
	GAC/sand	5.60 log			

Hydraulic loading rate (HLR)

Various hydraulic loading rates ranging from 2.45 to 15 m/h were applied in published studies (Appendix A1 and A2). From the filtration model by Rajagopalan and Tien (1976), particle removal decreases as filtration rate increases. However, this effect depends on particle size. If the particle size is larger, particle removals will not decline significantly when filtration rate increases (LeChevallier and Au, 2004). In a column test, Shaw *et al* (2000) found that when superficial velocity increased from 3.5 US gpm/sq ft (8.75 m/h) to 14 US gpm/sq ft (35 m/h), the removal efficiency of *Cryptosporidium* decreased gradually but the declining slope was negligible despite the wide range of loading rates.

Several pilot-scale studies have reported no apparent effect of changing HLR on oocyst removals. Adin *et al* (1999) conducted bench-scale filtration experiments at three HLRs (i.e. 1.5 m/h, 5 m/h, and 10 m/h). Their findings demonstrated no clear effect of changes in HLR on oocyst removals, while the removals of other particles (e.g. kaolin) decreased as HLR increased. Hijnen and Medema (2010) plotted *Cryptosporidium* removal data against HLR from all literature reviewed in their studies, resulting in no obvious relationships between HLR and oocyst removal at hydraulic loading rates of 20 m/h or less. Harrington *et al* (2003) tested various filter HLRs including 2 US gpm/sq ft (5 m/h), 4 US gpm/sq ft (10 m/h), 6 US gpm/sq ft (15 m/h), and 8 US gpm/sq ft (20 m/h) in their pilot-scale plants. No observable effects on oocyst removals or effluent turbidity were attributed to HLR in the range from 5 to 20 m/h during stable operation.

The effect of HLR on the removal of *Cryptosporidium* by filtration in all studies examined is summarized in Figure 2.5. Data incorporating non-detects were excluded when plotting this figure. This approach could be argued but the non-detects were removed because the removal data incorporating non-detects were reported as the lower bound and the incorporation of such data may distort the actual pattern.

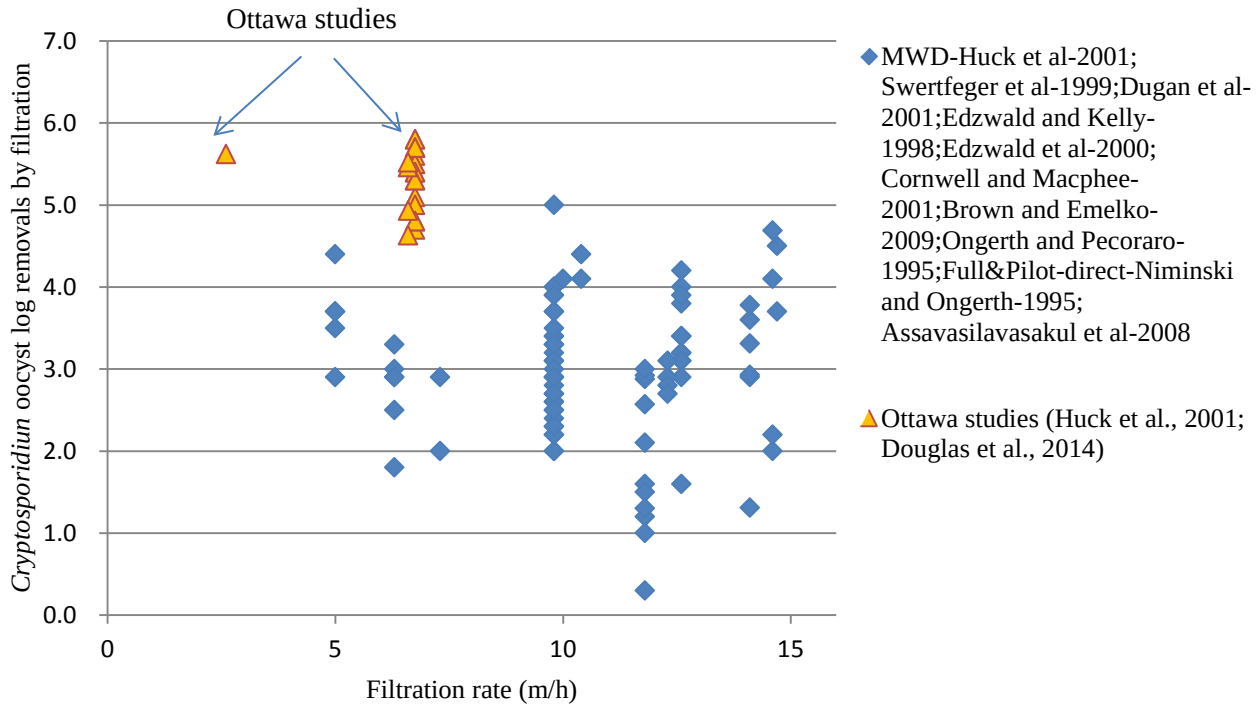


Figure 2.5 *Cryptosporidium* removals through filtration vs. hydraulic loading rate (removal data incorporating non-detects are excluded)

The Ottawa studies have consistently achieved considerably higher removals than other studies, with all oocyst removals exceeding 4.5 log. The higher removals have never been adequately explained, even when similar HLRs (in the vicinity of 6 m/h) were applied. Examination of the remaining data demonstrates no apparent relationship between oocyst removals that can be achieved and applied HLRs, in the commonly applied range from 5 to 15 m/h. This observation is consistent with findings from other studies (Adin *et al.*, 1999; Harrington *et al.*, 2003; Hijnen and Medema, 2010).

Higher HLRs are, however, associated with greater headloss which in turn predispose filters to oocyst breakthrough if filters are not operated properly to avoid turbidity targets. Dugan *et*

al (2001) compared oocyst removals by high rate (10 m/h) and low rate (5 m/h) pilot filters. Prior to breakthrough, the 10 m/h HLR resulted in average *Cryptosporidium* removal greater than 3.4 log, and the 5.0 m/h HLR filter achieved 3.6 log removal. Not unexpectedly, the high rate filter experienced earlier and substantial oocyst and turbidity breakthrough.

The effect of HLR on oocyst removal may be influenced by the type of coagulant applied prior to filtration. For example, no difference in performance was observed between high rate (14.6 m/h) and low rate (7.3 m/h) dual media filters downstream from ferric chloride coagulation; however, when alum was used, 2.9 log oocyst removals were achieved through the low HLR filters, which is slightly higher compared to 2.2 log for the high rate filters (Edzwald and Kelly, 1998). Dugan and Williams (2004) compared direct filtration using alum and ferric chloride. At a filter loading rate of 5 m/h, alum and ferric chloride yielded similar oocyst removals (i.e. > 4.2 log, > 4.1 log). However, when the filter loading rate increased to 10 m/h, the oocyst removal by the alum-dosed filter dropped substantially, to 1.9 log, compared the stable > 4.1 log removal for runs with ferric chloride. One hypothesis is that flocs formed by alum coagulation are more vulnerable to damage at higher HLRs, which led to earlier greater breakthrough compared to the ferric chloride trials. More investigation is required to assess whether this hypothesis can be verified and whether this behavior is applicable to other water sources as well.

Filter effluent turbidity

In general, good filter performance can be expected when filtered effluent turbidity is low (Health Canada., 2012b). When filter effluent turbidity exceeds 0.1 NTU, it is likely to lead to substantial deterioration in oocyst removals, which is illustrated in Figure 2.6 (Douglas and Campbell, 2015).

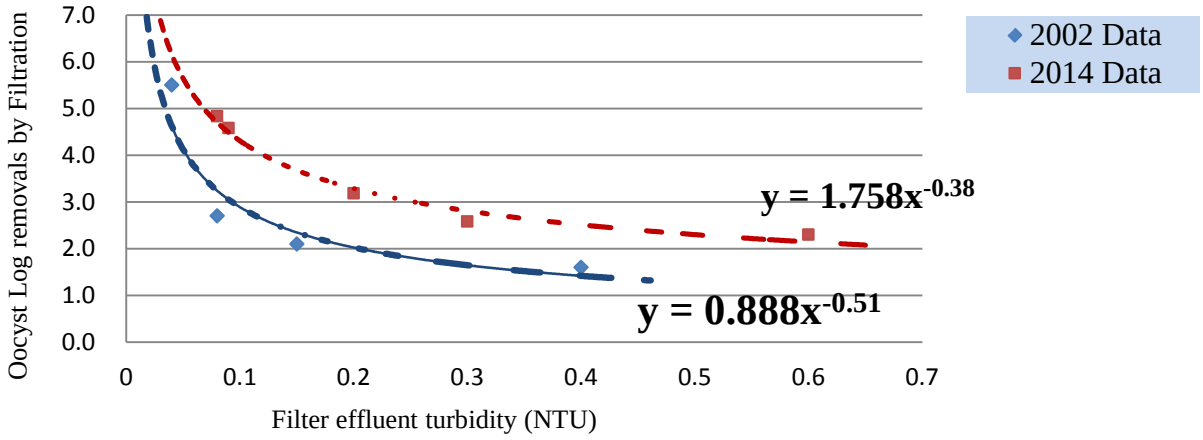


Figure 2.6 *Cryptosporidiu*m removals through filtration versus filter effluent turbidity at Ottawa pilot-plant (replicate experiments in 2002 & 2014) (Douglas and Campbell, 2015)

Figure 2.7 illustrates filter effluent turbidity reported in filtration studies by plotting data in Appendix Table A1. Studies with reported filter effluent turbidity less than 0.1 NTU are shown in yellow and studies with filter effluent turbidity greater than 0.1 NTU are shown in blue. The *Cryptosporidium* removals through granular media filtration processes for these two groups are shown in Figures 2.8 and 2.9, respectively. The majority of studies (8 out of 10) in the yellow group (with filter effluent turbidity less than 0.1 NTU) reported oocyst removals greater than 3 log. In comparison, studies in the blue group (with filter effluent turbidity greater than 0.1 NTU) demonstrated oocyst removals around 3 log or less than 3 log, substantially lower than values shown in the yellow group. This comparison indicates that lower filter effluent turbidity values appear to be associated with improved oocyst removals. The regression equations are provided by Douglas and Campbell (2015).

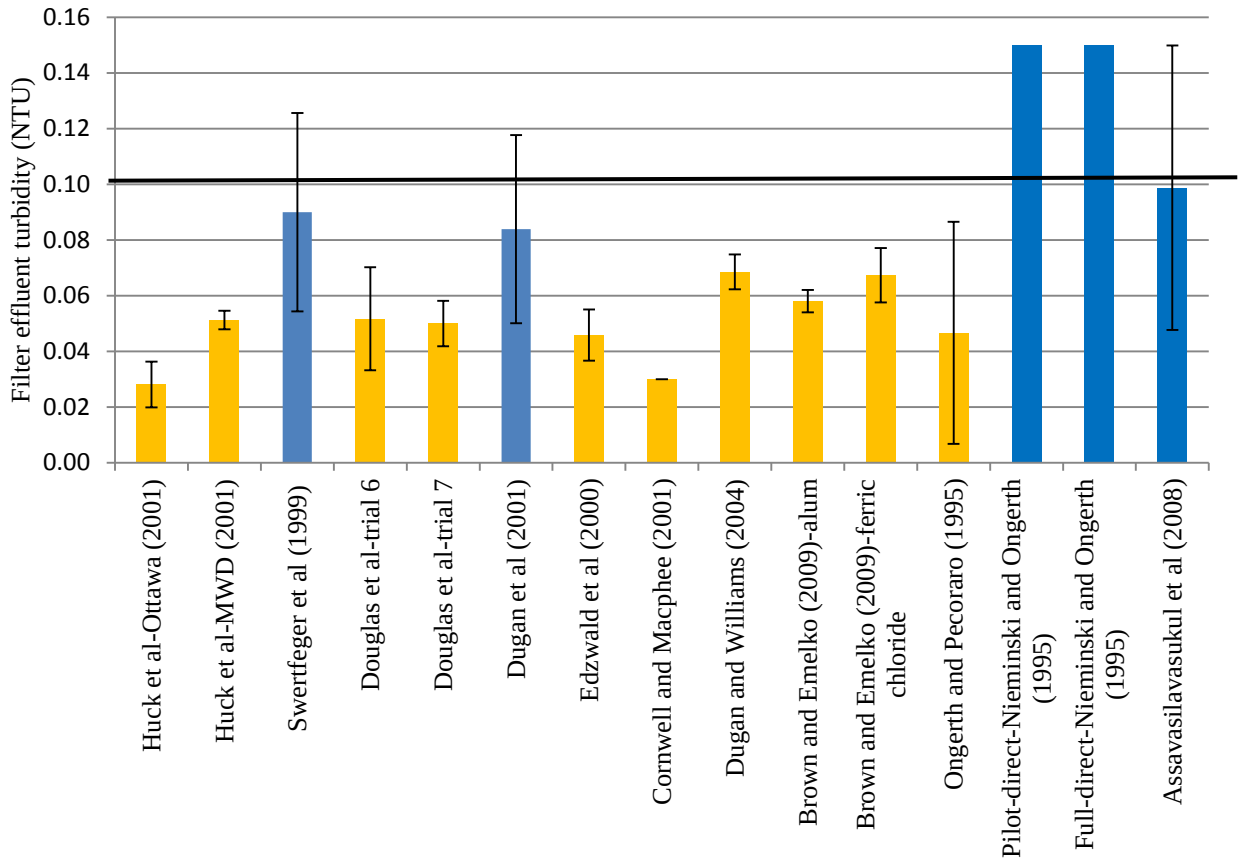


Figure 2.7 Filter effluent turbidity reported in studies (yellow bars refers to studies with filter effluent turbidity less than 0.1 NTU; blue bars refers to studies with filter effluent turbidity greater than 0.1 NTU)

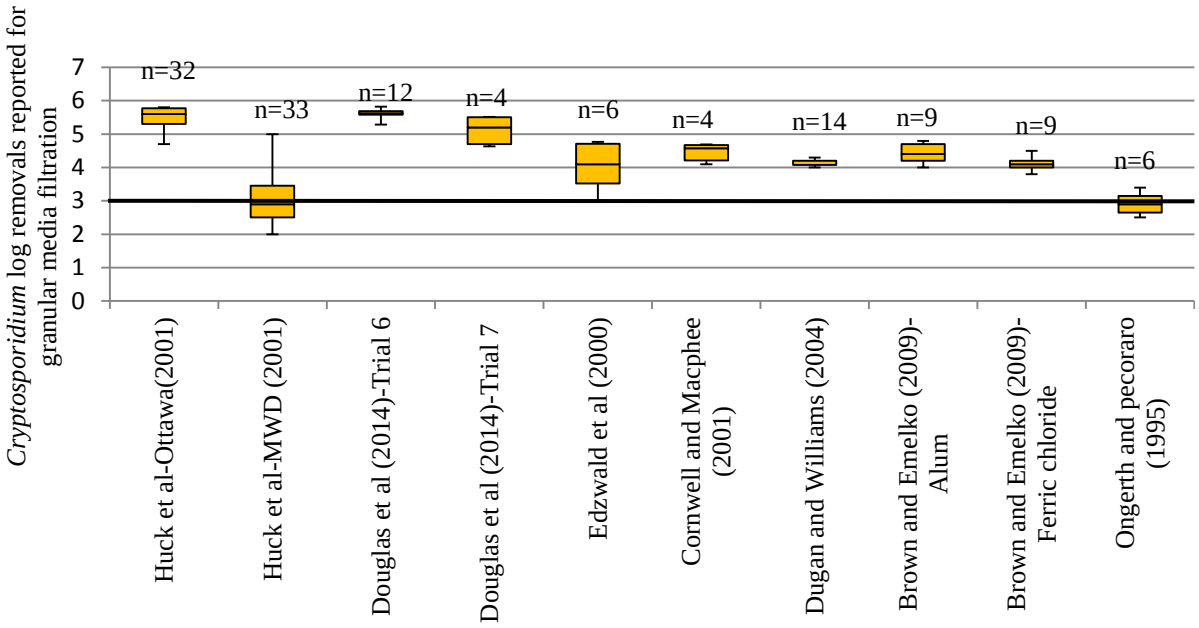


Figure 2.8 *Cryptosporidium* removals reported by granular media filtration in studies with filter effluent turbidity less than 0.1 NTU

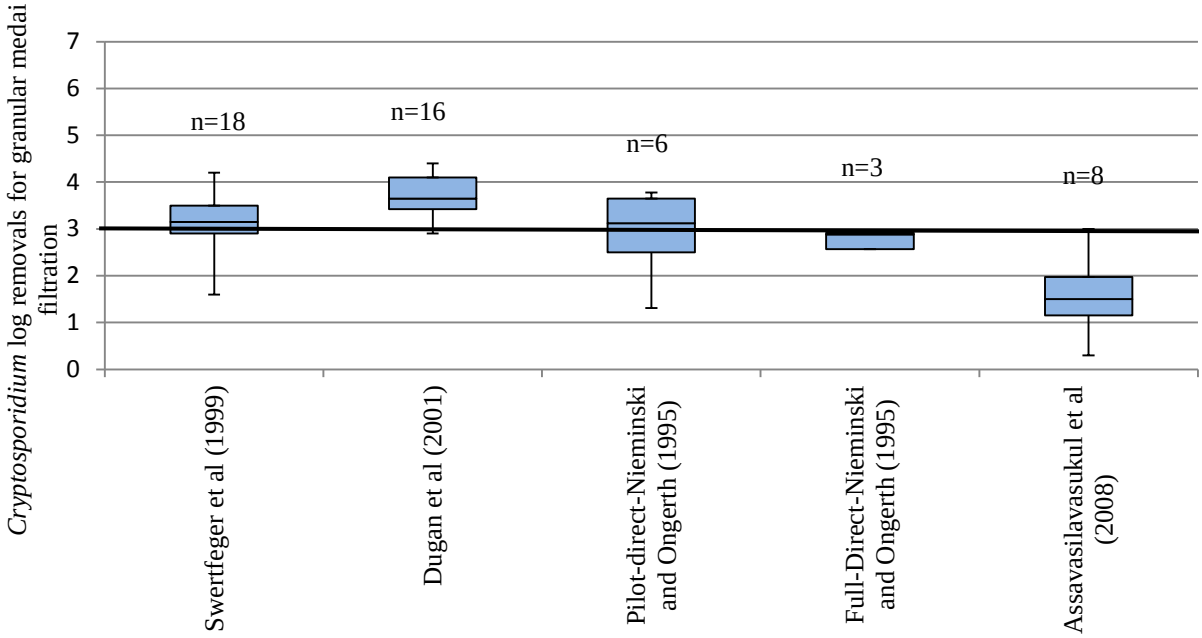


Figure 2.9 *Cryptosporidium* removals reported by granular media filtration in studies with filter effluent turbidity greater than 0.1 NTU

As a readily measured parameter, filter effluent turbidity is stringently mandated by regulations and guidelines to ensure health-based pathogen removals (USEPA, 2006; Health Canada; 2012b). The *Guidelines for Canadian Drinking Water Quality* (2012b) require the effluent turbidity from individual filters be less than or equal to 0.3 NTU in 95% of measurements and never exceed 1 NTU. The *Long Term 2 Enhanced Surface Water Treatment Rule* by USEPA (2006) released performance standards for combined filter effluent (CFE). 1.0 NTU was set as maximum and 0.3 NTU or less is required for 95% of monthly measurements.

Low filter effluent turbidity, however, cannot confirm the presence or absence of oocysts, nor the magnitude of oocyst removal. Huck *et al* (2002) reported a 2-log removal difference between two pilot-scale plants which had similar filter effluent turbidity. Emelko (2003) found very different oocyst log reductions associated with the same filter effluent turbidity in bench-scale experiments. In terms of the relationships between reduction of turbidity and

oocysts, no universal and precise relationships between turbidity reduction and that of oocysts has been observed (Health Canada, 2012b). Swertfeger *et al* (1999) and Dugan *et al* (2001) reported consistently lower turbidity log reductions than oocyst log reductions. Though three studies reported correlations between log reductions of turbidity and oocysts with correlation coefficients (R^2) ranging from 0.17 to 0.73 (LeChevallier *et al.*, 1991; LeChevallier and Norton, 1992; Nieminski and Ongerth, 1995), the bulk of the data suggested the relationship may be site-specific and may not be a one-to-one relationship.

Cryptosporidium spiked concentration

Occurrence surveys reveal a concentration range of <0.001 to 3 oocysts/L in raw water (Assavasilavasukul *et al.*, 2008b). To mitigate methodological difficulties in accurately quantifying indigenous oocysts which are present in extremely small numbers or even below the detection limit in filter effluent, the spiked concentration of *Cryptosporidium* oocysts in pilot plants is typically 6-8 orders of magnitude higher than those generally present in raw water. High quantity seeding in pilot plants is based on the assumption that filtration performance is not affected by influent spiked concentrations.

Several studies have investigated the effect of seeding concentration on oocyst removals (Table 2.5). A pilot-scale study conducted by Assavasilavasukul *et al* (2008a) applied spiked concentrations varying from 10 to 10^5 per liter to raw water with a low particle content. The results demonstrated that oocyst log removals by granular media filtration processes were dependent on influent seeding concentrations, as confirmed by regression analysis ($p<0.01$). The authors indicated that high spiked seeding sufficiently increased the particle concentration in influent water, which was exceptionally low in particles, and the increase in particle concentration enhanced the filter's oocyst removal performance.

All other located studies, however, have found comparable oocyst removals over a range of seeding concentrations. McTigue *et al* (1998) conducted a series of pilot-scale experiments

with varying oocyst concentrations in the range of 10-10^3 oocysts per liter, resulting in consistent log removals of 4.2 to 4.3. Emelko *et al* (2001) compared oocyst removals by high seeding (10^6 oocyst /L) and mid-high seeding (10^4-10^5oocyst /L), which resulted in median removals of 4.5 log and 4.8 log, respectively. Douglas *et al* (2014) conducted pilot filter runs with high (10^6 oocysts/L), mid (10^3 oocysts/L), and low (10^0 oocysts/L) seeding concentrations in a pilot plant fed with Ottawa River water. The experiments with mid and high seeding concentrations resulted in very similar log oocyst reductions for two replicates, while low seeding experiments led to non-detects in the filter effluent and the exact log removals could not be reliably calculated. It should be noted that the high *Cryptosporidium* load seeded in raw water in the Ottawa experiments did not give rise to a measurable change in turbidity, and had little effect on particle concentrations (Douglas *et al*., 2014), which is contrary to the observations reported by Assavasilavasukul *et al* (2008b). Based on these findings, a universal relationship between seeding concentration and oocyst removals for all source waters has not been identified, and the effect on oocyst removals may be dependent on source water content.

Table 2.5 Experiments with varying influent oocyst seeding concentrations

Studies	Seeding concentration (oocysts/L)	Oocyst removals	
McTigue et al (1998)	26	4.2 log	
	688	4.2 log	
	4,610	4.3 log	
Emelko et al (2001)	104-105	4.8 log (median)	
	106	4.5 log (median)	
Douglas et al (2014)	106	5.52 log	4.64 log
	103	5.46 log	4.93 log
	100	N/A	N/A

By plotting seeding concentration in filter influent vs. removal data from all literature studies, the effect of influent *Cryptosporidium* concentration on removal results can be examined (Figure 2.10). The linear regression was plotted and R^2 is 0.2612. No clear relationship between removal through filtration and influent pathogen concentration is observed, except

to say that it is possible to actually measure higher oocyst removals at higher seeding concentrations.

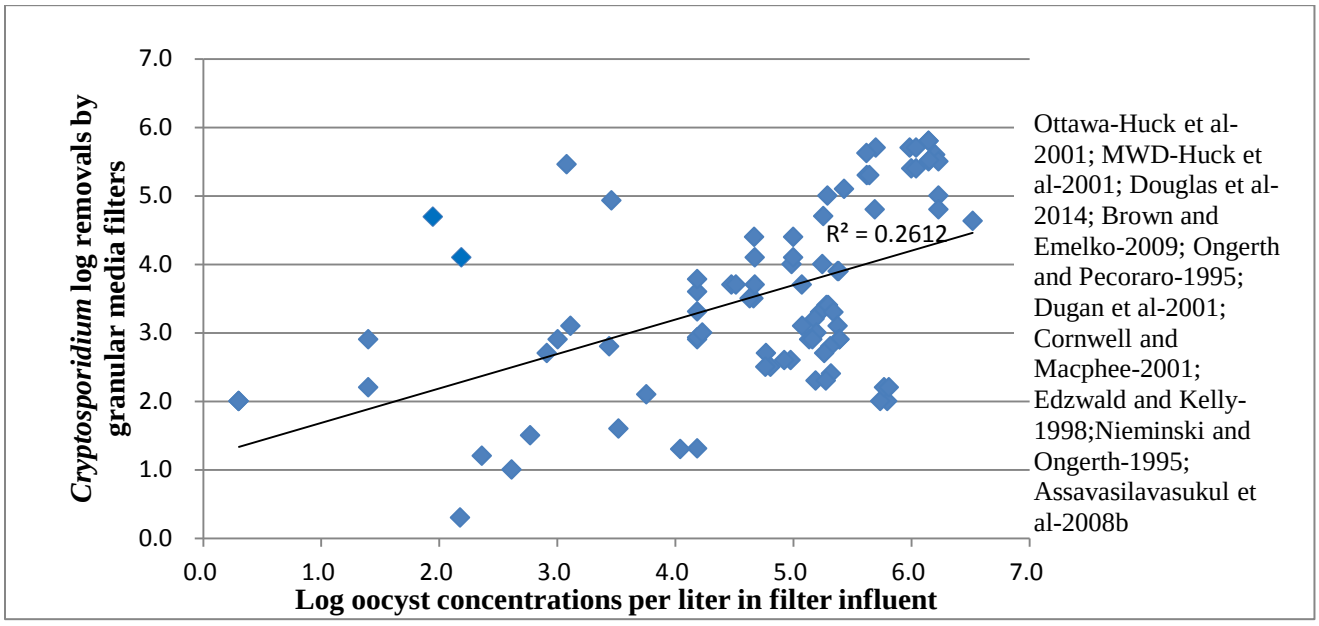


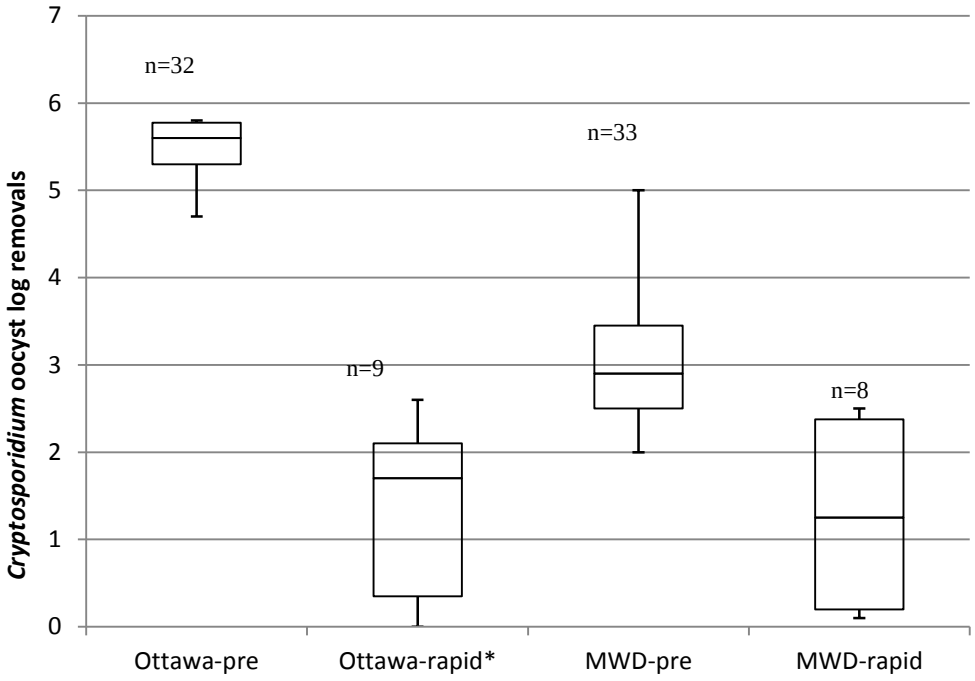
Figure 2.10 *Cryptosporidium* removals through filtration vs. influent oocyst concentration (data incorporating non-detects are excluded)

Seeding location

Studies have reported two common oocyst spiked locations: in the rapid mixer where oocysts were seeded directly, and in the filter influent where pre-coagulated oocysts were seeded. There is uncertainty about whether these two seeding protocols have an effect on oocyst removals by filtration. In a project for AWWA Research Foundation, Pilot-scale filtration experiments were conducted in Ottawa and at the Metropolitan Water District (MWD) of Southern California's La Verne Drinking Water Treatment Plant by seeding pre-coagulated oocysts into filter influent water during periods of stable operation. Limited trials were also conducted by seeding oocysts directly into a rapid mixer during stable operation (Huck *et al.*, 2001). In this study, the pre-coagulated protocol was chosen over seeding at the rapid mixer because there were losses of oocysts in preceding pipes and sedimentation tanks, leading to

lower levels in the filter influent which could result in non-detects in filter effluent, potentially leading to unreliable removal results. This seeding protocol was that described by Yates *et al* (1997), where oocysts were jar-coagulated first before being spiked into filter effluent. The authors suggested the coagulation and mixing conditions mimicked pilot-scale direct filtration processes quite well. A box-and-whisker plot (Figure 2.11) shows significantly lower oocyst reductions when seeding oocysts into the rapid mixer than when spiking pre-coagulated oocysts directly into filters. When comparing the log removal data, it should be noted that Ottawa trials with rapid mixer spiking resulted in non-detects in all filter effluent samples, which led to removals with uncertainty (only greater than [>] values could be reported which could substantially underestimate real removals). On the other hand, the MWD trials had countable oocysts in all filter effluent samples.

However, another study compared these two seeding scenarios for other surrogates including *E. coli* and microspheres, and observed comparable removals by filtration processes (Douglas *et al*., 2014). *Cryptosporidium* oocyst removals under these two seeding scenarios were not compared as it required spiking very high oocyst concentrations into raw water to be able to measure the oocyst concentration in the filter effluent and this was not possible in their study (Douglas *et al.*, 2014).



*: Non-detects were encountered in all filter effluent samples and the removals were reported as greater than the value.

Figure 2.11 Box-and-whisker plot for Ottawa and MWD with two seeding protocols (data adapted from Huck et al., 2001). Ottawa/MWD-pre refers to the experiments where pre-coagulated oocysts were seeded to filter influent; Ottawa/MWD-rapid refers to the experiments where oocysts were seeded at rapid mixer.

Cryptosporidium condition

Different oocyst pre-treatment and preparation methods may influence filtration performance for oocyst removal. Inactivated oocysts have commonly been used as surrogates for viable oocysts in pilot plants due to health concerns associated with spiking infectious oocysts. However, the processes to inactivate viable oocysts may alter the surface characteristics of oocysts, which are important during coagulation and filtration processes. Chemical or heat

treatment of oocysts has been reported to change oocyst surface charge, which play a role in coagulation and filtration (Lytle and Fox, 1994; Ongerth and Pecoraro, 1996); As well, heat or formalin pretreatment can alter the oocyst surface protein structure and affect the steric hindrance on the oocyst/sand interaction (Kuznar and Elimelech, 2005; Tufenkji *et al*., 2006). Macromolecules on the oocyst surface have been reported to produce additional electrosteric repulsion between oocysts and filter media, significantly affecting oocyst attachment (Kuznar and Elimelech, 2006). Few studies have compared the filtration behavior of inactivated oocysts with that of viable oocysts. Only one study could be found that compared removals of formalin-inactivated oocysts and viable oocysts by dual-media and tri-media filters during stable operation and coagulation failure (Emelko, 2003). This investigation demonstrated comparable removals for formalin-inactivated and viable oocysts. Williams and Dugan (2003) reported no statistically significant differences in removals by in-line filtration for oocysts of different age (2, 8 and 17 weeks of age) and preservation methods (phosphate buffered saline, potassium di-chromate, Ohio River preservation).

Detection limit

Due to limitations of past and current analytical methods, oocyst removals can only be accurately evaluated when a countable number of oocysts are present. Detection limits for filtered effluent have been reported from 0.25 oocyst/100 L to 200 oocysts/100 L (States *et al*., 1997; Gammie *et al*., 1998; Huck *et al*., 2001; Cornwell and MacPhee, 2001; Douglas *et al*., 2014). When no oocysts are detected in the filter effluent, the detection limit is used instead and the calculated removals are reported as more than the calculated value. As such, removal data prefixed with a “>” are associated with uncertainty.

Some spiked seeding studies and most full-scale studies encountered non-detects in filtered effluent (Appendices A and B). Full-scale studies with environmental oocysts (31-522 oocysts/100 L) in raw water have reported non-detects in filter effluent water and reported low oocyst removals ranging from 1.4 to 2.45 log (LeChevallier *et al*., 1991; LeChevallier

and Norton, 1992; Kelly *et al*., 1995; States *et al*., 1997), compared to a nearly 3 log or higher removal in pilot experiments seeding high concentrations of oocysts (Dugan *et al*., 2001; Huck *et al*., 2001). Though these full-scale studies with environmental oocysts, to a large extent, represent what happens in real world situations, the low concentration in raw water and high proportion of non-detects in filter effluent limit the determination of the true removals which could reasonably be expected if higher numbers of oocysts were encountered. Increasing the sample volume for filtered water or increasing influent oocyst concentrations by spiking oocysts is expected to increase the accuracy of removal results and lead to higher values approaching what pilot-scale experiments typically achieve. However, utilities are understandingly not willing to spiked oocysts at full-scale given the potential/perceived health and regulatory outcomes (even if the oocysts are inactivated). Few full-scale studies have had sufficiently high oocyst concentrations in raw water and detectable countable oocysts in filtered water to produce removal data that do not contain removals reported as '>'. Nieminski and Ongerth (1995) seeded 10^7 oocysts to an out-of-service full-scale plant filter, resulting in 1.89-2.88 log removals. In 1997, two full-scale water plants in Edmonton experienced spring runoff, with oocyst concentrations up to 10,300 oocysts/100 L measured in raw water (Gammie *et al*., 1998). With oocysts detected in filtered water, the log removals in these two plants were 3.0 log and 3.1 log, respectively, which was similar to results from pilot seeding experiments reported in the literature.

Results adjusted for recovery efficiency

Only a proportion of oocysts can be detected due to significant losses of oocysts during detection and interference of suspended solids or algae (Health Canada, 2012a). The concept of recovery efficiency is introduced to account for these losses and to better describe the actual oocyst concentration from measured oocyst values (Health Canada, 2012a). Recovery efficiency can vary from study to study, and it also varies within one study throughout treatment processes (i.e. raw water, settled water, filtered water). Very few studies have adjusted oocyst removal estimates by applying recovery efficiencies. Therefore, assessment

of removal results from different studies should be interpreted with some caution. Efficiencies of the detection methods used should be accounted for as efficiencies have improved remarkably in the past couple of decades. Some studies reported similar recovery efficiencies for influent water and filtered effluent, claiming the log removals were calculated without consideration of recovery efficiency and those adjusted by recovery efficiency are quite close (Assavasilavasukul *et al*., 2008b; Dugan *et al*., 2001; Huck *et al*., 2001). However, if there is a significant discrepancy between influent and effluent recovery efficiency, log removal estimated without incorporating recoveries may be inaccurate.

2.4 Conclusions

In water treatment plants not employing membrane technologies and innovative disinfection methods (e.g. UV), *Cryptosporidium* oocyst removal relies primarily on physicochemical removal processes (coagulation/flocculation/clarification/rapid granular filtration processes) as the major treatment barriers. Published full- and pilot-scale studies have demonstrated a wide range in *Cryptosporidium* oocyst removals averaging from 1.4 log to 5.8 log through filtration (with or without the effect of pre-treatment), with the reasons behind the variability still not well understood. The peak of reported filtration studies on *Cryptosporidium* removal occurred between the period of 2000 to 2004, and a decreasing trend in number of publications was observed after that time, suggesting most filtration studies were conducted at least a decade ago.

To investigate whether the process and experimental differences among studies contribute to the substantial variability in removal results, a critical review was conducted to examine the effect of potentially influencing factors individually by reviewing findings from published studies or by relating oocyst removal data from all literature to that factor.

Non-detects in filter effluent (treated) water may be at least partly responsible for the lower than expected oocyst reductions reported in full-scale studies. With oocysts detected in filtered water, log removals in full-scale plants were 2.38, 2.5, 3.0, and 3.1, which approach

results obtained from many spiked seeding experiments. The majority of spiked seeding studies have demonstrated more than 3 log oocyst removal through granular media filters (median values). It can therefore be concluded that the majority of well operated filtration plants can achieve 3 log oocyst removals, although it may still be possible that some plants cannot.

The literature review suggests that filter effluent turbidity cannot serve as a quantitative indicator but low effluent turbidity generally corresponds to better oocyst removals. No systematic effect of temperature, coagulation type, coagulant pH, filter media, and hydraulic loading rate on oocyst removals has been reported. Studies have not demonstrated consistent findings as to the effect of seeding concentration. Limited research has been conducted to assess the effect of *Cryptosporidium* oocyst condition and spiked location. With the one or two studies available, spiked location may have some influence, while *Cryptosporidium* condition (i.e. oocyst inactivation, oocyst age) has not been found to influence oocyst removal results. The handling of non-detects and recovery efficiency may influence the accuracy of reported removal data and should be accounted for when reviewing past and future studies.

Limitations exist in the above analysis as the effect of each factor is assessed individually, however, it is possible that the oocyst removals may be influenced by the combined effect of two or more factors (i.e. hydraulic loading rate and coagulant type, filter media and coagulation pH, etc.), and there is as yet insufficient data in existing studies to assess the effect of confounding factors. Unfortunately, research in this area has almost been discontinued with only a few studies having been published in the past 5 years (Figure 2.1). Other variables among published studies such as total organic carbon, mixing conditions, use of coagulant and/or filter aids, and choice of detection methods also potentially contribute to the wide ranges of reported removals, however, previous studies have not conducted experiments designed to assess these factors.

Chapter 3
Developing a Questionnaire for Acquiring Industry Knowledge in Assessing Factors Influencing *Cryptosporidium* Removal by Filtration

3.1 Summary

Published filtration studies to-date have reported a substantial variation in oocyst log removals, and the reasons behind these wide variations are not readily apparent. Information from published studies was evaluated in an attempt to better understand the effect of some potentially influential factors (Chapter 2). As an outcome of this review, it was felt that opinions from drinking water professionals on the factors which may have an impact on reported *Cryptosporidium* removals by granular media filters would enhance research into this important topic.

A framework was designed to access industry knowledge and insights that might not have been reflected in published papers. A structured list of potentially influencing factors was identified and suggested options/alternatives for each factor were proposed. A questionnaire was developed to seek professionals' opinions on the relevance of each factor in influencing *Cryptosporidium* removals. In total, 135 drinking water professionals in two major categories were identified, including those who had direct research experience in *Cryptosporidium* and/or surrogate removal through filtration processes, as well as those who have served as a regulator, designer, operator, or manager for drinking water treatment processes.

A trial run was conducted to seek feedback from seven drinking water professionals on a draft version of the questionnaire. There was a general consensus that it was too complicated for those without a research background and it took longer than anticipated to complete it. Based on the feedback and recommendations, major revisions were made including the removal of a request to assign relative weight to suggested levels/options, adding opportunities for respondents to self-rate their knowledge level, and providing the basis for each of their responses. The objective of the questionnaire was not to predict removal or replace the need for pilot-scale studies. It was to provide useful information to water industrial professionals on factors that most influence filter performance in the context of *Cryptosporidium* oocyst removal.

3.2 Establishment of the Framework

A simple tick box type questionnaire was designed to collect insight and opinions on the relevance of each factor in influencing *Cryptosporidium* removals.

The initially proposed questionnaire framework included two questionnaires. The aim of the first questionnaire was to seek expert opinion on refining the factor list and developing applicable levels/options used to assess the effect of each factor. It was intended that the second questionnaire investigate comparisons between groups and factors, as well as ask for suggested weights to assign to levels/options for each factor. The expected outcome was a structured weighted list that could help indicate the influence of combinations of factors of selected levels on *Cryptosporidium* removals by filtration.

Feedback from the trial run led to several major revisions which included simplifying the original strategy to conduct only one questionnaire, and not to include a component comparing the influence of applicable levels/options. The test run results and revisions are discussed more fully in Section 3.4.

3.2.1 Identification of List of Structured Factors

The first step was to identify a list of factors potentially influencing *Cryptosporidium* removal results. In reviewing literature studies, it was found that studies varied with respect to water source, filter design and operational configurations (e.g. filter media type, coagulant type, hydraulic loading rate), and analytical methods and experimental configurations (i.e. detection limit, type of oocyst inactivation for spiking studies, seeding protocol, etc.). Previous investigators have attributed the wide range in reported oocyst removals to variables in raw water quality, treatment differences, influent microorganism concentrations, microorganism type (environmental vs. pre-cultured), temperature, process set-up and operation, analytical reliability, processed sample volumes, and detection limits (Huck *et al*., 2002; Assavasilavasukul *et al*., 2008; Hijnen and Medema, 2010).

This study incorporates the previously identified variables and some additional variables among published filtration studies which were identified as potentially influencing factors as a result of an up-to-date critical review. Overall, thirty potential influencing factors were proposed and categorized into six groups, including raw water quality, coagulation conditions, filter design, filter operation, experimental differences, and analytical differences (Table 3.1).

Table 3.1 List of proposed influencing factors

Category	Groups of factors	Examples of factors
Process factors	Raw water quality	oocyst concentration, total organic carbon, temperature, influent water turbidity
	Coagulation conditions	coagulant type, mixing conditions/energy, coagulation pH, coagulant aid
	Filter design	type of filtration, filter media type, L/d ratio, filtration mode, hydraulic loading rate, total media depth
	Filter operation	filter effluent turbidity, backwash scheme,

		recycling of backwash water, percent bed expansion, backwash trigger, filter ripening practices, filter aids
Experimental factors	Experimental differences	oocyst spiked concentration, seeding location, oocyst condition, *Cryptosporidium* species
	Analytical differences	detection methods, recovery efficiency, detection limit, influent vs. effluent recovery efficiency, occurrence and handling of non-detects

3.2.2 Proposed Levels/options for Identified Factors

Three suggested levels/options were typically proposed for each factor to assess its influence on *Cryptosporidium* removal when changing from one level/option to another. For factors that can be numerically described such as influent water turbidity, temperature, coagulation pH, levels with ranges were proposed. On the other hand, for factors that were not associated with values, such as coagulant type, filter media type, and coagulant aid, choices of options were used instead. For example, backwash scheme included the use of water alone, air scour, and collapse pulsing. Tables 3.2-3.7 list the proposed levels/options for all thirty factors in the six groups.

In the first questionnaire, the proposed levels/options were listed for respondents to indicate whether the ranges of levels or choices of options were applicable to assess the effect of identified factors.

Table 3.2 Suggested levels/options for 'raw water quality' factors

Raw Water Quality	Suggested Levels/Options
Oocyst concentration	Low (1-10 oocysts/100L)
	Medium (10-100 oocysts/100L)
	High (>100 oocysts/100L)
Influent water turbidity	Low (<5 NTU)
	Medium (5-50 NTU)

	High (>50 NTU)
Total organic carbon (TOC)	Low (<2 mg/L)
	Medium (2-5 mg/L)
	High (>5 mg/L)
Temperature	Low (<4℃)
	Medium (4-15℃)
	High (>15℃)

Table 3.3 Suggested levels/options for 'coagulation conditions' factors

Coagulation Conditions	Suggested Levels/Options
Coagulant type	Polyaluminum chloride (PACl)
	Alum
	Ferric compounds
	Other
Mixing conditions (hydraulic detention time× velocity gradient-G×t)	No levels suggested at this point in time
Coagulation pH	pH<6.5
	6.5<pH<8
	pH>8
Coagulant aid	No coagulant aid
	Activated silica
	Cationic silica

Table 3.4 Suggested levels/options for 'filter design' factors

Filter Design	Suggested Levels/Options
Type of filtration	Conventional filtration (preceded by sedimentation)
	Conventional filtration (preceded by dissolved air flotation)
	Direct filtration (including flocculation)
	Inline filtration
Filter media type	Mono-media filter (sand)
	Mono-media filter (anthracite)
	Mono-media filter (GAC)
	Dual-media filter (anthracite/sand)
	Dual-media filter (GAC/sand)
	Tri-media filter (anthracite/sand/garnet)
Total filter media depth	<75 cm
	75-125 cm
	>125 cm

L/d ratio (depth of a granular media filter bed over media effective size)	<1000
	1000-1200
of the filter media)	>1200
Hydraulic loading rate	< 5 m/h (2 US gpm/ft^2)
	5-10 m/h (2-4 US gpm/ft^2)
	>10 m/h (4 US gpm/ft^2)
Filtration mode	Constant rate
	Declining rate

Table 3.5 Suggested levels/options for 'filter operation' factors

Filter Operation	Suggested Levels/Options
Filter effluent turbidity (at least 95% measurement)	<0.05 NTU
	<0.1 NTU
	<0.3 NTU
	<1 NTU
	>1 NTU
Backwash scheme	Water
	Air Scour
	Collapse pulsing (air and water flow simultaneously and/or concurrently)
Recycling of backwash water	No recycling of filter backwash water
	Recycling of untreated backwash water to plant influent water
Percent bed expansion (after backwash)	<15%
	15-30%
	>30%
Backwash trigger	Time
	Turbidity

	Headloss
Management of filter ripening	No filter-to-waste
	Filter-to-waste
	Extended Terminal Subfluidization Wash (ETSW)
Filter aid	No filter aid
	Iron or ferric salts
	Anionic polymer
	Cationic polymer
	Nonionic polymer

Table 3.6 Suggested levels/options for 'experimental differences' factors

Experimental Differences	Suggested Levels/Options
Oocyst spiked concentration	10-10^2oocysts/L and lower
	10^2-10^4 oocysts/L
	10^4-10^6 oocysts/L and higher
Seeding location	Rapid mix
	Filter influent water (pre-coagulated oocysts)
	Filter influent water (oocysts not pre-coagulated)
Oocysts conditions	Viable (with appropriate precautions to avoid contamination of potable water)
	Formalin-inactivated
	Heat-inactivated
***Cryptosporidium* species**	*Cryptosporidium hominis*
	Cryptosporidium parvum

Table 3.7 Suggested levels/options for 'analytical differences' factors

Analytical Differences	Suggested Levels/Options
Detection methods	Immunofluorescence assay (IFA)
	Flow cytometry
	Molecular methods
Recovery efficiency	<40%
	40%-60%
	>60%
Recovery efficiency of influent vs. filter effluent water	Equal
	Influent recovery> filter effluent recovery
	Influent recovery< filter effluent recovery
Detection limit	10^{-3} oocysts/L and lower
	10^{-3}-1 oocysts/L

	>1 oocyst/L
Occurrence and handling of non-detects	No non-detects
	Non-detects treated as detection limit
	Non-detects treated as 1/2 of detection limit

3.2.3 Questionnaire Development

Questionnaire#1 entitled "Expert Assessment of List of Potential Factors Influencing *Cryptosporidium* Removal by Rapid Granular Filtration" (Appendix B) was the test version of questionnaire, and included a brief background on *Cryptosporidium* removal by granular media filtration, objective of the questionnaire, and tick box type questions for respondents to answer. The questionnaire was developed in the form of a fillable Adobe Acrobat® where answers can be entered and saved. Two cover letters were designed for drinking water professionals, one for those with research experience and another for those with experience in full-scale treatment facilities (Appendix B).

Respondents were asked to indicate the relevance of each factor influencing *Cryptosporidium* removal results by clicking one of the buttons below the "thumbs up" and "thumbs down", which corresponded to five response choices of no influence, very mild influence, mild influence, moderate influence, and strong influence. The comment section was provided but not required for opinions on the applicability of suggested levels/options. Figure 3.1 is an example for the assessment of oocyst concentration in influencing *Cryptosporidium* removals. The respondent indicated that oocyst concentration in raw water mildly influenced *Cryptosporidium* removal by filtration, and the suggested levels/options were applicable for assessing its influence.

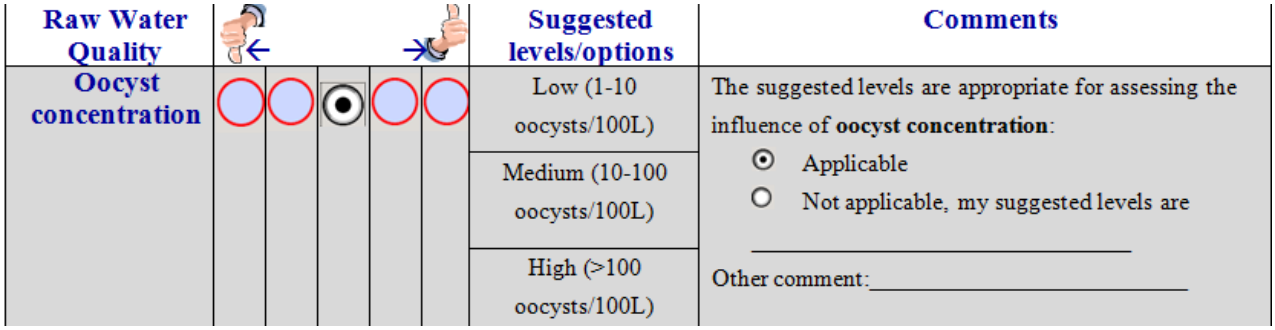


Figure 3.1 Example of question seeking opinions on the relevance of a particular influence (test version)

3.3 Recruitment of Professionals to Complete Questionnaire

Documenting industry knowledge from drinking water professionals on the factors which may have an impact on reported *Cryptosporidium* removals by granular media filters would enhance research into this important topic. However, given that the number of *Cryptosporidium* studies is not large and most experiments were conducted at least ten years ago, it can be expected that first-hand knowledge and experience with factors affecting *Cryptosporidium* removals is being lost over time. As well, the professionals who have had substantial involvement in *Cryptosporidium* removal are not large in number. Only drinking water professionals who were considered to, or be expected to, possess sufficient knowledge and experience on this topic were identified and contacted. In this study, two categories of professionals were identified: the first category is drinking water professionals who have had direct involvement in *Cryptosporidium* and/or surrogate removal experiments and/or have conducted review studies of *Cryptosporidium* removals; the second category are drinking water professionals who have been directly involved in regulation, design, operation, or management of drinking water treatment processes. Table 3.8 is a brief summary of the composition of professionals identified for the questionnaire.

Table 3.8 Drinking water professionals identified

	Number
All professionals	135
Professionals with research experience	56
Professionals involved in full-scale treatment facilities	79
Professionals with unconfirmed contact information	25

3.3.1 Drinking Water Professionals with Research Experience

The first category of drinking water researchers were identified as those who have conducted research investigating *Cryptosporidium* and/or surrogate removals through filtration. The experience and insights they have gained and may not necessarily be completely reflected in published reports or papers could shed light upon factors that might be important for *Cryptosporidium* removal. A list of researchers was developed by identifying corresponding authors of published papers and identifying faculty members involved in *Cryptosporidium* research at universities worldwide. It was recognized that some of researchers may have retired or moved to other institutions over the past years, and therefore some of their contact information may be unconfirmed and outdated. Overall, fifty-six researchers in this area were identified, with most of them from North America and a few from Europe and Asia.

3.3.2 Drinking Water Professionals with Real-life Experience

The second category of drinking water professionals were those who have been directly involved in the design, operation, management, or regulation of full-scale drinking water treatment facilities, such as full-scale plant manager, public health professional, regulator, and filter manufacturer. Although they may not have been involved in investigations specifically targeting *Cryptosporidium* or surrogate removal, their experience and knowledge with drinking water treatment processes and conditions under which they are challenged have provided them with valuable insights as to factors that might be important for such removals. In total, seventy-nine professionals were identified as operators, designers, managers, or regulators of full-scale drinking water plants. These professionals were largely from municipalities, consulting companies, and regulatory organizations in North America.

3.4 Trial Run

3.4.1 Benefits of Trial Run

A trial run, which is also referred to pilot testing, is an integral component of a survey project. Pilot testing includes an assessment of all elements of the questionnaire and the cover letter by a small group of professionals (Susan, 2004). All elements and steps of the survey project can be tested. For example the:

a. Cover letter: Does the cover letter motivate participation?
b. Questionnaire:
    - Do the expected results from the questionnaires collect the information needed and meet the objective of the study?
    - Are the questions clearly understood by the respondents in the same way as it is designed?
    - Is the questionnaire format user-friendly?
    - Are the response choices/scales relevant and should more/less options be added?

It is not possible to envision all potential misinterpretations or bias associated with the questions and format of a questionnaire. Conducting pilot testing helps to mitigate such issues, correct undetectable errors, and maximize the response rate.

3.4.2 Selecting Participants for Trial Run

Two types of professionals in the pilot test are typically required: those who are representative of the population to be surveyed and those with experience in survey or data analysis (Susan, 2004). The seven participants selected for the trial run for this research met the above requirement. Participants included two professionals who have been directly involved in both *Cryptosporidium* research and operation/management of treatment plants,

and five university drinking water researchers with one of them having conducted a survey project before.

Participants were provided with a mock cover letter and questionnaire. They were asked to complete the questionnaire the same way as it would be completed in the actual survey. In addition to completing the questionnaire questions, they were also asked to provide feedback regarding the structure, content, intent, or any part of the questionnaire that was not clearly understood.

3.4.3 Feedback and Results from Trial Run

Four out of the seven participants completed the questionnaires, one finished half the questions, and two participants did not answer all questions in the questionnaire. All of them provided detailed feedback on the cover letter and the questionnaire itself. Aside from suggestions for minor revisions and wording changes, the major remarks are summarized as follows.

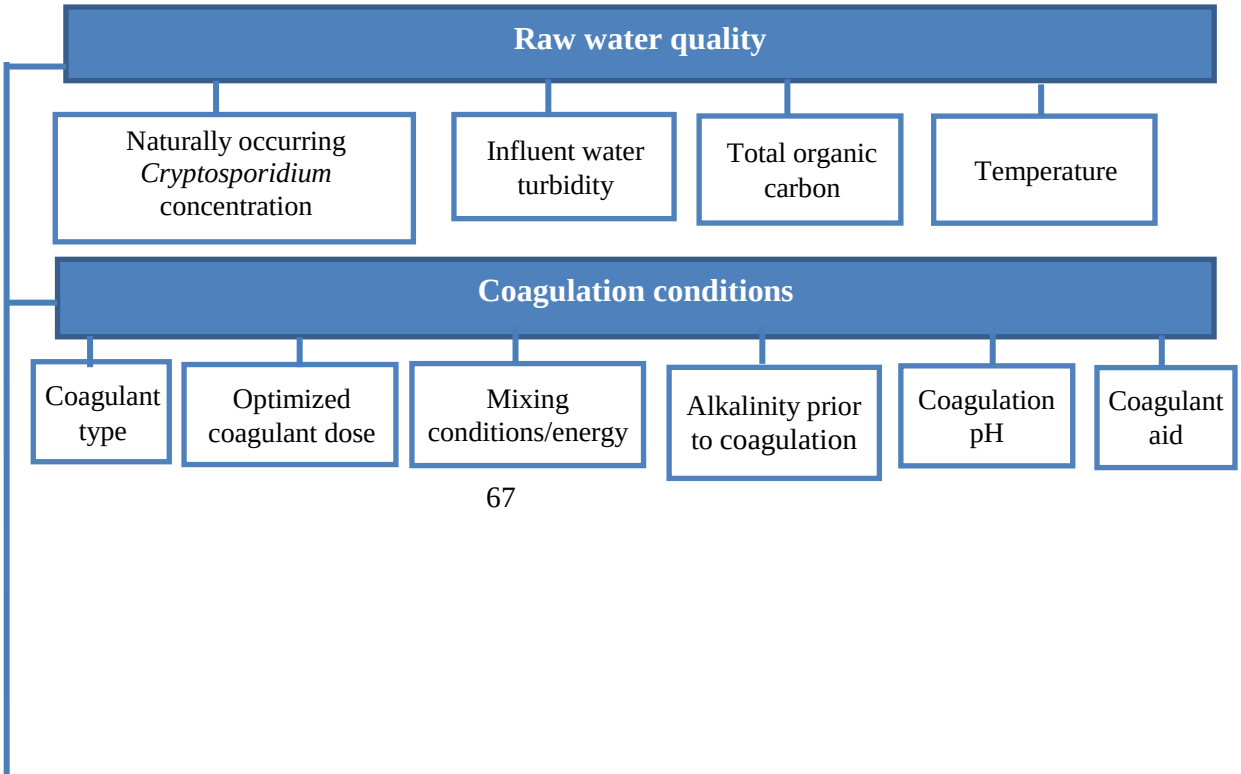
- The questionnaire might be too complicated for those involved in plant operation/management, and especially for public health professionals and regulators who typically do not work in the field.
- The concept of conducting two sets of questionnaires does not motivate respondents and may intimidate participants, leading to low response rates.
- Asking all professionals to compare the relative importance of groups and factors in influencing oocyst removals and to assign weights to suggested levels/options is not feasible. Even researchers with the most research experience on this topic found it difficult and unsure how to answer to such questions.
- The number of response choices for rating the relevance of a factor in influencing oocyst removals should be reduced.
- What if the respondent does not feel comfortable or does not possess sufficient knowledge to answer a particular question? Ensure that the questionnaire does not

force participants to guess.

- It might be useful to survey respondents' self-rated knowledge level and previous research experience on *Cryptosporidium* removal.
- It is useful to let respondents qualify their answers by asking them to indicate from which perspective/experience their response is based on. It is also useful to differentiate responses, such as those based on general engineering knowledge from responses based on past research experience for subsequent data analysis.
- Factors such as coagulant dose, chlorinated backwash water, and alkalinity should be considered for addition to the structured list of factors for assessment.

3.4.4 Revision and Final Version

Based on the feedback gathered, major revisions were made to conduct only one questionnaire, and exclude the option to compare the influence of suggested levels/options. Questions were added at the beginning of the questionnaire for respondent to self-rate their knowledge level and direct research involvement with *Cryptosporidium* removal by filtration. Additional factors including optimized coagulant dose, alkalinity prior to coagulation, and the presence of chlorinated backwash water were added to the original structured list of potential influencing factors, resulting in a total of thirty-three factors for assessment. Figure 3.2 presents the final version of structured list of potential influencing factor.



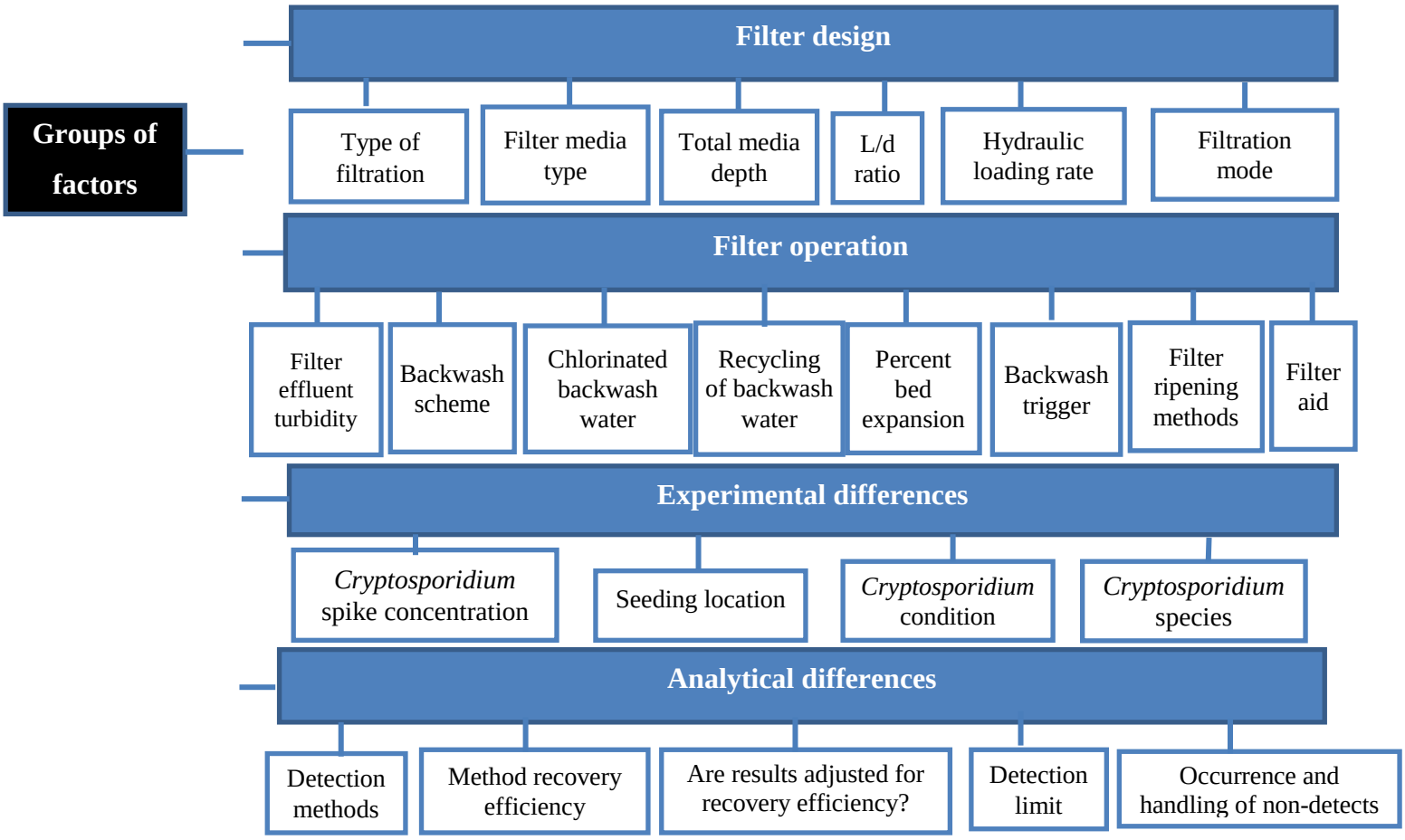


Figure 3.2 List of potential factors influencing reported Cryptosporidium removal by granular media filtration (final version)

Figure 3.3 is an example of the questions after revision. Response choices for relevance of influence were reduced from five to three options being no influence, some influence, and strong influence, while an option of “do not know” was added. An option requesting the basis for each response was added (past research experience, operational perspective/experience, and general engineering knowledge). An open-ended comment section was provided.

Raw Water Quality	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments
Naturally occurring *Cryptosporidium* concentration	○	○	○	○	I rate the relevance of **naturally occurred *Cryptosporidium* concentration** in influencing *Cryptosporidium* removals based on my: ○ Past research experience ○ Operational perspective/experience ○ General engineering judgement ○ Other_____	_____ _____ _____

Figure 3.3 Example of questionnaire questions seeking opinions on relevance of influence (final version)

After completing the trial run and making necessary revisions to all elements of the questionnaire and cover letter, the final version of questionnaire was ready for distribution. The ready-to-distribute version of the questionnaire entitled 'Questionnaire-Drinking Water Professionals Assessment of List of Potential Factors Influencing *Cryptosporidium* Removal by Rapid Granular Filtration' is provided in Appendix B.

3.5 Conclusions

This chapter described the development of a framework documenting industry knowledge on factors that might have an influence on *Cryptosporidium* oocyst removals reported through granular media filters. The steps included proposing a structured potentially influencing list of factors and suggesting applicable levels/options, followed by the design of multiple-choice questions and open-ended questions to seek professional insight and opinion. Potential

participants were identified and categorized into two groups. A trial run was conducted by surveying seven drinking water professionals with sufficient knowledge on this topic and with experience on questionnaire development. Based on the feedback, several revisions were made to maximize response rate, correct undetectable errors, and most importantly, to make sure the questionnaire enabled the acquisition of data needed for this research.

The most important limitations of such a questionnaire relate to attracting respondents who are predisposed to respond and have time to participate. It is also important to acknowledge that respondents' opinions can be subjective and varied; however, it is a useful tool to harvest industry knowledge on specific issues, especially those that have not been well documented in print. The collective viewpoint provided valuable insights and thoughts from professionals who have been substantially involved in the drinking water industry. Experience grained from developing this questionnaire leads to the following recommendations: (1) initiate pilot testing of the developed questionnaire at the earliest stage possible to avoid substantial revisions; and (2) involve professionals with both knowledge on questionnaire development and sufficient background on the topic to identify an objective which is reasonably achievable prior to conducting a survey project.

Chapter 4
Harvesting Industry Knowledge to Assess Factors Influencing *Cryptosporidium* Removal by Filtration

4.1 Summary

A confidential questionnaire was distributed to 135 drinking water professionals to collect their opinions on factors which may have an impact on reported *Cryptosporidium* oocyst removals by granular media filters. In total, 39 drinking water professionals completed the assessment survey corresponding to a response rate of 35%. More than 70% of respondents had direct involvement in research on *Cryptosporidium* and/or surrogate removal through filtration. Consensus was reached on the most influential being optimized coagulant dose (95% of respondents rated it as being a strong influence) and filter effluent turbidity (81% rated it as a strong influence), while the least influential were *Cryptosporidium* species and chlorinated backwash water (0% rated them as being strongly influential). A weighting system was proposed to evaluate the overall influence of an identified factor on *Cryptosporidium* removal through filtration, based on response data and the knowledge basis for a response given by participants. A sensitivity analysis was conducted to evaluate the robustness of the weighting system. Based on all questionnaire responses, the weighting system ranked the importance of optimized coagulant dose, filter effluent turbidity, *Cryptosporidium* oocyst detection limit, *Cryptosporidium* recovery adjustment, and *Cryptosporidium* spiked concentration as the most influential factors. The questionnaire results were compared with literature findings, demonstrating consistency in most findings.

4.2 Distribution of Questionnaires

The questionnaires and cover letters were distributed to 135 drinking water professionals who were considered to, or be expected to, possess sufficient knowledge and experience on the topic. Participants were provided with two weeks to complete the questionnaire.

Table 4.1 summarizes questionnaire distribution of recipients and the response rate. 21 drinking water professionals responded that they did not possess sufficient knowledge or experience on this topic and therefore chose not to answer the questionnaire. In total, 39 drinking water professionals filled and returned the questionnaires. Of those, 17 of respondents were from the first category (i.e. professionals with research experience), and 22 were from the second category (i.e. professionals involved in full-scale treatment facilities). The response rate was 35% excluding the professionals with unconfirmed contact information. One returned questionnaire was excluded due to lack of sufficient responses to be meaningful in an overall context.

Table 4.1 Summary of questionnaire responses

	Number or percentage
Questionnaires sent	135
Professionals with research experience	56
Professionals involved in full-scale treatment facilities	79
Professionals with unconfirmed contact information (e-mails returned, invalid address)	25
Professionals who have not been directly involved in Cryptosporidium research	21
Questionnaires completed	39
Response rate	35%

4.3 Background Survey of Respondents

Participation in this survey was voluntary and respondent's identities and affiliations are not identified. A background survey at the beginning of the questionnaire asked the respondent to

provide a self-assessment of their knowledge on *Cryptosporidium* removal, involvement in *Cryptosporidium* research, and their affiliation category (Figures 4.1 to 4.3). Based on background survey results, the majority of respondents felt that they possessed sufficient knowledge and experience on this topic and they were ultimately able to provide valuable input.

About half (49%) of respondents self-rated their knowledge level on *Cryptosporidium* removal in the context of drinking water treatment as extensive and 48% rated their knowledge level as moderate (Figure 4.1). Only 3% of respondents indicated that they had minimal knowledge.

Respondents described their involvement in *Cryptosporidium* research with 71% having been or currently being involved in *Cryptosporidium* research in some capacity while 29% had no direct involvement (Figure 4.2). There was a group of respondents who have conducted research not only on *Cryptosporidium* but also on surrogate removal, in addition to having authored literature reviews (26% of all respondents). These individuals would be expected to able to provide high quality input.

The respondents' affiliation categories are shown in Figure 4.3. Half were researchers (or combined with another affiliation). 16% of respondents were water consultants and regulators each accounted for 16% of respondents (total of 32% combined). About 10% indicated that they were full-scale drinking water treatment plant operators and/or managers. Other affiliation categories included process engineer, educator, and water quality technologist.

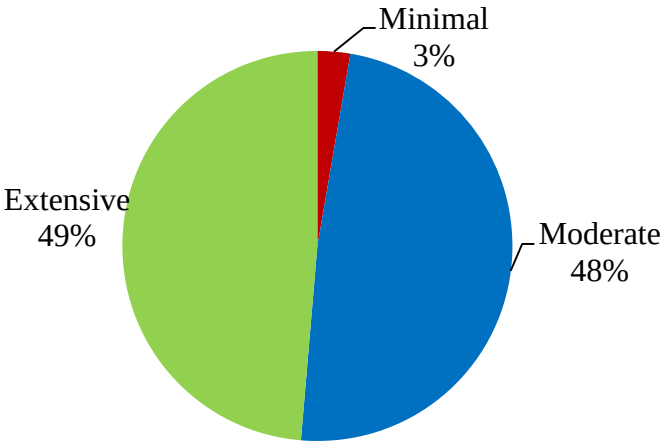


Figure 4.1 Respondent's self-assessment of knowledge on *Cryptosporidium* removal by rapid granular filtration

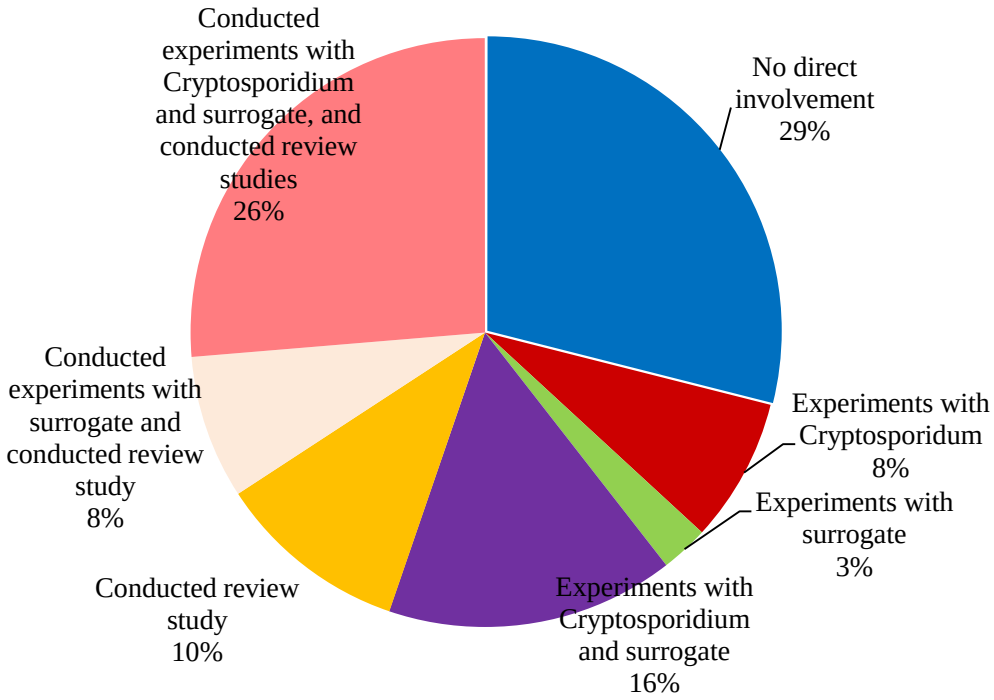


Figure 4.2 Involvement of respondents in research on *Cryptosporidium* and/or surrogate removal by filtration

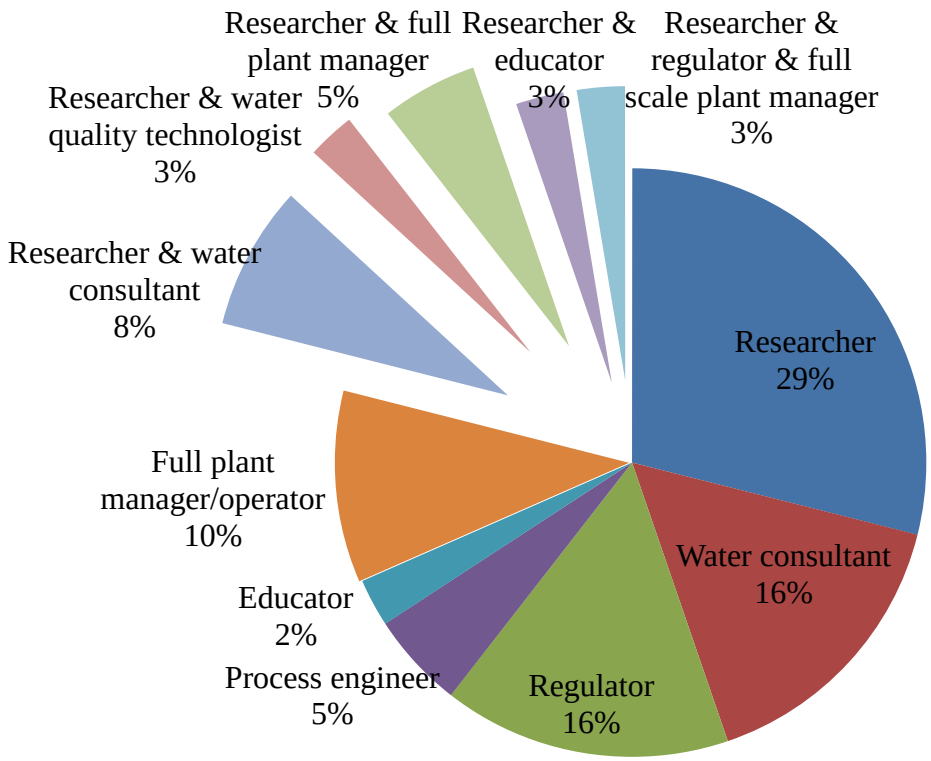


Figure 4.3 Affiliation of respondents

4.4 Questionnaire Results

Respondents were asked to indicate the relevance of each identified factor in influencing *Cryptosporidium* removal results from three choices including 'no influence', 'some influence', and 'strong influence', or they could click on an option to convey that they did not know. They were also asked to provide the knowledge basis upon which they were providing their answer. A comment section was provided but not required. Responses from questionnaires therefore included three components: relevance of influence; basis for

response; and open-ended comments. All responses were entered and analyzed in Microsoft Excel® 2010. The following section presents the distribution of responses in the form of bar charts. Distribution of responses attributed to each of the three knowledge bases is also shown. The distribution of responses from professionals with direct involvement in *Cryptosporidium* research only is broken out. Respondents' opinions and remarks are categorized and summarized in Appendix C.

4.4.1 Overview of Responses

Replies referring to the relevance of identified factors in influencing reported oocyst removals without differentiating between the backgrounds of the respondents are presented in Figure 4.4. The blue, red, and green bars represent percentage of responses indicating the influence of identified factor on oocyst removal results as 'strong influence', 'some influence', and 'no influence', respectively. The purple bars represent the percentage of 'do not knows'. At a first glance, professionals' opinions on the influence of different factors vary considerably, as the length of bars of different colors changes apparently from one identified factor to another. The "no influence" (green bars) accounted for the smallest proportion of all responses. The influence of the nine factors on the right side of the figure (experimental and analytical differences) was less frequently answered and responses rating their influence on oocyst removal are few in number.

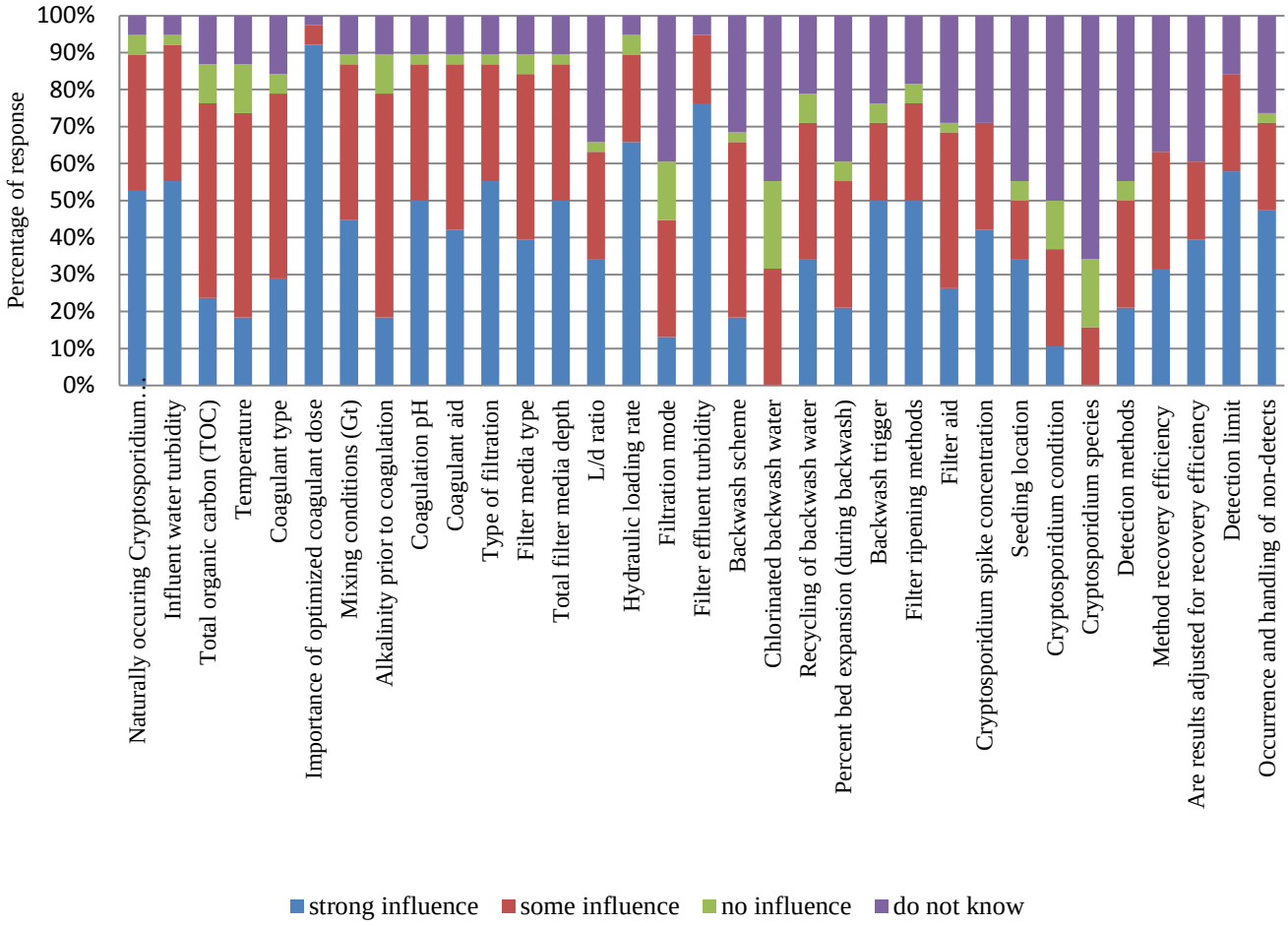


Figure 4.4 Opinions on the relevance of identified factors as they pertain to *Cryptosporidium* removal, from all knowledge bases/backgrounds (including 'do not know' responses)

Figure 4.5 represents the percentage of 'do not know' responses in descending order ranging from 66% to 3%. The five factors with the highest 'do not know' percentages are *Cryptosporidium* species, *Cryptosporidium* condition, chlorinated backwash water, seeding location, and detection methods, where more than 40% of respondents indicated that they were not sure or did not know what the effect of these factors would be based on their background. By comparison, the majority of respondents indicated they possessed sufficient

knowledge to assess the influence of factors such as optimized coagulant dose, filter effluent turbidity, hydraulic loading rate, influent water turbidity, and naturally occurring *Cryptosporidium* concentrations where between 95% and 99% of respondents felt competent to provide an opinion.

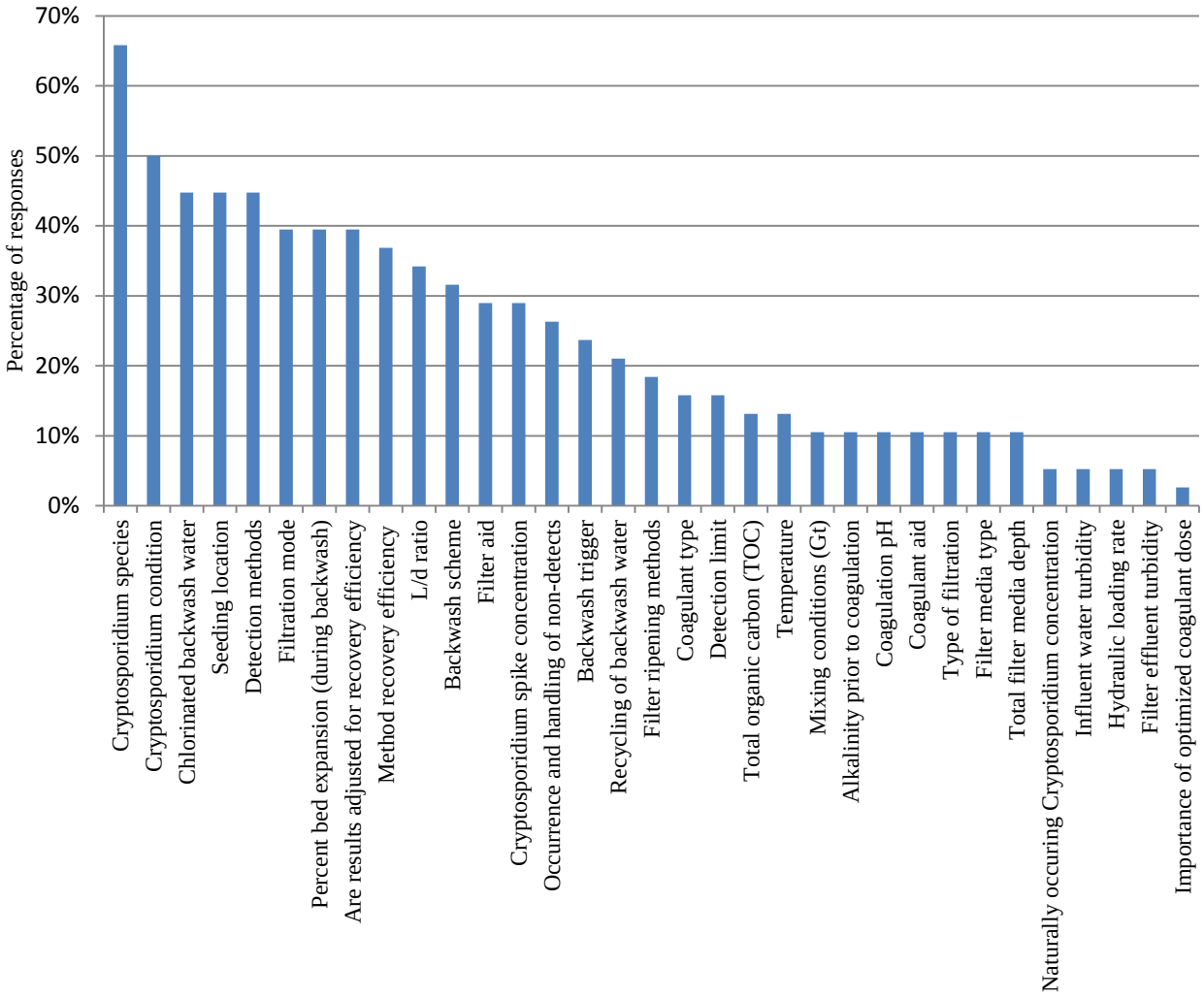


Figure 4.5 Percentage of 'do not know' responses pertaining to the effect of a given factor on *Cryptosporidium* removal data by filtration

The higher the percentage of ‘do not know’ answers, the lower number of responses assessing the influence of the given factor on removal results. These responses of ‘strong influence’, ‘some influence’, and ‘no influence’ are used in the following discussion and applied in the weighting system to identify the most influential and least influential factors. The influence for factors with higher percentage of ‘do not know’ are analyzed by using fewer responses and therefore the findings related to such factors are based on smaller database than findings for factors for which the majority of respondents were able to rate. In Table 4.2, the 33 potentially influencing factors are categorized into three groups based on their percentages of ‘do not know’ answers: factors with greater than 40% ‘do not know’ answers are in the high designation group; factors for which 20% to 40% of respondents do not know their effect fall into the medium designation group; and factors with less than 20% ‘do not know’ answers are defined as low designation group. It can be seen that experimental and analytical factors for the most part fall in the medium and high groups.

Table 4.2 Groups of factors based on percentage of 'do not know' answers

Percentage of ‘do not know’	Designation group	Factors
>40%	High	*Cryptosporidium* species; *Cryptosporidium* condition; Chlorinated backwash water; seeding location; detection methods
20%-40%	Medium	filtration mode; percent bed expansion; are results adjusted for recovery efficiency; method recovery efficiency; L/d ratio; backwash scheme; filter aid; *Cryptosporidium* spiked concentration; occurrence and handling of non-detects; backwash trigger; recycling of backwash water
<20%	Low	filter ripening method; coagulant type; detection limit; total organic carbon; temperature; mixing condition; alkalinity prior to coagulation; coagulation pH; coagulant aid; type of filtration; filter media type; total filter media depth; Naturally occurring *Cryptosporidium* concentration; influent water turbidity; hydraulic loading rate; filter effluent turbidity; importance of

		optimized coagulant dose

Excluding the ‘do not knows’ and focusing only on assessments of ‘strong influence’, ‘some influence’ and ‘no influence’, Figure 4.6 illustrates some interesting findings. Optimized coagulant dose and filter effluent turbidity were rated as being strong influences by 95% and 81% of respondents, respectively; making these two stand out from other factors when comparing the heights of the blue bars. On the contrary, none of the 38 respondents considered the use of chlorinated backwash water and the *Cryptosporidium* species as having a strong influence, while more than 40% of respondents considered these two factors as having no effect at all on oocyst removals through granular media filtration. A closer examination illustrates that all respondents considered five factors as either strongly or somewhat influential, with none of them assessing their effects as having no influence at all. The five factors are: (1) importance of optimized coagulant dose, (2) filter effluent turbidity, (3) *Cryptosporidium* oocyst method recovery efficiency, (4) recovery efficiency (adjusted for or not), and (5) detection limit.

By looking at response of ‘strong influence’ only (blue bars), the most influential five factors (starting with most influential) are: (1) Importance of optimized coagulant dose, (2) filter effluent turbidity, (3) Hydraulic loading rate, (4) detection limit, and (5) back wash trigger. By looking at response of ‘no influence’ only (green bars), the least influential five factors are (starting with the least influential) are: (1) *Cryptosporidium* species, (2) chlorinated backwash water, (3)/(4) filtration mode/*Cryptosporidium* species, and (5) temperature. These results will be compared with findings from weighting systems in section 4.5.2.

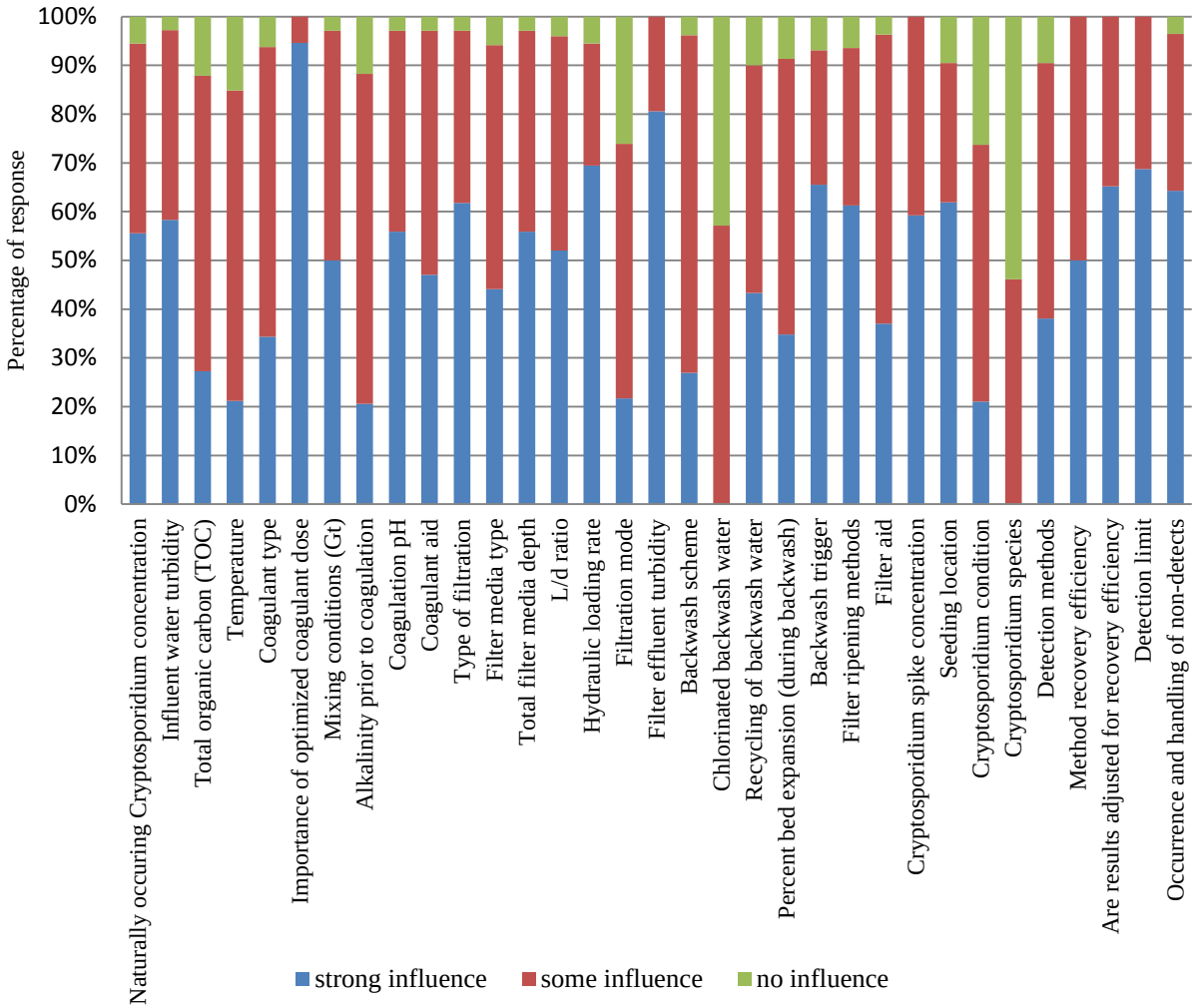


Figure 4.6 Opinions on the relevance of identified factors as they pertain to *Cryptosporidium* removal from all respondents (excluding 'do not know' responses)

4.4.2 Number of Responses Attributed to Each of the Three Knowledge Bases

When examining the influence of identified factors, respondents were also asked to specify the basis upon which they responded. The three choices were research experience, operational perspective, and general engineering knowledge. Figures 4.7 to 4.9 illustrate the number of responses based on these three choices. The number of responses based on

research experience is relatively small for the factors grouped under ‘filter operation’, while being large for factors grouped under ‘experimental differences’ and ‘analytical differences’ (Figure 4.7). The number of responses based on operational perspective is very small or even zero for factors grouped under the ‘experimental differences’ and ‘analytical differences’ categories, which makes sense as knowledge on these categories is typically acquired through conducting filtration experiments (Figure 4.8). The number of responses based on general engineering knowledge is generally evenly distributed over the thirty-three factors (Figure 4.9).

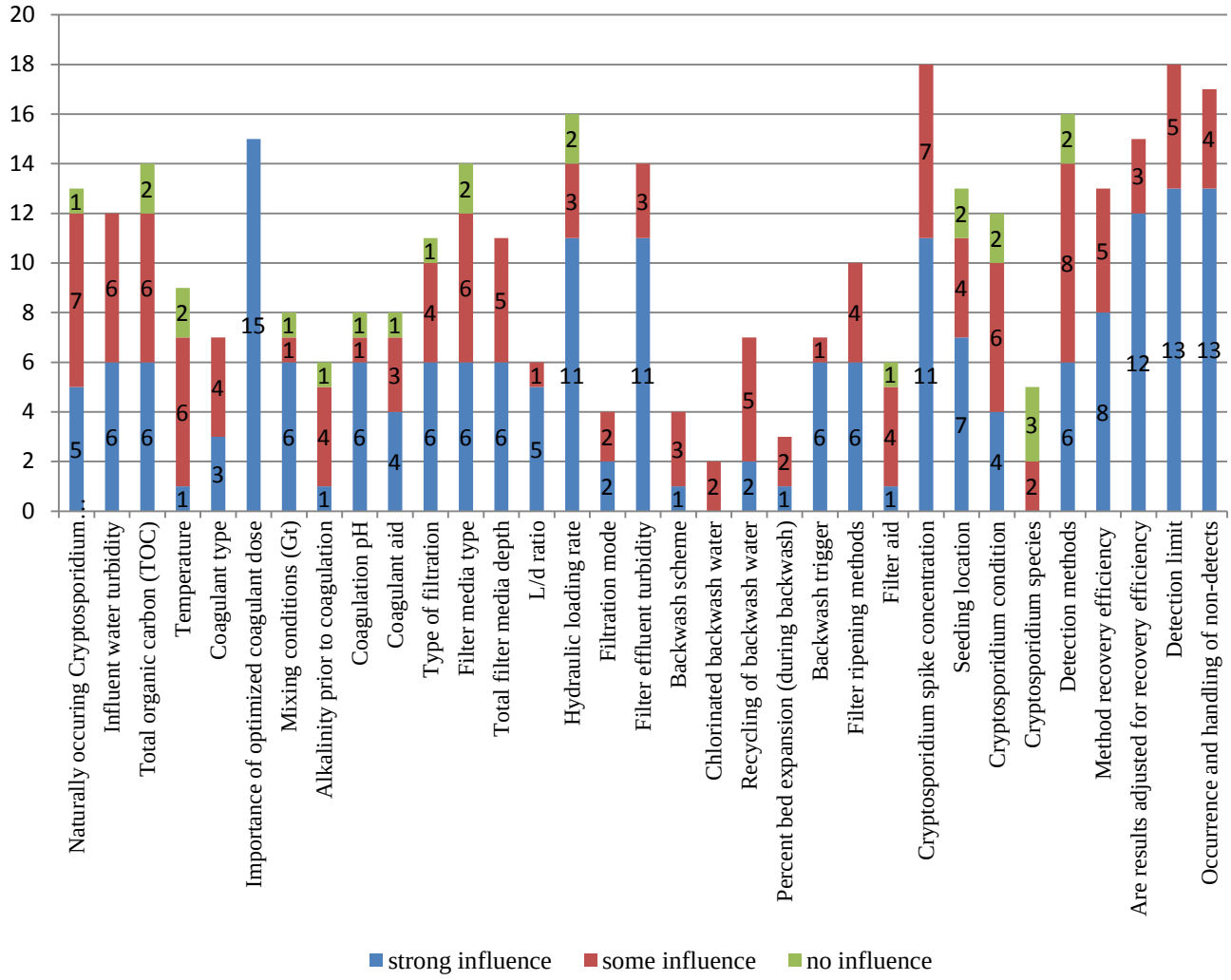


Figure 4.7 Number of responses based on research experience

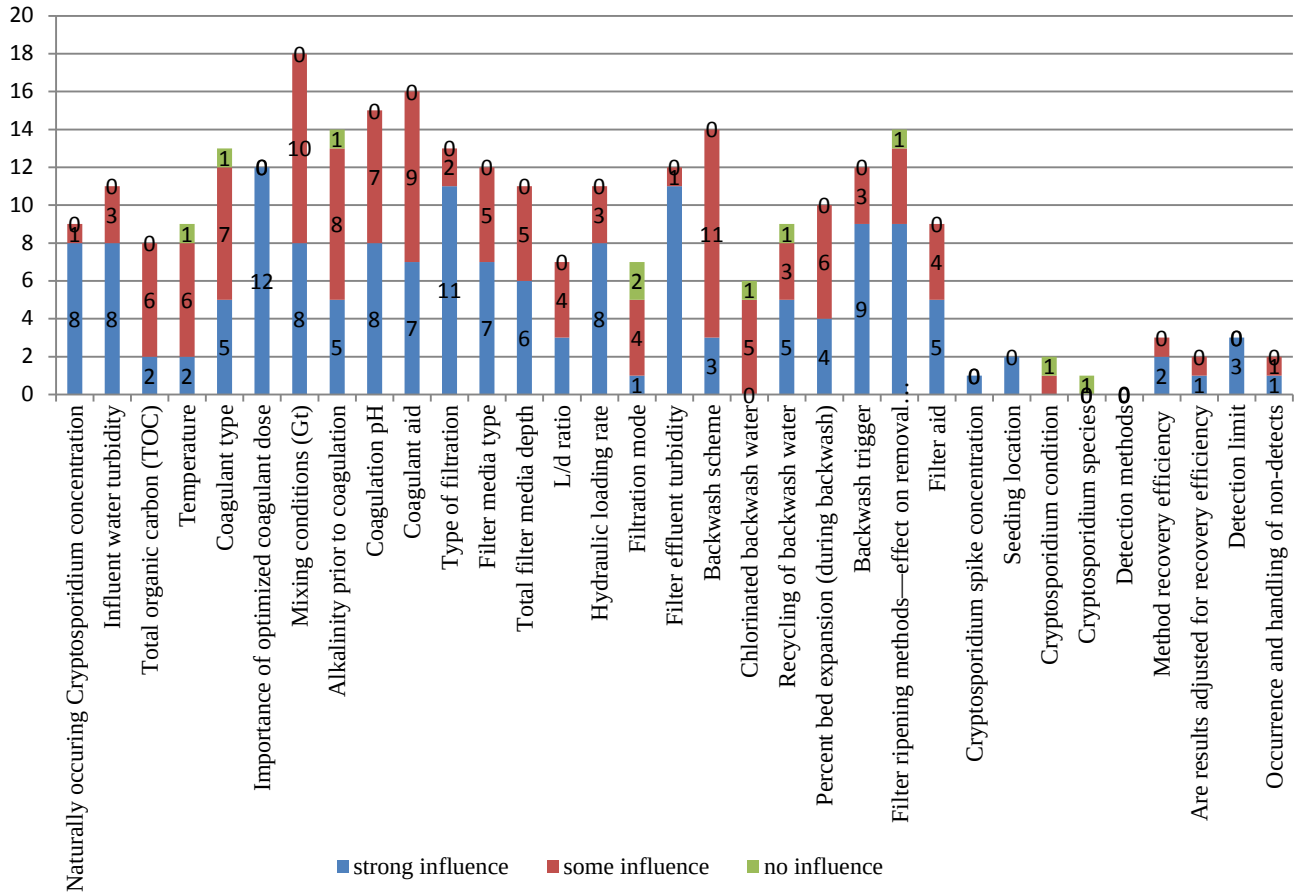


Figure 4.8 Number of responses based on operational experience

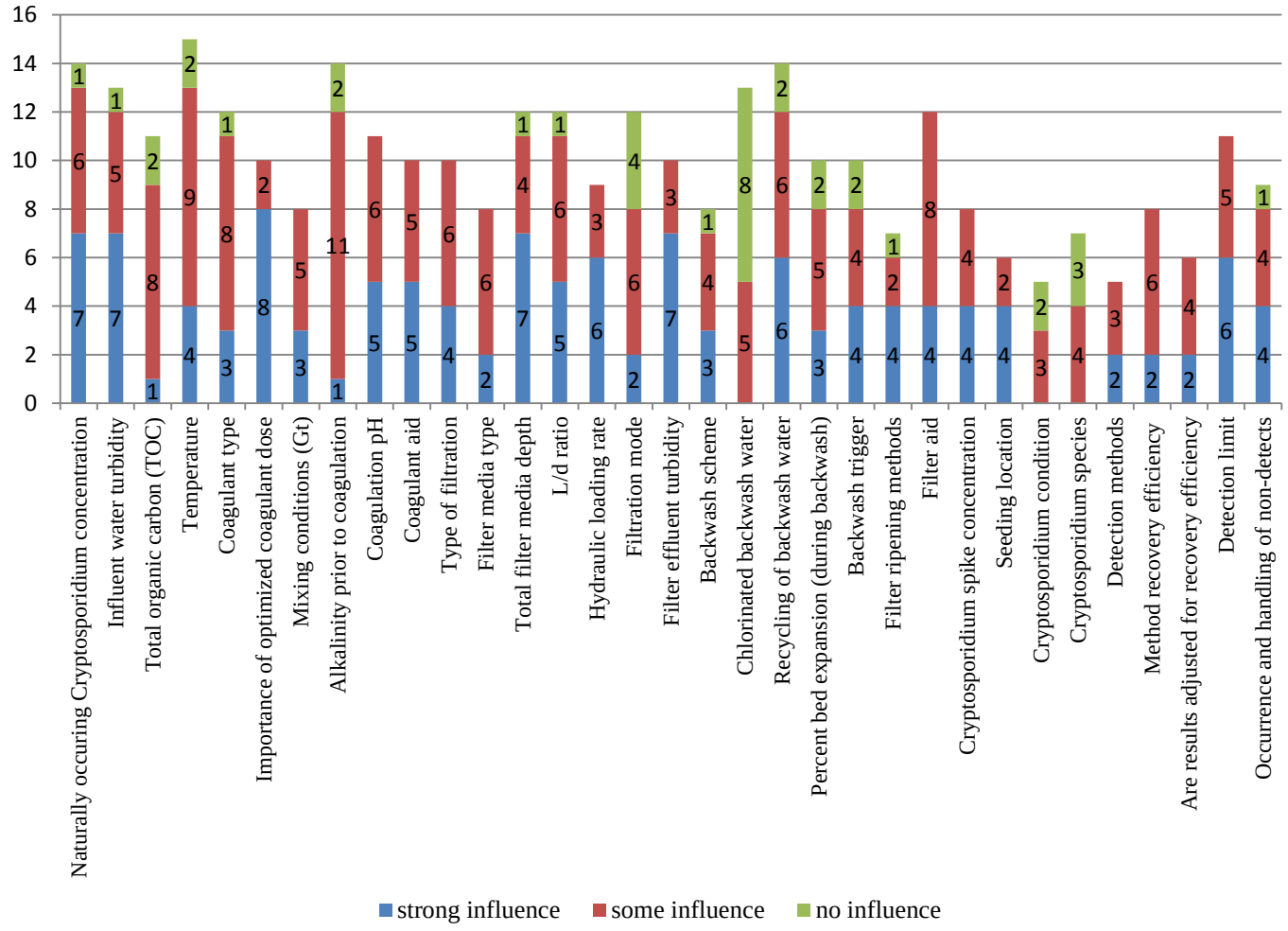


Figure 4.9 Number of responses based on general engineering judgment

4.4.3 Distribution of Responses Attributed to Each of the Three Knowledge Bases

Figures 4.10 to 4.13 present the distribution of responses based on research experience, operational perspective, and general engineering knowledge, respectively. Figure 4.11 does not include factors listed under 'experimental differences' and 'analytical differences' as the number of responses is scarce (3 responses or less for each factor). These three figures were developed to compare with either other and demonstrate considerable variations in the distribution of responses for some factors. For example, the distribution of responses varies

by at least 20% between Figure 4.10 (based on research experience) and Figure 4.11 (based on operational perspective) for factors such as naturally occurring *Cryptosporidium* concentration, influent water turbidity, mixing energy, coagulation pH, type of filtration, L/d ratio, filtration mode, recycling of backwash water, and filter aid, while opinions appears to be quite consistent for the influence of the other factors. The distribution of responses between research experience (Figure 4.10) and general engineering knowledge (Figure 4.12) seems to be more different as the percentages varies at least 20% for about half of factors (15 factors).

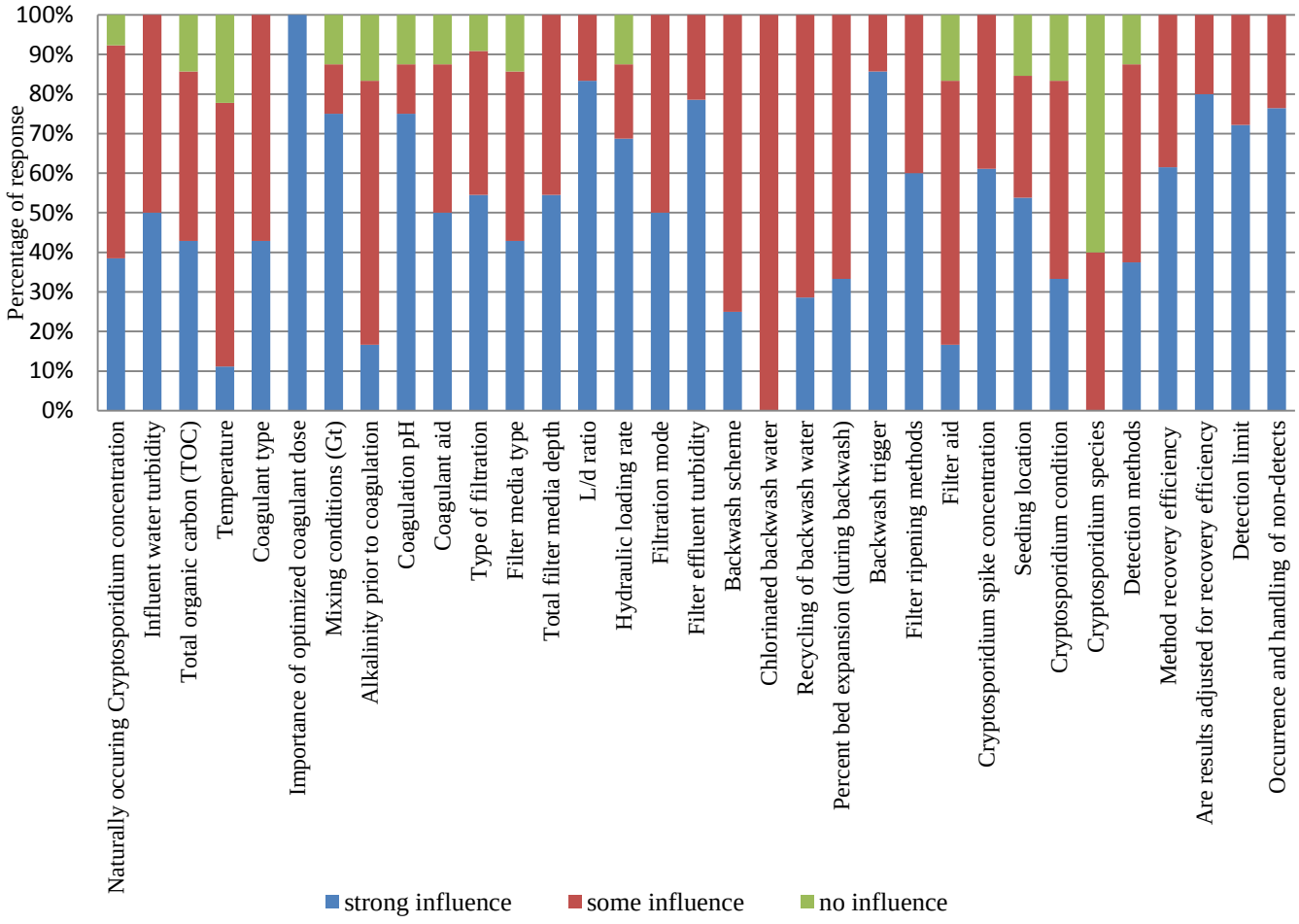


Figure 4.10 Opinions on the relevance of identified factors as they pertain to *Cryptosporidium* removal based on research experience

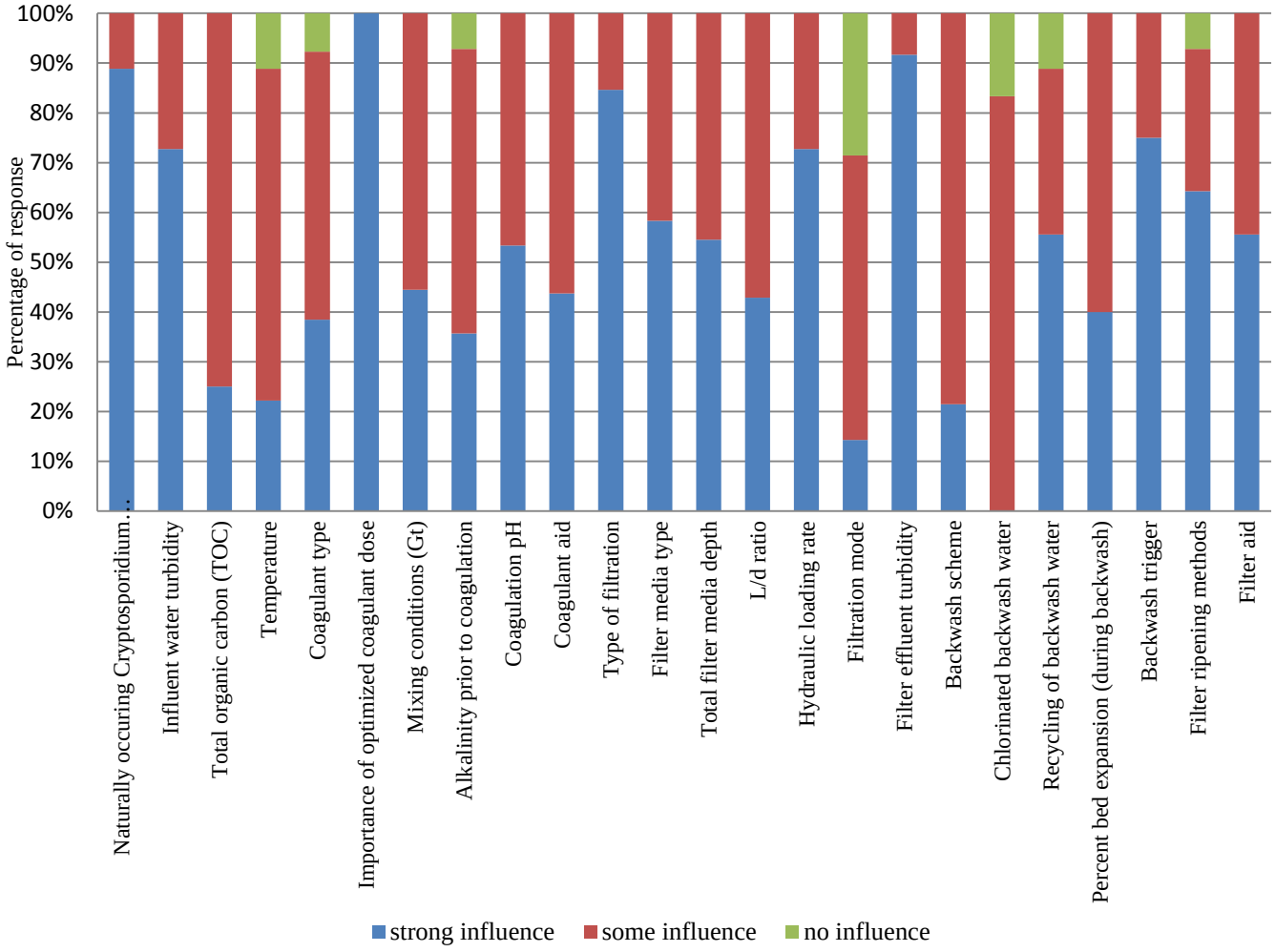


Figure 4.11 Opinions on the relevance of identified factors as they pertain to *Cryptosporidium* removal based on operational perspective

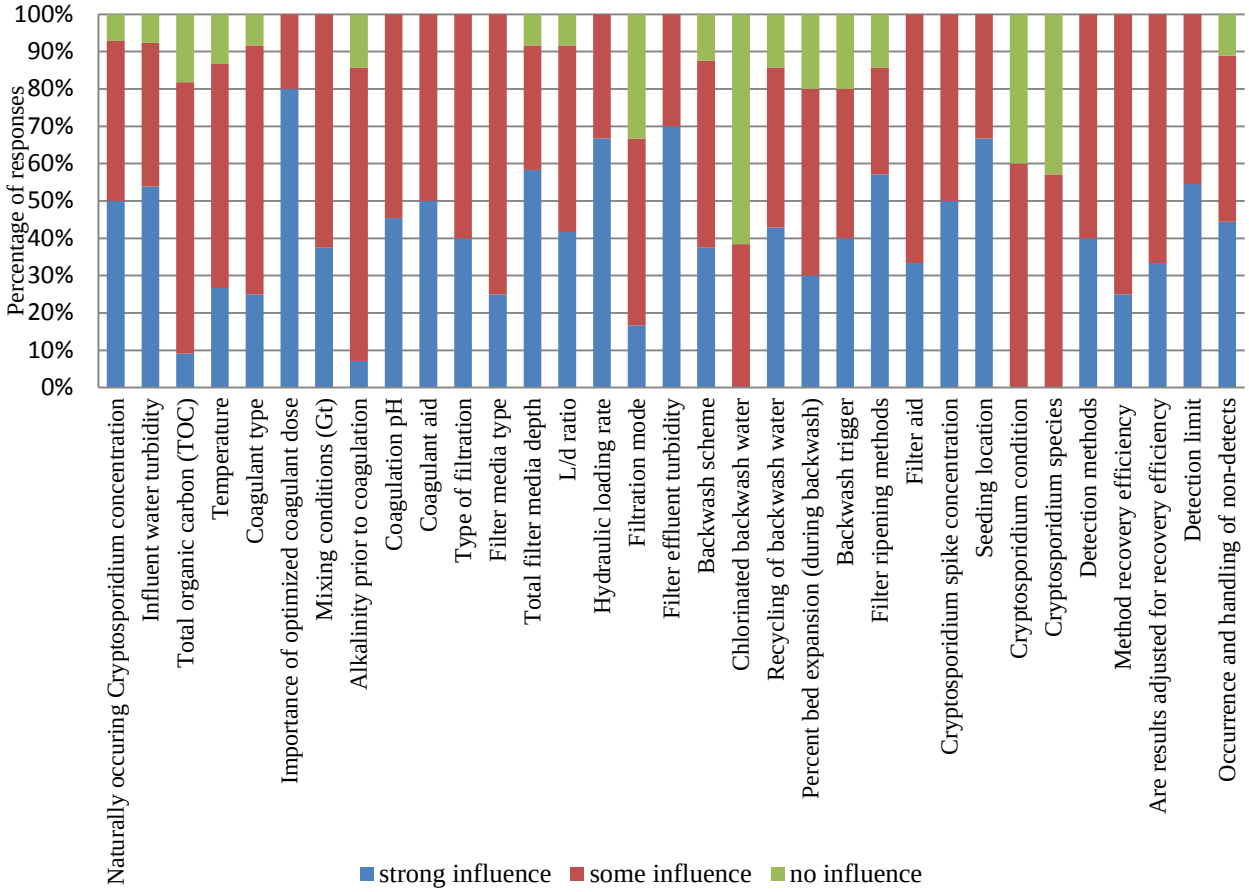


Figure 4.12 Opinions on the relevance of identified factors as they pertain to *Cryptosporidium* removal based on general engineering judgment

4.4.4 Distribution of Responses from Professionals with Direct Involvement in *Cryptosporidium* Research

Figures 4.13 and 4.14 show screened responses from those who have been directly involved *Cryptosporidium* removal research as indicated in the background survey. The percentage of 'do not knows' is slightly lower than what is shown in Figure 4.4. A small difference in

distribution of responses is observed (less than 20%) when comparing Figure 4.13 to Figure 4.4, and when comparing Figure 4.14 to Figure 4.6.

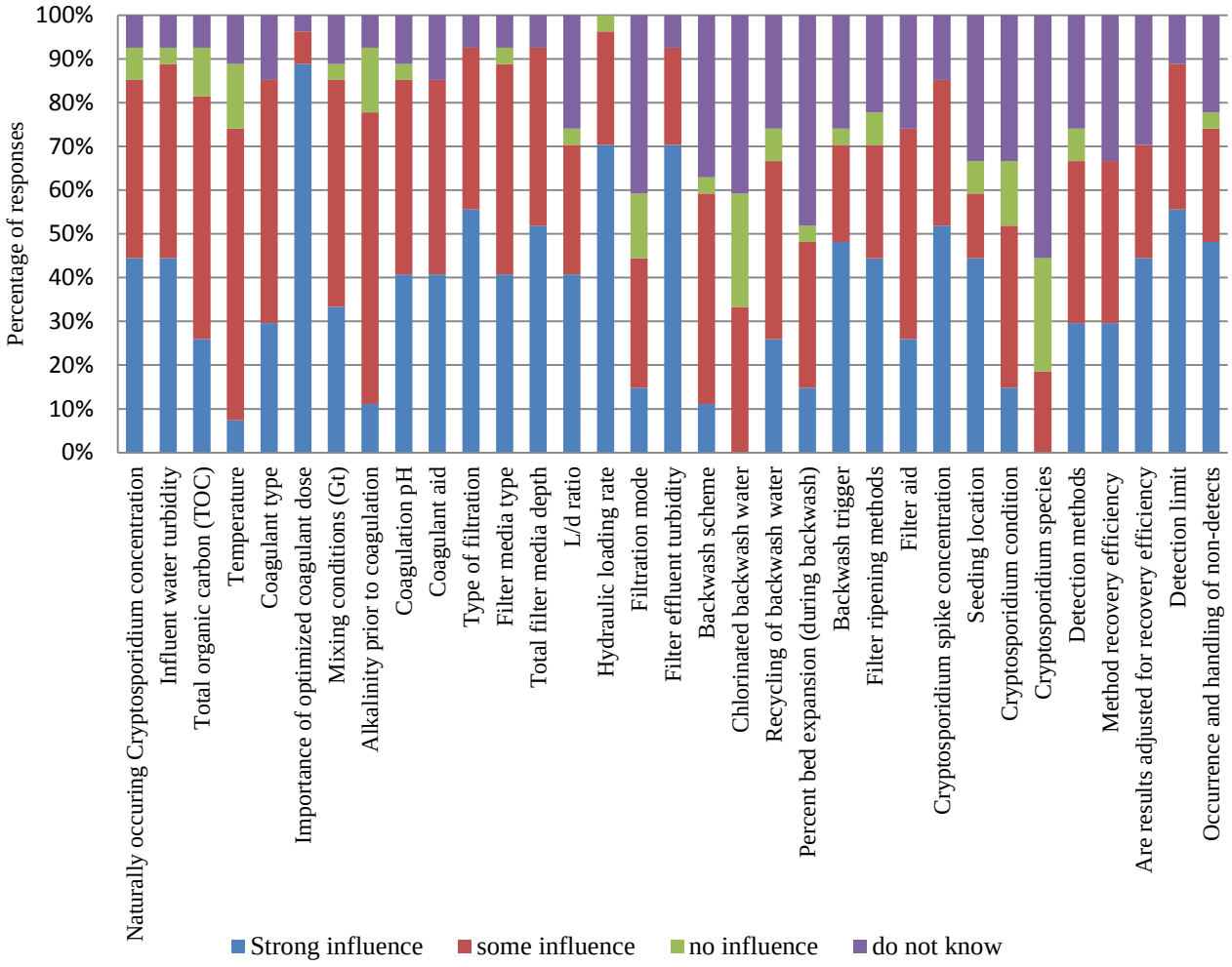


Figure 4.13 Percentage of relevance of influence for respondents with direct involvement in *Cryptosporidium* research (including 'do not knows')

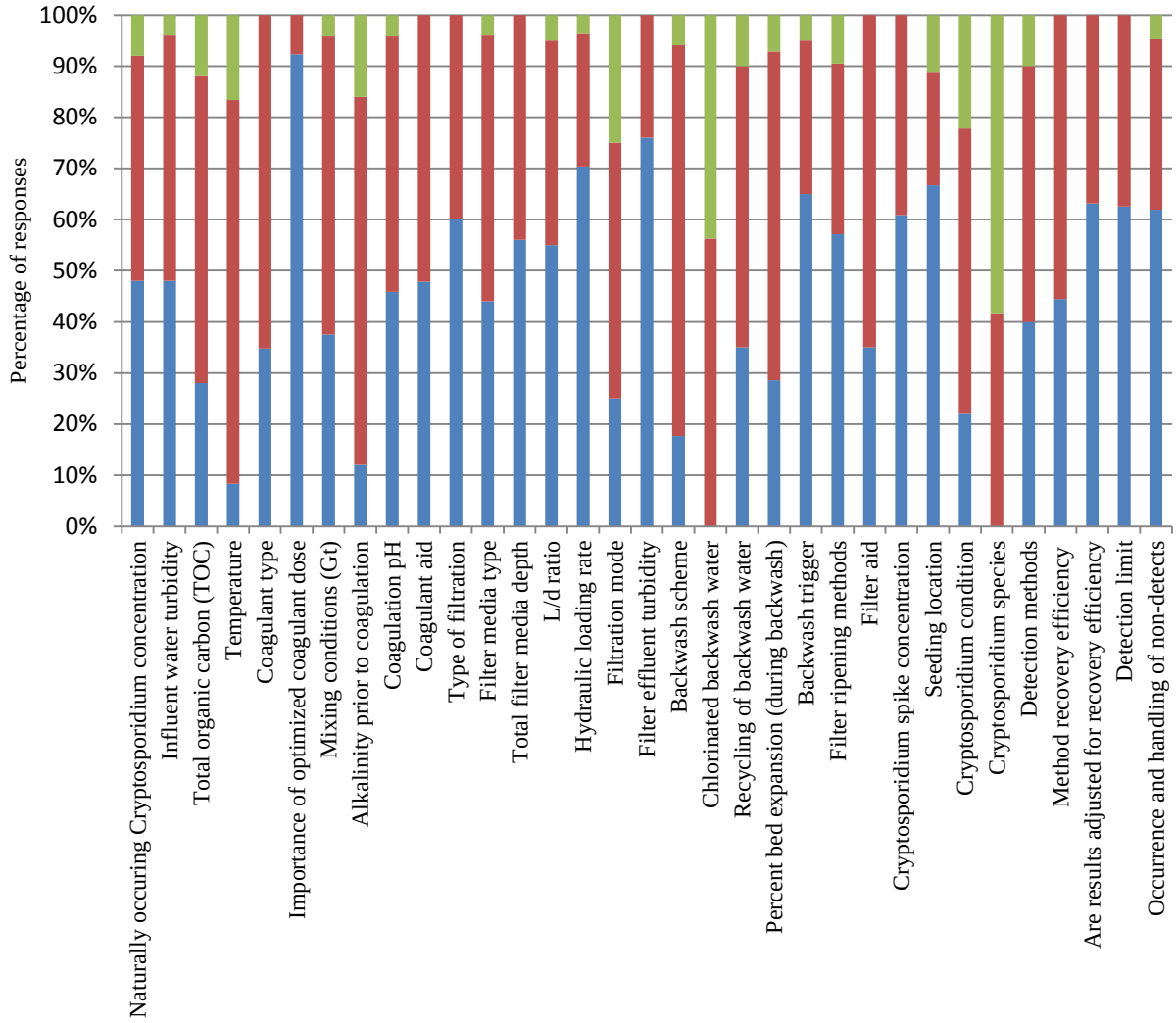


Figure 4.14 Percentage of relevance of influence for respondents with direct involvement in research (excluding ‘do not knows’)

4.4.5 Insight and Remarks from Questionnaire

In addition to providing opinions on the relative influence of the identified factors, participants also shared their thoughts and insights gained from hands-on research or operational experience. In total, 260 comments were collected and are recorded in Appendix

C. The comments of similar aspects are grouped and summarized into major remarks (left side of the table) and paraphrased (right side of the table).

Respondents commented on the potential of each factor to influence oocyst removals, providing supplemental information in addition to their choices of relevance of influence. They also attempted to provide explanations for the substantial variability in removal data. For example, one respondent stated that although coagulation conditions and filter design are crucial, oocysts must be seeded at sufficiently high concentrations to ensure the presence of detectable oocysts in treated water. In the opinion of the respondent, seeding concentration and analytical differences were considered to be the first and second most important influencing factors for achieving high log removals. Recommendations were also proposed in their comments, such as lowering filter effluent turbidity standards/regulations/guidelines to 0.1 NTU from those currently in place, and adhering to a consistent approach for handling non-detects for calculation purposes. Table 4.3 presents some examples of interesting comments from respondents.

The following section presents a condensed summary of remarks on the potential effect of each of the identified factors. Detailed comments can be found in Appendix C. The comments reach a consensus on some factors, such as the important role of optimized coagulant dose, and the minor roles of temperature and alkalinity on coagulation with respect to oocyst removals. However, for factors such as L/d ratio, backwash scheme, filtration mode, bed expansion during backwash, and *Cryptosporidium* species, the comments illustrate that the effect of such factors were not clear and the scientific findings to assist with evaluation of these was lacking. Respondents' opinions with respect to the role and influence of other factors vary and in some instances are conflicting.

Raw water background *Cryptosporidium* concentrations (not spiked)

- Influent *Cryptosporidium* concentration affects analytical accuracy and precision in

filtered samples thus influencing oocyst log removal calculation

- High influent *Cryptosporidium* concentrations pose a challenge for treatment
- When influent oocyst concentration increases, *Cryptosporidium* removals through filtration increase as well

Influent water turbidity

- Influent water turbidity plays a role in filtration theory
- Turbidity can challenge treatment process effectiveness
- Turbidity interferes with *Cryptosporidium* detection and thus potentially influences removals
- *Cryptosporidium* removal is higher at increased turbidity levels
- The type of turbidity rather than the absolute turbidity may play a role

Total organic carbon (TOC)

- TOC affects coagulation performance and requires coagulant dose adjustment
- TOC can be an indicator of the level of *Cryptosporidium* contamination as spikes in concentration can be the result of various events occurring upstream or in the vicinity of a water intake
- TOC has less impact on *Cryptosporidium* removal than does turbidity
- TOC has some effect on oocyst method recovery

Temperature

- Temperature influences treatment processes, primarily coagulation/flocculation/ sedimentation; little impact on filtration
- *Cryptosporidium* concentrations may be associated with water temperature
- Temperature influences biological activity/predation which has low impact on *Cryptosporidium* removal by filtration compared to other variables

Coagulant type

- The effect of coagulant type is site specific
- Similar filtration performance can be achieved with different coagulant types

Importance of optimized coagulant dose

- Optimized coagulant dose is very important for *Cryptosporidium* removal by filtration

Mixing conditions

- Mixing conditions influence coagulation conditions
- The effect of mixing conditions is site specific
- The effect of mixing condition is not significant

Alkalinity prior to coagulation

- Alkalinity plays a minor role in coagulation processes (as it relates to particle vs. NOM removal)

Coagulation pH

- Optimized coagulation pH is crucial for coagulation
- Lower coagulation pH may lead to higher *Cryptosporidium* removal

Coagulant aid

- Addition of a coagulant aid can be beneficial but may be site specific

Type of filtration

- Conventional treatment performs better for the removal of *Cryptosporidium* than does direct and inline filtration
- Without clarification, as is the case for direct or inline filtration, filters have to work

harder to remove *Cryptosporidium*

- In direct filtration plants, filters experience higher oocyst loading and are relied upon more than filters in conventional plants with upstream sedimentation processes
- Coagulant dose is critical for all three types of filtration

Filter media type

- There are no substantial effects of filter media type on *Cryptosporidium* removal
- Mono-media filters prone to rapid headloss development
- Dual-media filtration provides an advantage in terms of removing particles

Total filter media depth

- Deep filters perform better
- Filter media depth has no significant effect on *Cryptosporidium* removal efficacy
- A minimum filter media depth is needed, but its effect on oocyst log removal is otherwise not clearly linked

L/d ratio

- L/d ratio is a useful parameter for sizing filter media, but its effect on *Cryptosporidium* removal is not clear

Hydraulic loading rate

- Filters with lower hydraulic loading rates have demonstrated improved filter performance
- There is systematic difference in *Cryptosporidium* removal performance at various hydraulic loading rates

Filtration mode (e.g. declining vs constant rate)

- There is no consensus as to the effect of filtration mode on *Cryptosporidium* removal

efficacy

Filter effluent turbidity

- The current regulation for filter effluent turbidity needs to be more stringent to optimize *Cryptosporidium* removals (e.g. 0.1 NTU)
- Particle counts are a better indicator for *Cryptosporidium* removal than filter turbidity
- Filter effluent turbidity is indicative of the effectiveness of filter performance
- Slight increases in turbidity need to be carefully monitored and/or responded to from an operational perspective

Backwash scheme

- The effect of different backwash schemes is not yet clear

Chlorinated backwash water

- Since chlorine is ineffective as it pertains to *Cryptosporidium* inactivation, chlorinated backwash water has no influence
- Chlorine affects the biological activity in the filter, which may have some influence on *Cryptosporidium* removal

Recycling of backwash water

- Recycling of backwash water increases *Cryptosporidium* loading on filtration processes
- Recycling of backwash water may influence filter performance
- The impact of recycling on *Cryptosporidium* by filtration is irrelevant or small if accompanied by well-operated clarification processes

Percent bed expansion (during backwash)

- Adequate expansion is important to remove attached oocysts trapped in the filter bed;

its effect on *Cryptosporidium* removal is not clear

Backwash trigger

- The opinions for selecting backwash trigger types vary (see Appendix C for detail)

Filter ripening methods

- Opinions on filter ripening configuration vary, extended terminal subfluidization may have a role to play
- Filter ripening may be a vulnerable period during which *Cryptosporidium* oocysts can be released

Filter aid

- Opinions on the value of filter aids vary (see Appendix C for detail)

***Cryptosporidium* spiked concentration**

- A sufficiently high *Cryptosporidium* seeding concentration is needed to achieve reliable counts in filter effluent to allow for oocyst log removal through filters to be accurately estimated
- *Cryptosporidium* log removal increases as influent spiked concentration increases
  Higher spiking concentration resulting in more rapid breakthrough of a *Cryptosporidium* surrogate has been reported

Seeding location

- Preferable to spike oocysts into source water
- The absence of any coagulation is expected to have a substantial effect
- The mixing and transferring of seeded oocysts into water is a source of variability in *Cryptosporidium* removal quantification

***Cryptosporidium* oocyst condition**

- *Cryptosporidium* condition affects oocyst surface charge
- *Cryptosporidium* condition has little to no effect on removal

***Cryptosporidium* species**

- Limited information available on the effect of *Cryptosporidium* species

Detection methods

- Opinions on the impact of detection methods vary

Method recovery efficiency

- The recovery efficiency provides a reliable estimate of how much *Cryptosporidium* is required for spiking
- Methods of analysis are extremely variable; recovery efficiency provides information on laboratory performance and matrix effects

Are results adjusted for recovery efficiency?

- Recovery efficiency should be accounted for to accurately describe *Cryptosporidium* log removals
- Caution should be exercised when adjusting for recovery efficiency

Detection limit

The detection limit sets the spiked concentration needed

The detection limit should always be 1 oocyst per volume of water analyzed

Occurrence and handling of non-detects

- This factor leads to controversy and discussion
- Non-detects should be interpreted carefully and be treated in a consistent manner

Table 4.3 Selected important/interesting comments from questionnaire

• Many respondents remarked on the need to regulate turbidity to be 0.1 NTU or less (rather than simply making it an unenforceable target)
• Extended terminal subfluidization was suggested for consideration as the practice can achieve low filtered water particle counts, comparable to those in a filter-to-waste configuration
• All of our experiments have been performed with live *Cryptosporidium* oocysts, work by Ongerth and Pecoraro (1996) demonstrated significant differences in surface charge between inactivated and live oocysts
• One respondent remarked that not all *Cryptosporidium* oocysts are recovered at the same rate and therefore adjusting all results based on the recovery of one strain may not be appropriate
• Detection limit is always 1 per whatever volume filtered and it is critical to ensure high enough volume to provide meaningful information; the 10 L sample volume which is recommended by USEPA may be too low for accurate detection and thus strongly impacts published occurrence of *Cryptosporidium* in US source water
• Need sufficiently high *Cryptosporidium* concentration to calculate "real" removal; otherwise the removal data can only be expressed in the form of ">"

4.5 Evaluation of Overall Influence

In a survey project, the coding of data is commonly applied to support data-based decisions (Susan, 2004). In this research, a weighting system was proposed to assess the overall influence of an identified factor on *Cryptosporidium* removal through filtration, by incorporating all response choices of 'no influence', 'some influence' and 'strong influence', while also taking into consideration the different knowledge bases from which respondents

drew upon. The weighting system introduces what is known as the 'summative extent of influence', which can be calculated for each factor through coding all data (response choices and knowledge bases). Two basic coding documentations were applied to calculate the summative extent of influence for each factor. Higher values indicate stronger influence and smaller (or even negative values) indicate less influence. Through data coding, factors believed to significantly influence and least influence oocyst removals were identified from drinking water professionals' responses. Sensitivity analyses were conducted to check the robustness of the weighting system by applying alternative coding documentation.

4.5.1 Development of a Weighting System to Incorporate Responses

Define Summative Extent of Influence for each factor

$$\frac{1}{N}\sum(Score\ for\ Relevance\ of\ influence \times weight\ for\ response\ basis)$$

(N: number of responses)

Coding documentation

Prior to beginning the coding, a coding documentation can provide clear directions as to how the coding was done (Susan, 2004). Two coding documentations were proposed as base scenarios to calculate the summative extent of influence (Tables 4.4 and 4.5). In both coding documentations, the responses of 'strong influence' and 'some influence' were assigned a score of 1 and 0.5, respectively, while the response of 'no influence' was assigned a score of -1. In coding documentation A, the three knowledge bases were treated equally. Coding documentation B assigned equal weight to responses based on past research and operational experience but only half of the weight was assigned to responses based on general engineering knowledge. In this case, answers derived from past research and operational experience were given twice the credit that answers based on general engineering knowledge were.

Table 4.4 Response coding documentation A

Score for relevance of influence	Weight for response basis
Strong influence = 1	Past research = 1
Some influence = 0.5	Operational experience = 1
No influence = -1	Engineering knowledge = 1

Table 4.5 Response coding documentation B

Score for relevance of influence	Weight for response basis
Strong influence = 1	Past research = 2
Some influence = 0.5	Operational experience = 2
No influence = -1	Engineering knowledge = 1

4.5.2 Results

The summative extent of influence was calculated for thirty-three factors using coding documentation A (Figure 4.15) and coding documentation B (Figure 4.16). It can be seen that the calculated values vary considerably over the thirty-three factors (from 0.97 to -0.3 in Figure 4.15; from 0.85 to -0.27 in Figure 4.16). The five factors with the highest values are labeled in yellow, and five factors with the lowest values are labeled in grey. In the case of coding documentation A where all three knowledge bases were treated equally, the five most influential factors (starting with the most influential) were (1) importance of optimized coagulant dose, (2) filter effluent turbidity, (3) detection limit, (4) results adjusted for recovery, and (5) *Cryptosporidium* spiked concentration. The five least influential factors (starting with the least influential) were (1) *Cryptosporidium* species, (2) chlorinated backwash water, (3) *Cryptosporidium* condition, (4) filtration mode, and (5) temperature. When coding documentation B was applied, the five most and least influential factors

remained the same with changes in the order of some factors. As can be seen in the figures, the values for some factors are quite similar, which explains why side by side factors may replace one another in terms of their order within each list when the weight for knowledge basis changes. Table 4.6 summarizes the five most and least influential factors identified from coding documentation A, from coding documentation B, and from 'without weighting' scenario (identifying most influential factors with the highest percentage of 'strong influence' response, and identifying least influential factors with the highest percentage of 'no influence' from Figure 4.6). The 'without weighting' scenario does not take into account the overall influence of all response choices and different knowledge basis. In this scenario, factors of hydraulic loading rate, backwash trigger replaces factors of *Cryptosporidium* spiked concentration and are results adjusted for recoveries in the list of most influential factors, while the five least influential factors remained the same compared to results from base weighting scenarios. Table 4.6 also presents in brackets the 'do not know' category associated with each factor. The higher the percentage of 'do not know' answers, the fewer the responses used to analyze the effect of the factor and thus the influence of that factor is less certain. For example, factors of '*Cryptosporidium* species, chlorinated backwash water, *Cryptosporidium* condition, although listed as the least influential factors, fall in the high designation group (percentage of 'do not know' greater than 40%). The finding that these factors are the least influential is less certain owing to the lower number of respondents who actually assessed their influence.

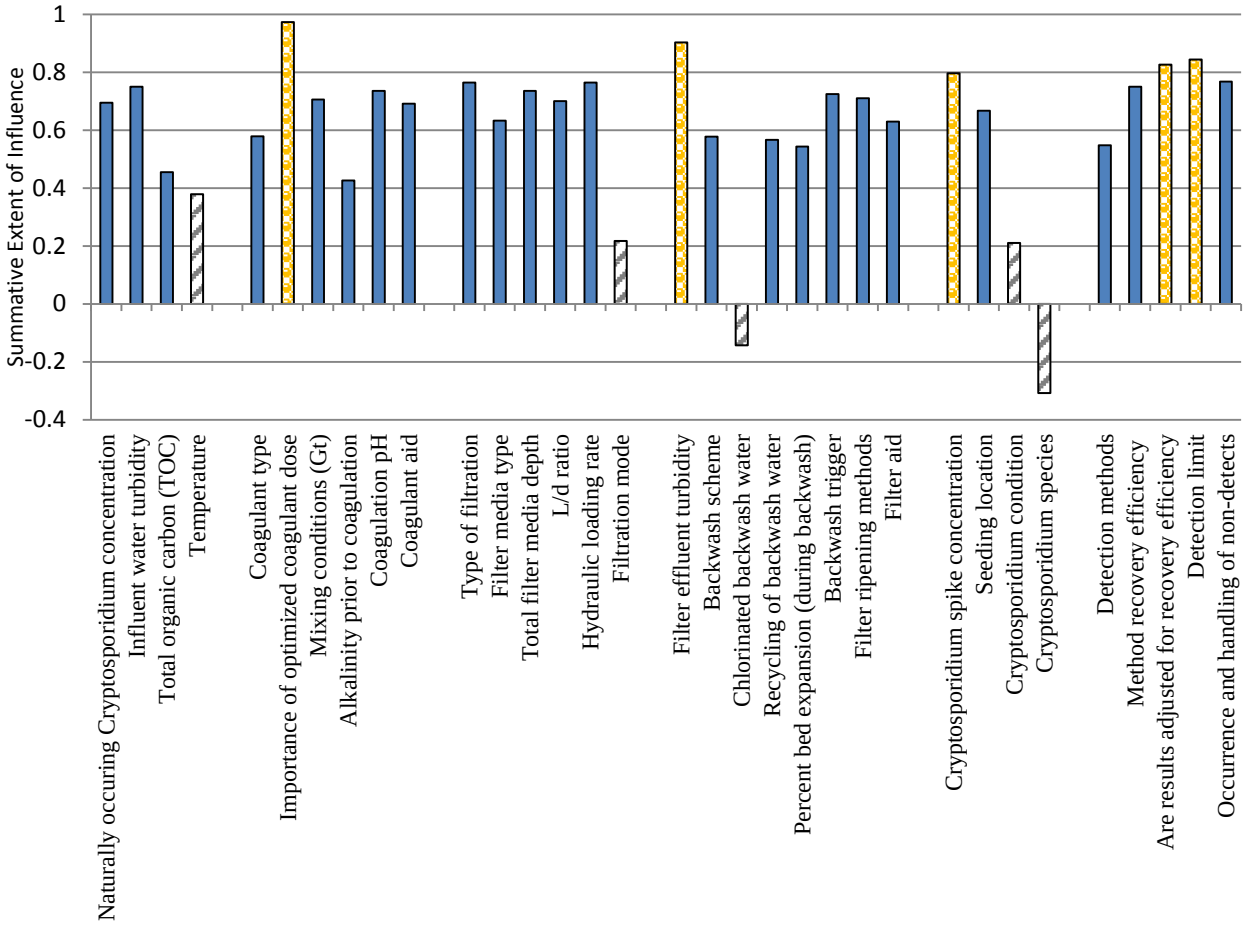


Figure 4.15 Summative extent of influence calculated from coding documentation A

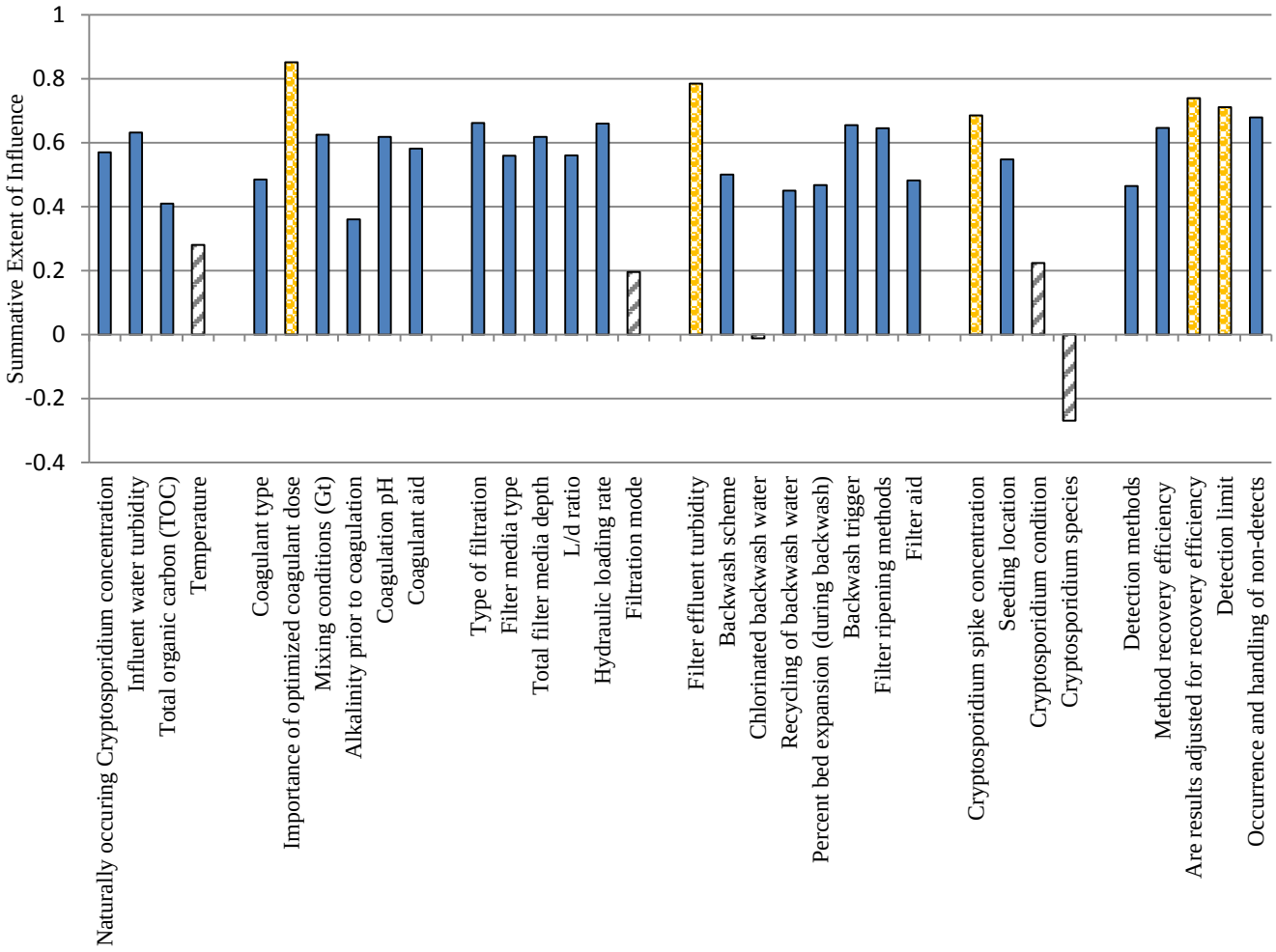


Figure 4.16 Summative extent of influence calculated from coding documentation B

Table 4.6 Five most influential and least influential factors identified

	Coding documentation A ('do not know' percentage)	Coding documentation B ('do not know' percentage)	Without weighting ('do not know' percentage)
Five most influencing factors (starting with the most influential)	1. importance of optimized coagulant dose (low) 2. filter effluent turbidity (low) 3.detection limit (low) 4. results adjusted for recovery (medium) 5. *Cryptosporidium* spiked concentration (medium)	1. importance of optimized coagulant dose (low) 2. filter effluent turbidity (low) 3. results adjusted for recovery (medium) 4. detection limit (low) 5. *Cryptosporidium* spiked concentration (medium)	1. importance of optimized coagulant dose (low) 2. filter effluent turbidity (low) 3. hydraulic loading rate (low) 4. detection limit (low) 5. backwash trigger (medium)
Five least influencing factors (starting with the least influential)	1. *Cryptosporidium* species (high) 2. chlorinated backwash water (high) 3. *Cryptosporidium* condition (high) 4. filtration mode (medium) 5. temperature (low)	1. *Cryptosporidium* species (high) 2. chlorinated backwash water (high) 3. filtration mode (medium) 4. *Cryptosporidium* condition (high) 5. temperature (low)	1. *Cryptosporidium* species (high) 2. chlorinated backwash water (high) 3.* filtration mode (medium) 3. **Cryptosporidium* condition (high) 5. temperature (low)

*these two factors tied in the ranking

4.5.3 Sensitivity Analysis

To further evaluate the impact of coding documentation on the results and verify the robustness of the analysis, four alternative coding documentations were also applied. The sensitivity analysis confirms the minor impact of coding documentations on the identification of the most and least influential factors.

In coding documentation C, the score for relevance of influence remained the same as the base scenarios, while the weights for knowledge basis were intentionally set to be quite different (3 for research, 2 for operational and 1 for engineering knowledge respectively) (Table 4.7). The five most and least influential factors list were the same as in the two base scenarios, demonstrating the robustness of the weighting system.

Table 4.7 Response coding documentation C

Score for relevance of influence	Weight for response basis
Strong influence = 1	Past research = 3
Some influence = 0.5	Operational experience = 2
No influence = -1	Engineering knowledge = 1

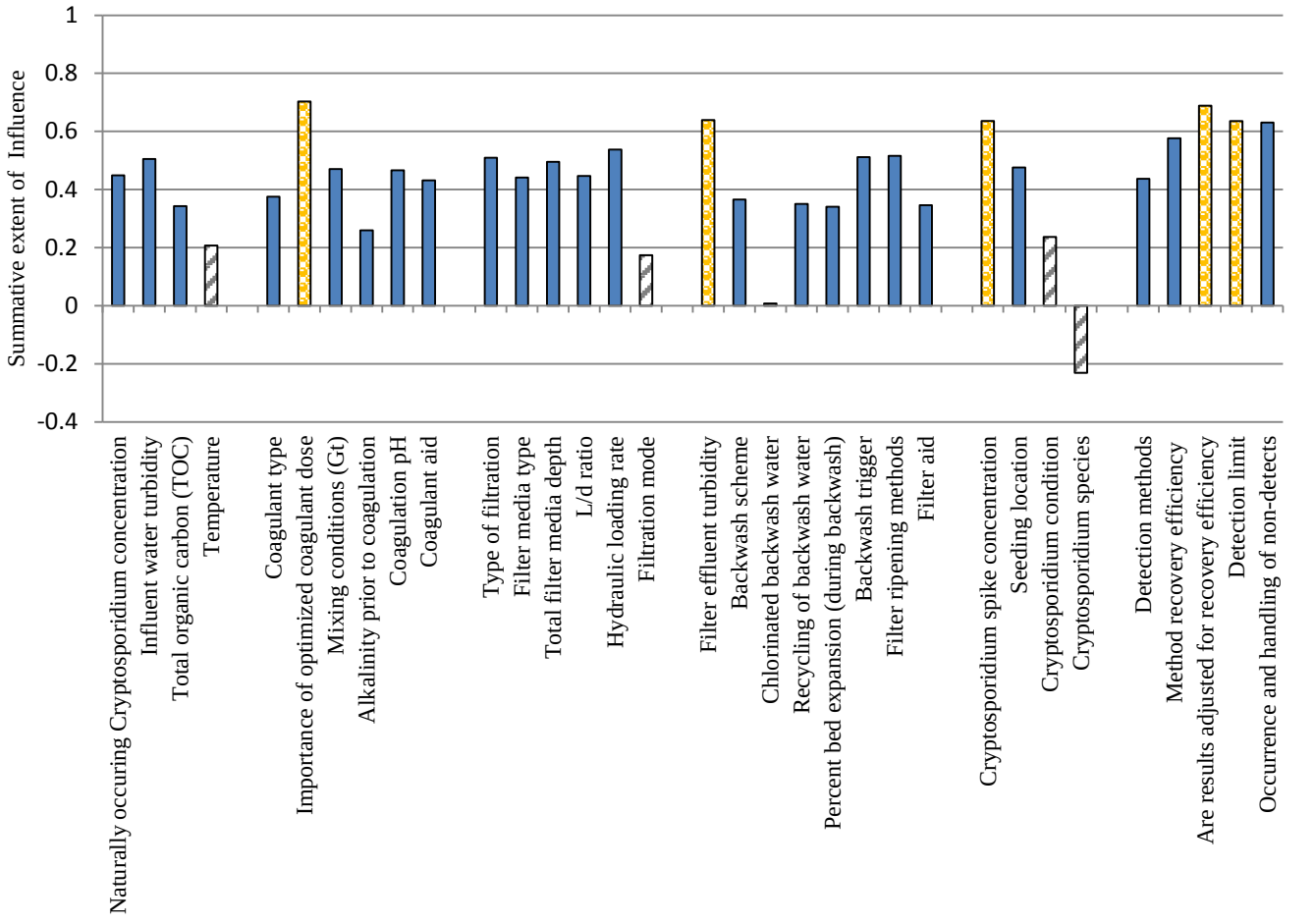


Figure 4.17 Summative extent of influence calculated from coding documentation C

In coding documentations D, E, and F, the ‘no influence’ response was assigned a score of 0, rather than a score of -1 as adopted in the previous scenarios (A, B and C) (Tables 4.8-4.10). The three response bases were treated equally in coding documentation D. In coding documentation E, past research and operational experience were assigned equal weight while half of the weight was assigned to responses based on general engineering knowledge. In coding documentation F, the weights assigned to research, operational experience, and engineering knowledge were 3, 2, and 1, respectively.

These three figures are compared with the base scenarios, revealing minor changes in results of most and least influential factors. In Figures 4.18 and Figure 4.19, the most influential five factors are (1) optimized coagulant dose, (2) filter effluent turbidity, (3) hydraulic loading rate, (4) detection limit, and (5) results adjusted for recoveries. In this case, 4 out of 5 were the same as the base scenarios with ‘hydraulic loading rate’ replacing ‘*Cryptosporidium* spiked concentration’ on the list. The least influential five factors remained unchanged from the base scenarios. When weights were set as 3:2:1 for research, operational experience, and engineering judgment, the five most influential factors remained the same as in the base scenarios, and ‘alkalinity prior to coagulation’ replaced ‘*Cryptosporidium* condition’ in the list of least influential factors (Figure 4.20).

One issue with scenarios D, E, and F is that the score of 0 does not reflect the changes in response weight. In this setting, all ‘no influence’ answers, no matter which response basis is used, are treated equally in the calculation, which potentially distorts the results. As a result, coding documentation D, E, and F were not selected as base scenarios and are only demonstrated in this sensitivity analysis.

Table 4.8 Response coding documentation D

Score for relevance of influence	**Weight for response basis**

Strong influence = 1	Past research = 1
Some influence = 0.5	Operational experience = 1
No influence = 0	Engineering knowledge = 1

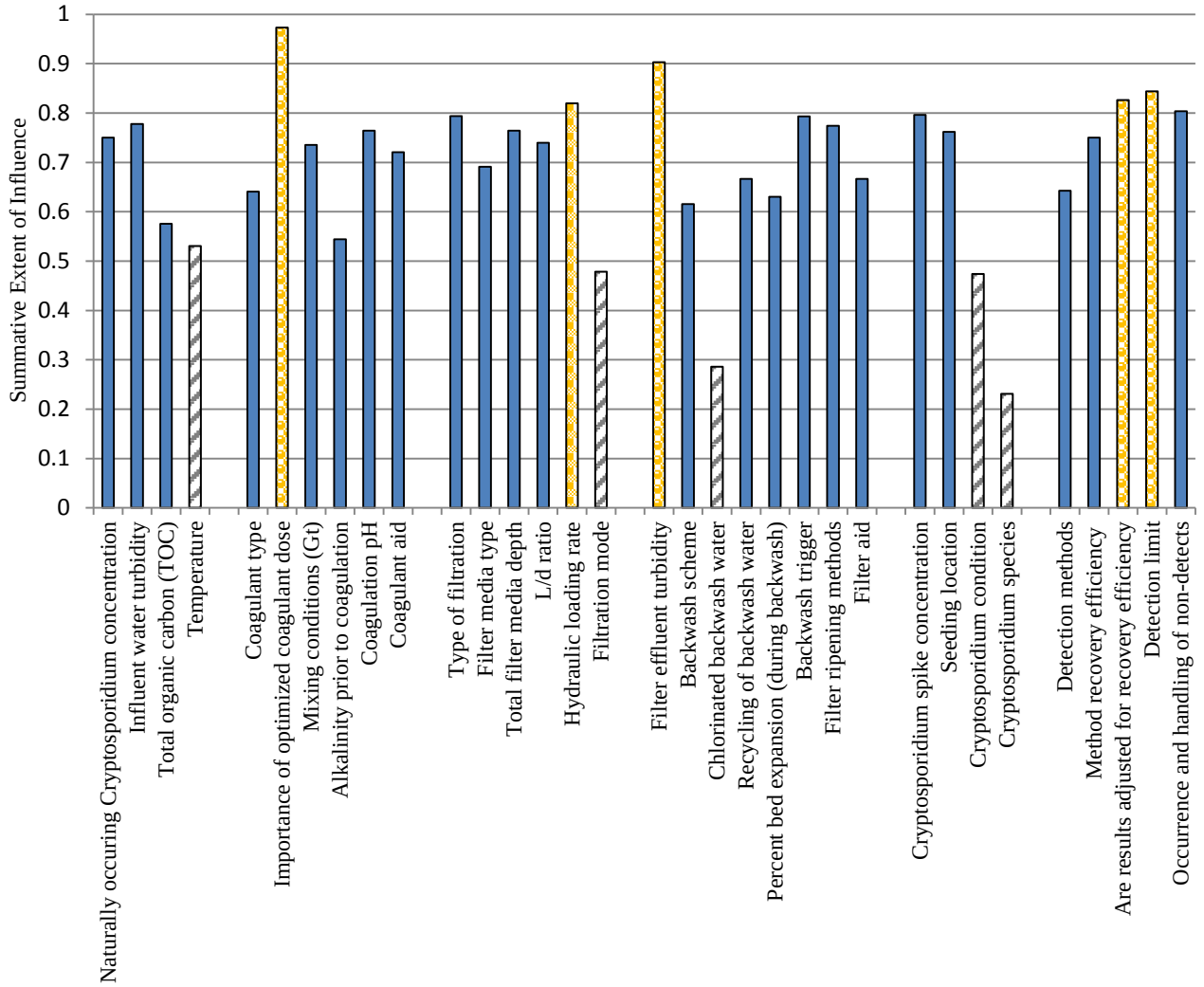


Figure 4.18 Summative extent of influence calculated from coding documentation D

Table 4.9 Response coding documentation E

Score for relevance of influence	**Weight for response basis**
Strong influence = 1	Past research = 2

Some influence = 0.5	Operational experience = 2
No influence = 0	Engineering knowledge = 1

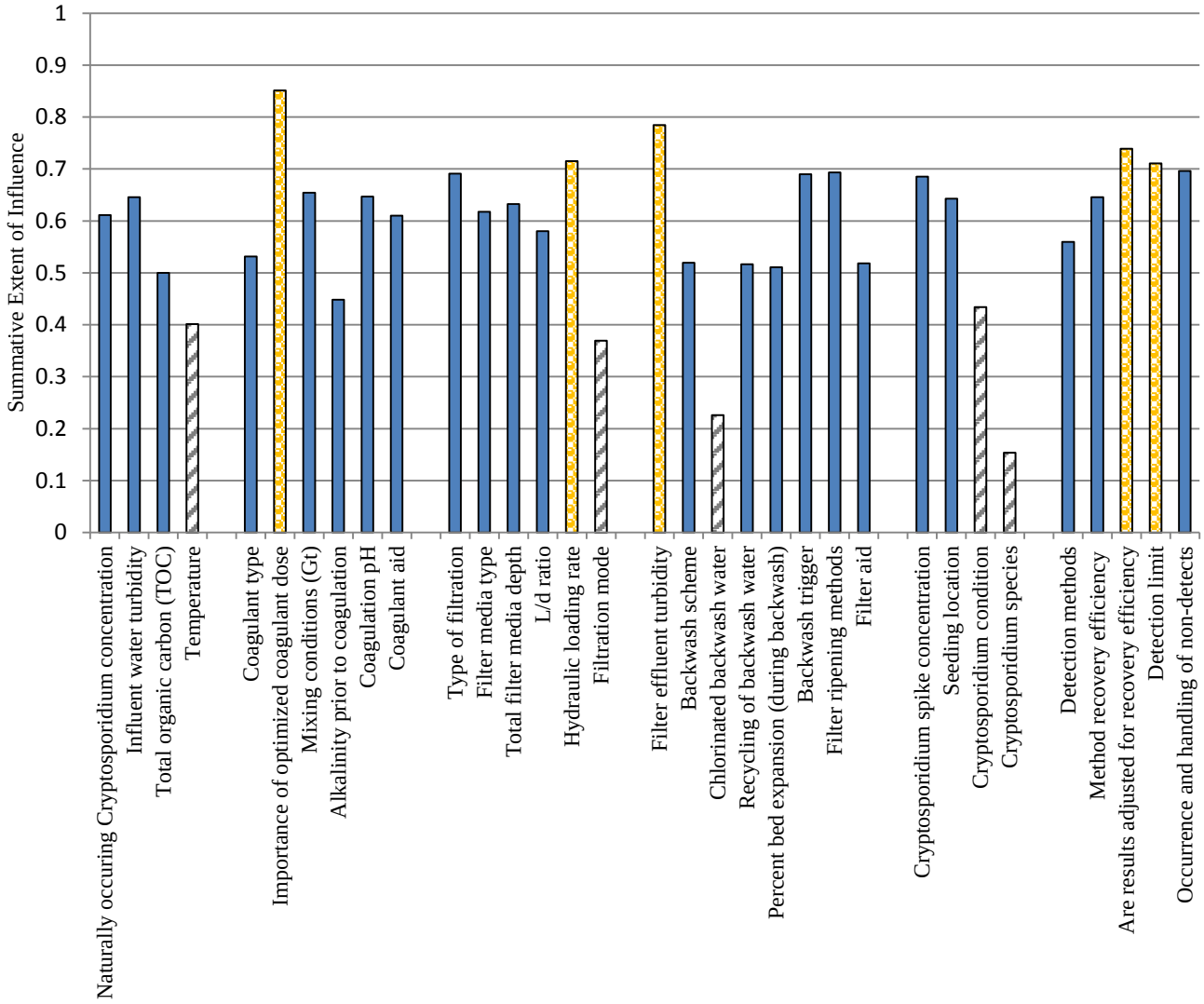


Figure 4.19 Summative extent of influence calculated from coding documentation E

Table 4.10 Response coding documentation F

Score for relevance of influence	**Weight for response basis**
Strong influence = 1	Past research = 3

Some influence = 0.5	Operational experience = 2
No influence = 0	Engineering knowledge = 1

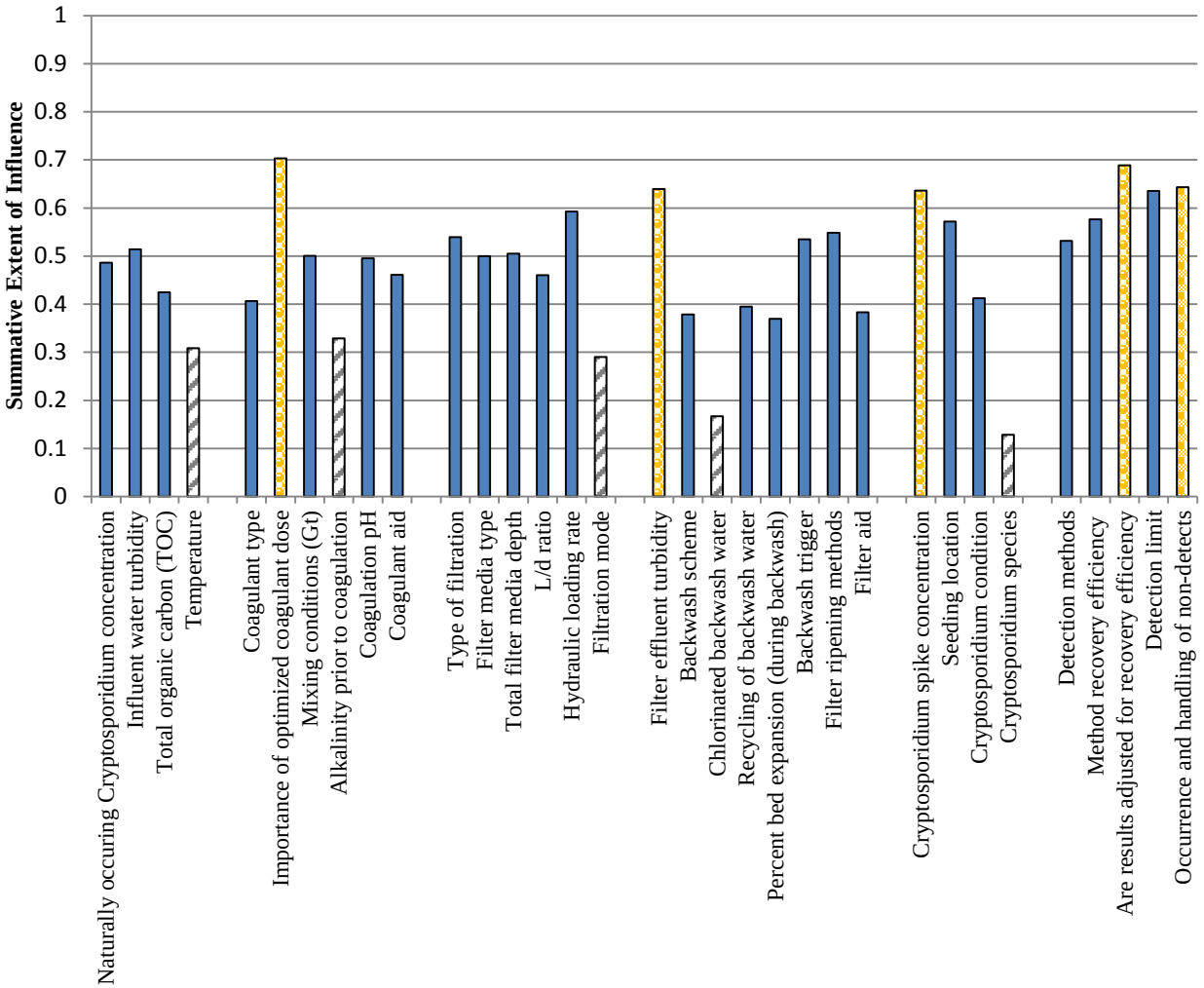


Figure 4.20 Summative extent of influence calculated from coding documentation F

4.6 Comparison of Questionnaire to Published Findings

Questionnaire participants attempted to explain the reasons behind substantial variability in removal data by identifying factors that may be important in removal studies. Respondents reached a consensus on the strong influence of the importance of optimized coagulant dose and filter effluent turbidity, and also the lack of influence of chlorinated backwash water and *Cryptosporidium* species (Figure 4.6). Through the analysis of collected data, factors believed to most influence oocyst removal were identified as being (in order of importance) (1) optimized coagulant dose, (2) filter effluent turbidity, (3) detection limit, (4) results adjusted for recoveries, and (5) *Cryptosporidium* spiked concentration. The five factors believed to be least influential (starting with least influential) were (1) *Cryptosporidium* species, (2) chlorinated backwash water, (3) *Cryptosporidium* condition, (4) filtration mode and (5) temperature.

Findings from published filtration studies were compared with questionnaire results. The questionnaire results were remarkably consistent with what might be expected based on literature findings. Several filtration studies have emphasized the importance of optimized coagulant dose, which is the most important factor identified by respondents (Ongerth and Pecoraro, 1995; Dugan *et al*., 2001; Huck *et al*., 2001; Dugan and Williams, 2004; Brown and Emelko, 2009). While filter effluent turbidity cannot serve as a quantitative indicator, this parameter is stringently regulated and the attainment of specific values allows a utility to claim *Cryptosporidium* removal credits by maintaining turbidities below the set amount (USEPA, 2006; Ontario Ministry of Environment, 2006; Health Canada, 2012b). As discussed in Chapter 2, the reporting of oocyst concentrations in filter effluent (treated) water below the detection limit, may explain the lower than expected oocyst reductions reported in

full-scale studies. Most published filtration studies did not adjust removal results by recovery efficiency, which may have had an influence on the accuracy of removal data. No systematic effect of temperature on removal data have been reported in studies (Swertfeger *et al*., 1999; Huck *et al*., 2001; States *et al.,* 2002), and limited filtration studies have demonstrated little influence of *Cryptosporidium* oocyst condition such as oocyst age and oocyst inactivation (Emelko, 2003; Williams and Dugan, 2003), which is consistent with questionnaire findings where factors of temperature and *Cryptosporidium* condition were rated in the list of least influential factors.

Hydraulic loading rate was listed as the third most influential factors when weighting was not applied (ranking based on percentage of answers of 'strong influence'). However, when weighting system was applied to incorporate all response choices and response basis, this factor was not rated as one of the five most influencing factors (Table 4.5). It is observed that there is a considerable number of "no influence' answers on the effect of hydraulic loading rate, which lower the summative extent of influence value in the weighting system. Compared to literature findings, previous studies reported no apparent effects of changing HLR on *Cryptosporidium* removals (Adin *et al*., 1999; Harrington *et al*., 2003; Hijnen and Medema, 2010).

Cryptosporidium spiked concentration, which was rated as being among the most influential from questionnaire results, has not demonstrated consistent findings in published studies as to its effect on oocyst removal with three studies finding no apparent effect (McTigue *et al*., 1998; Emelko *et al*., 2001; Douglas *et al*., 2014), and one indicating that oocyst removals were dependent on *Cryptosporidium* spiked concentration (Assavasilavasukul *et al*., 2008b).

For the remaining three least influential factors (chlorinated backwash water, filtration mode, and *Cryptosporidium* species), no studies from which to draw conclusions could be located.

In addition, the questionnaire has provided useful information on factors for which the effect has not yet been assessed in filtration experiments. Given that most research studies were conducted at least ten years ago (Figure 2.1), it can be expected that first-hand knowledge and experience with factors affecting oocyst removals will be lost over time. Fortunately, guidelines and the sharing of knowledge among drinking water professionals have entrenched measures which will protect consumers.

4.7 Conclusions

This chapter presented some statistics related to the distribution of questionnaires, respondent's qualifications, responses, and analysis of questionnaire data. The background survey of respondents confirmed that the majority of participants self-assessed that they possessed sufficient knowledge with respect to *Cryptosporidium* removal and were able to provide useful input. The questionnaire responses provided the opportunity to record the relevance of influence of each factor, the basis upon which each answer was assessed, and open-ended comments. The distribution of response choices were presented in several ways. An analysis of this information revealed the varied opinions among professionals of diverse background and viewpoint relating to the drinking water industry. However, overwhelming, consensus was reached on the importance of 'optimized coagulant dose' (95% of respondents rated it as strong influence) and 'filter effluent turbidity' (81% rated as strong influence), as well as the least influential being '*Cryptosporidium* species' and 'chlorinated backwash water' (0% rated them as strong influence). Based on the literature this is not unexpected so knowing this helps to inspire confidence in other study findings. That said, it was unclear if respondents with different exposure to the issue or training answered in different ways. To incorporate response choices and the bases upon which respondents answered, a weighting system was introduced to analyze questionnaire data which identified the most and least influential factors associated with *Cryptosporidium* removal. Sensitivity analyses were

conducted and the robustness of the weighting system was validated. Based on weighted assessments the factors believed to most influence removal data were:

- optimized coagulant dose
- filter effluent turbidity
- oocyst detection limit
- adjustment of results for oocyst recovery
- *Cryptosporidium* oocyst spiked concentration

There were a couple of differences between the top 5 factors identified prior to and following weighting. Specifically, backwash trigger and hydraulic loading were replaced by adjustment of results for oocyst recovery and *Cryptosporidium* oocyst spiked concentration.

Factors thought to be the least influential were identified as:

- *Cryptosporidium* species
- chlorinated backwash water
- *Cryptosporidium* condition
- filtration mode
- temperature

The findings from the questionnaires were generally consistent with other attempts to attribute specific factors to uncertainty reported in literature. The questionnaire adds to the body of scientific knowledge by ranking the factors that may account for the disparity in *Cryptosporidium* oocyst removals reported among various studies/reports. Despite this, it was not possible to definitively identify any single factor which accounts for a substantial portion of the variability. In fact, the differences may not be attributable to single factor but to a group of factors. In addition, the research narrows down the factors that are contributing to the uncertainty. New research studies can take these into account by designing studies to differentiate between their impacts or a least reduce the uncertainty within each factor. For example, spiked concentrations should be as high as reasonably achievable, coagulant dose

should be optimized, and filter effluent turbidity should be optimized to achieve the very low effluent turbidities that are required to reliably estimate maximum possible removals. Particular attention needs to be paid to the oocyst handling and analysis components of such studies as three of the top five issues identified as being important relate to problems associated with these. However, an unexpected finding of this work was that in the past 5 years research on this topic has dramatically slowed with only two publications appearing in the refereed literature. This could delay the resolution of the identified issues and may have implications for regulators and human health outcomes

Chapter 5
Conclusions and Recommendations

5.1 Conclusions

This research was conducted to investigate reasons behind the substantial variability in *Cryptosporidium* oocyst removals reported in the drinking water treatment literature by attempting to link them to differences in raw water characteristics, coagulant conditions, filter design, filter operation, and analytical and experimental methods. The problem was approached by first conducting an updated thorough review of the literature, followed by the development, distribution, and analysis of a questionnaire to access industry knowledge and insights that might not necessarily be reflected in the peer-reviewed literature. This research narrowed down the factors contributing to uncertainty associated with *Cryptosporidium* removal data by ranking the influence of each of a number of factors. It also identified some issues/factors whose effects have not yet been assessed, and provided useful information and some speculation which may not have been reflected in published studies.

Chapter 2 reviewed factors potentially affecting *Cryptosporidium* oocyst removals by granular media filtration. The following conclusions were extracted from the review:

1. Published full- and pilot-scale studies have documented a wide range in *Cryptosporidium* oocyst removals averaging from 1.4 log to 5.8 log through filtration (with or without the effect of pre-treatment).
2. The peak of filtration studies on *Cryptosporidium* removal occurred between 2000 and 2004, with 23 filtration-based publications having been located. Research in the area has dropped off dramatically with only 2 studies appearing in print in the past 5 year period.
3. Though filter effluent turbidity cannot serve as a quantitative surrogate, lower values appear to be associated with improved oocyst removals.

4. No systematic effect of temperature, coagulant type, coagulant pH, filter media, hydraulic loading rate, *Cryptosporidium* condition (i.e. oocyst inactivation, age) on *Cryptosporidium* removals by filtration was reported in the studies reviewed.
5. Studies have not demonstrated consistent findings as to the effect of *Cryptosporidium* spiked seeding concentration on removal results.
6. The presence of non-detects in filter effluent may explain the lower than expected oocyst reductions reported in full-scale studies.
7. The handling of non-detects and recovery efficiency may influence the accuracy of removal data, and should be accounted for when reviewing past and future studies.
8. There is as yet insufficient data in existing studies to assess the effect of confounding factors.

Chapters 3 and 4 presented the development of a questionnaire followed by an analysis of input provided by respondents. Thirty-three potentially influencing factors were identified and categorized into six groups after reviewing published studies, the effect of which were examined through the acquisition of knowledge via a questionnaire. The questionnaire responses included three components; the relevance of influence of a particular factor (strong influence, some influence, no influence, or do not know), the basis upon which each answer was provided (research experience, operational experience, or general engineering knowledge), and an option to include open-ended comments. A total of 135 questionnaires were distributed to drinking water professionals with. 39 being completed, representing a response rate of 35%. In addition, 260 open-ended comments were collected. The following conclusions were drawn from the development and analysis of questionnaire responses:

1. Statistics from the background survey revealed that majority of respondents demonstrated adequate knowledge on this topic and were able to provide valuable input (more than

70% of respondents having direct involvement in research on *Cryptosporidium* or/and surrogate removals through filtration).

2. More than 40% of respondents indicated that they lacked knowledge in assessing the effect of factors such as *Cryptosporidium* species, *Cryptosporidium* condition, chlorinated backwash water, seeding location, and detection methods.
3. There was consensus on the most influential being the importance of optimized coagulant dose (95% of respondents rated it as a strong influence) and filter effluent turbidity (81% rated it as a strong influence).
4. There was consensus on the least influential being *Cryptosporidium* species and chlorinated backwash water (0% rated them as being a strong influence).
5. A weighting system was introduced to code questionnaire data in an effort to identify the most and least influential factors associated with *Cryptosporidium* removal. Sensitivity analyses were conducted to verify the robustness of the weighting system by applying alternative coding documentation. The results indicated that:

   Factors believed to most influence removal data were:

   - optimized coagulant dose
   - filter effluent turbidity
   - oocyst detection limit
   - adjustment of results for oocyst recovery
   - *Cryptosporidium* oocyst spiked concentration

   Factors thought to be the least influential were identified as:

   - *Cryptosporidium* species
   - chlorinated backwash water
   - *Cryptosporidium* condition

- filtration mode
- temperature

The findings from questionnaires were generally consistent with other attempts to attribute specific factors to uncertainty reported in literature. However, published studies have not reached consensus as to the effect of *Cryptosporidium* spiked concentration, and have not examined the effect of chlorinated backwash water, filtration mode, and *Cryptosporidium* species on removal results.

5.2 Implications for the Drinking Water Industry

The wide range of *Cryptosporidium* oocyst removals reported, from 1.4 log to 5.8 log, posed uncertainties in developing expectations for the removal capability that might be reasonably achieved by filtration processes. This research attempted to explain the reasons behind the substantial variability by linking it to differences in raw water characteristics, coagulant type, filter design, filter operation, and analytical or experimental methods, through incorporating both published data and capturing industry knowledge. The questionnaire results add to the body of scientific knowledge by ranking the factors that may most or least account for the disparity in *Cryptosporidium* oocyst removals reported in the literature.

This research narrowed down the factors contributing to uncertainty associated with *Cryptosporidium* removal data. Useful information for the drinking water industry to understand and assess the effect of their plant's design and operation, raw water quality, and coagulation conditions in the context of *Cryptosporidium* removal through granular media filters was acquired. For example, to ensure *Cryptosporidium* removals through filtration processes, the questionnaire findings suggest that coagulant dose should be optimized and filter effluent turbidity should be maintained as low as possible. Respondents also made some recommendations for drinking water filtration practices such as lowering filter effluent turbidity standards/regulations/guidelines to 0.1 NTU from those currently in place.

Questionnaire respondents also identified some issues/factors for which the effect has not yet been assessed in published filtration experiments, and provided useful information and some speculation which may not have been reflected in published studies, based on their research or real-world experience.

Given that most filtration studies were conducted at least ten years ago (Figure 2.1), it can be expected that first-hand knowledge and experience with factors affecting oocyst removals will be lost over time. Fortunately, guidelines and the sharing of knowledge among drinking water professionals have entrenched measures which will protect consumers. When compared to literature findings, the questionnaire results demonstrated consistency in most respects, illustrating that knowledge on this topic has been well documented and applied among drinking water professionals including researchers, water consultants, full-scale plant operators and managers, and regulators. The findings do, however, support lowering the regulated filter effluent turbidity from 0.3 NTU in most jurisdictions to 0.1 NTU. This of course comes with cost and technological considerations which may not be achievable in smaller communities.

A limitation in this research lies in the fact it was not able to examine the effect of confounding factors. There is as yet insufficient data to assess the effect of the multiple confounding factors in existing published studies (as discussed in Chapter 2). Similarly, the questionnaire acquired industry knowledge on the effect of individual factors rather than the effect confounding factors. However, based on the literature review and questionnaire results, it may not be possible to single out any single factor which accounts for a substantial portion of the variability; in fact, differences may not be attributable to any single factor but a group of factors. The potential effect of combined factors still needs to be considered when examining *Cryptosporidium* removals in a particular drinking water treatment plant.

5.3 Recommendations

5.3.1 Recommendations for Future Surveys

Experience gained from this research has provided valuable insight which can be used to streamline the development of a follow-up questionnaire. This includes: (1) involving professionals with both knowledge on questionnaire development and sufficient background on the topic to identify an objective which is reasonably achievable prior to conducting a survey project, (2) designing the data coding methods before establishing the questionnaire questions, and (3) initiating pilot testing of the developed questionnaire at the earliest stage possible to avoid substantial revisions.

5.3.2 Recommendation for Future Research on *Cryptosporidium* Removal

The questionnaire respondents ranked the influence of each of a number of factors and speculated on additional information that may not have been reflected in literature. New research studies can take this into account by designing studies to differentiate between their impacts or a least reduce the uncertainty within each factor. For example, spiked concentrations should be as high as reasonably achievable, coagulant dose should be optimized, and filter effluent turbidity should be optimized to achieve the very low effluent turbidities that are required to reliably estimate maximum possible removals. The questionnaire findings pointed to some issues/factors for which the effect has not yet been assessed or at least adequately addressed in published filtration experiments. These should be considered when planning future research to more definitively answer the question leading to this research, which was to investigate reasons behind the substantial variability in oocyst removals through filtration reported in the literature.

As suggested in the literature review and questionnaire responses, experimental and analytical differences among studies appear to be responsible for considerable variability in oocyst removal data. For example, factors including oocyst detection limit, adjustment of

results for oocyst recovery, and *Cryptosporidium* oocyst spiked concentration were rated among most influential factors. Recommendations were proposed by questionnaire respondents to deal with the uncertainty associated with experimental and analytical differences, such as adhering to a consistent approach for handling non-detects and recovery efficiency adjustment when calculating *Cryptosporidium* removals. In addition to the thirty-three factors identified, other factors potentially influencing *Cryptosporidium* removals were also proposed including the presence of algae, intermittent (discontinuous) filtration, and flow variation. These should be considered for evaluation in future work.

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Appendix A

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	23.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.6E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>4.9	Ottawa-Huck *et al.*, 2001
N/A[7]	23.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.1E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>4.7	
N/A[7]	23.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.8E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	4.7	
N/A[7]	23.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	2.7E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.1	
N/A[7]	20.1	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.1E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.7	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	20.1	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	7.9E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.6	Ottawa-Huck *et al.*, 2001
N/A[7]	20.1	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	9.7E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.7	
N/A[7]	20.1	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	9.2E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.7	
N/A[7]	16.9	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.04	No	1.2E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.8	
N/A[7]	16.9	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.4E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.8	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	16.9	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.3E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.8	Ottawa-Huck *et al.*, 2001
N/A[7]	16.9	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.4E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.8	
N/A[7]	14.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.4E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.8	
N/A[7]	14.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.4E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.8	
N/A[7]	14.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.4E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	5.8	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	14.5	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	1.4E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.5	Ottawa-Huck *et al.*, 2001
N/A[7]	2.3	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.6E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.6	
N/A[7]	2.3	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.7E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.0	
N/A[7]	2.3	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.7E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	4.8	
N/A[7]	2.3	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.7E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.5	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	18.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.04	No	1.1E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.7	Ottawa-Huck *et al*., 2001
N/A[7]	18.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.0E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.4	
N/A[7]	18.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.1E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.4	
N/A[7]	18.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	1.2E+6	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.8	
N/A[7]	24.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64,	6.75	0.05	No	7.6E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.6	

						S[4]/27.9											

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (℃)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	24.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.04	No	8.0E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.6	Ottawa-Huck *et al.*, 2001
N/A[7]	24.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.04	No	7.3E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.6	
N/A[7]	24.7	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.04	No	8.2E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	Treated as DL[25]	>5.6	
N/A[7]	1.6	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.02	No	4.2E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.3	

N/A[7]	1.6	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	4.4E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.3	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	1.6	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	5.0E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	5.7	Ottawa-Huck *et al.*, 2001
N/A[7]	1.6	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.03	No	4.9E+5	Inactiv--ated	FI[5]	IFA[6]	2	Not applied	No non-detect	4.8	
N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.08	No	30	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>1.2	

N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.07	No	710	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>2.6	
N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.06	No	300	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>2.2	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

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FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.06	No	210	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>2.0	Ottawa-Huck *et al.*, 2001
N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.05	No	120	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>1.8	

N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.05	No	90	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>1.7	
N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.05	No	10	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>0.7	
N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.05	No	0	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>0	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	23.8	Alum/40	6	AS[1]/ 2	C[2]	A[3]/ 40.64, S[4]/27.9	6.75	0.05	No	0	Inactiv--ated	RM[8]	IFA[6]	2	Not applied	Treated as DL[25]	>0	Ottawa-Huck *et al*., 2001

0.61	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	9.48E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.6	MWD-Huck *et al.*,2001
0.61	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	8.36E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.6	
0.61	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	6.42E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.5	
0.62	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	5.86E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.7	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		

0.81	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.91E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.4	MWD-Huck *et al.*, 2001
0.82	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.69E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.3	
0.86	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.97E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.4	
0.85	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.52E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.2	
0.85	24	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.38E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.9	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality	Coagulation conditions	Filter design	Filter operation	Experimental differences	Analytical differences	Oocyst log	References

FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects	removal by filtration	
0.83	24	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	4.61E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.5	MWD-Huck *et al.*, 2001
0.84	24	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	9.69E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	4.0	
0.84	24	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.95E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	5.0	
0.95	25	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.99E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.7	
0.95	25	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.18E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.7	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality	Coagulation conditions	Filter design	Filter operation	Experimental differences	Analytical differences	Oocyst log	References

FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects	removal by filtration	
0.95	25	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.76E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	4.0	MWD-Huck *et al*., 2001
0.93	25	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.42E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.9	
0.80	21	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.19E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.3	
0.53	15	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.38E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.1	
0.53	15	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.45E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.9	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.53	15	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.46E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.9	MWD-Huck *et al.*, 2001
0.52	15	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.06E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.8	
0.53	13	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	6.26E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.0	
0.52	13	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	5.44E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.0	
0.50	13	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	5.88E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.2	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.50	13	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	6.44E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.2	MWD-Huck *et al.*, 2001
0.51	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.83E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.7	
0.49	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.54E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.3	
0.49	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	2.09E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.4	
0.51	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.89E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.3	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.62	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.19E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.1	MWD-Huck *et al.*, 2001
0.60	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.57E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	3.0	
0.62	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	1.36E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.9	
0.62	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	5.78E+4	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	No non-detect	2.5	
0.39	14	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	2.28E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	0.2	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.39	14	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	2.14E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	0.1	MWD-Huck *et al*., 2001
0.39	14	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	1.90E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	0.2	
0.39	14	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	2.16E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	0.2	
0.59	16	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	4.47E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	2.5	

0.59	16	Alum/5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	3.96E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	2.3	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (℃)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.57	16	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.06	No	5.06E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	2.3	MWD-Huck *et al.*, 2001
0.56	16	Alum/ 5	7.8	CP[9] /1.5	C[2]	A[3]/ 50.8, S[4]/20.3	9.8	0.05	No	6.00E+3	Inactiv--ated	RM[8]	IFA[6]	N/A[7]	Not applied	No non-detect	2.4	
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	S[4]/75	6.3	0.06	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	2.9	Swertfeger *et al.*, 1999
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	A[3]/90, S[4]/30	12.6	0.06	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.2	
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	A[3]/150, S[4]/30	12.6	0.05	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.8	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	S[4]/75	6.3	0.06	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.0	Swertfeger *et al*., 1999
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	A[3]/90, S[4]/30	12.6	0.06	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.1	
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	A[3]/150, S[4]/30	12.6	0.05	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	4.0	
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	S[4]/75	6.3	0.06	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	2.5	

1.97	14	Alum	N/A[7]	N/A[7]	C[2]	A[3]/90, S[4]/30	12.6	0.06	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.2	
1.97	14	Alum	N/A[7]	N/A[7]	C[2]	A[3]/150, S[4]/30	12.6	0.05	F[11]	1.7E+5 to 1.3E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	2.9	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		**Coagulation conditions**			**Filter design**			**Filter operation**		**Experimental differences**			**Analytical differences**				**Oocyst log removal by filtration**	**References**
FI[5] turbidity (NTU)	**Temperature (°C)**	**Coagulant type / dosage (mg/L)**	**Coagulation pH**	**Coagulation aid**	**Type of filtration**	**Filter media /depth (cm)**	**Hydraulic loading rate (m/h)**	**Filter effluent turbidity (NTU)**	**Filter aid**	**Oocyst spiked concentration in FI[5] (oocysts/L)**	***Cryptosporidium* condition**	**Seeding location**	**Detection methods**	**Detection limits (oocysts/L)**	**Recovery efficiency**	**Occurrence and handling of non-detects**		
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	S[4]/75	6.3	0.11	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	1.8	Swertfeger *et al*., 1999
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	A[3]/90, S[4]/30	12.6	0.12	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	1.6	

1.33	23	Alum	N/A[7]	N/A[7]	C[2]	A[3]/150, S[4]/30	12.6	0.14	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.9	
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	S[4]/75	6.3	0.11	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.3	
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	A[3]/90, S[4]/30	12.6	0.12	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.4	
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	A[3]/150, S[4]/30	12.6	0.14	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.4	
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	S[4]/75	6.3	0.11	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	2.9	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		**Coagulation conditions**			**Filter design**			**Filter operation**		**Experimental differences**			**Analytical differences**				**Oocyst log removal by filtration**	**References**
FI[5] turbidity (NTU)	**Temperature (°C)**	**Coagulant type / dosage (mg/L)**	**Coagulation pH**	**Coagulation aid**	**Type of filtration**	**Filter media /depth (cm)**	**Hydraulic loading rate (m/h)**	**Filter effluent turbidity (NTU)**	**Filter aid**	**Oocyst concentration in FI[5] (oocysts/L)**	***Cryptosporidium* condition**	**Seeding location**	**Detection methods**	**Detection limits (oocysts/L)**	**Recovery efficiency**	**Occurrence and handling of non-detects**		
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	A[3]/90, S[4]/30	12.6	0.12	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	3.1	Swertfeger *et al*., 1999
1.33	23	Alum	N/A[7]	N/A[7]	C[2]	A[3]/150, S[4]/30	12.6	0.14	F[11]	2.5E+5 to 1.1E+6	Inactiv--ated	FI[5]	FC[12]	N/A[7]	Not applied	No non-detect	4.2	
3.5	20	Alum/30	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.02	No	1.45E+05[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	2.9	Dugan *et al*., 2001

2.4	20	Alum/10	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.08	No	4.66E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	4.4	
0.63	20	Ferric/15	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.14	No	6.01E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	75%; treated as 1 oocysts/EV[24]	>3.2	
4.2	20	Ferric/15	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.15	No	3.26E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	3.7	
2.1	20	Alum/50	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.06	No	4.26E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	3.5	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log Removal by filtration	References
FI[5] turbidity (NTU)	Temperature (℃)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
2.1	20	Alum/50	N/A[7]	N/A[7]	C[2]	S[4]/76	5	0.06	No	4.26E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	22%; treated as 1 oocysts/EV[24]	>3.6	Dugan *et al*., 2001

1.1	20	Alum/ 40	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.06	No	4.81E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	38%; treated as 1 oocysts/EV[24]	>3.6	
1.2	20	Ferric/ 30	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.08	No	4.81E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	33%; treated as 1 oocysts/EV[24]	>3.3	
0.3	20	Alum/ 15	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.09	No	3.06E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	13%; treated as 1 oocysts/EV[24]	>4.3	
0.3	20	Polym er/14	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.09	No	3.06E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	13%; treated as 1 oocysts/EV[24]	>4.4	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		**Coagulation conditions**			**Filter design**			**Filter operation**		**Experimental differences**			**Analytical differences**				**Oocyst log removal by filtration**	**References**
FI[5] turbidity (NTU)	**Temperature (°C)**	**Coagulant type / dosage (mg/L)**	**Coagulation pH**	**Coagulation aid**	**Type of filtration**	**Filter media /depth (cm)**	**Hydraulic loading rate (m/h)**	**Filter effluent turbidity (NTU)**	**Filter aid**	**Oocyst concentration in FI[5] (oocysts/L)**	***Cryptosporidium* condition**	**Seeding location**	**Detection methods**	**Detection limits (oocysts/L)**	**Recovery efficiency**	**Occurrence and handling of non-detects**		

1.9	20	Alum/ 40	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.08	No	3.56E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	33%; treated as 1 oocysts/EV[24]	>3.6	Dugan *et al.*, 2001
1.9	20	Alum/ 40	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	10	N/A[7]	No	3.56E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	>3.4	
2.3	20	Alum/ 20	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.10	No	4.71E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	17%; treated as 1 oocysts/EV[24]	>4.1	
2.3	20	Alum/ 20	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	10	N/A[7]	No	4.71E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	4.1	
1.4	20	Alum/ 60	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	5	0.08	No	4.71E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	3.7	
1.4	20	Alum/ 60	N/A[7]	N/A[7]	C[2]	A[3]/51, S[4]/25	10	N/A[7]	No	4.71E+04[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	>3.7	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality	Coagulation conditions	Filter design	Filter operation	Experimental differences	Analytical differences	Oocyst log	References

FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects	removal by filtration	
0.7-0.8	5	Ferric chloride /17.5	6	No	C[2]	Dual media	7.3	N/A[7]	No	2	N/A[7]	R[13]	N/A[7]	N/A[7]	N/A[7]	N/A[7]	2	Edzwald and Kelley, 1998
0.7-0.8	5	Ferric chloride /17.5	6	No	C[2]	Dual media	14.6	N/A[7]	No	2	N/A[7]	R[13]	N/A[7]	N/A[7]	N/A[7]	N/A[7]	2	
0.8	5	Alum/20	6.5	No	C[2]	Dual media	7.3	N/A[7]	No	25.1	N/A[7]	R[13]	N/A[7]	N/A[7]	N/A[7]	N/A[7]	2.9	
0.8	5	Alum/20	6.5	No	C[2]	Dual media	14.6	N/A[7]	No	25.1	N/A[7]	R[13]	N/A[7]	N/A[7]	N/A[7]	N/A[7]	2.2	
0.71-0.75	2.5	Alum/22	6.7	CP[9]/1	C[2]	A[3]/60, S[4]/30	14.6	0.03-0.05	No	1.90E+02*	Inactiv--ated	R[13]	IFA[6]	N/A[7]	N/A[7]	100%; treated as 1 oocyst/EV[24]	>3.7*	Edzwald *et al*., 2000

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Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water	Coagulation	Filter design	Filter	Experimental differences	Analytical differences	Oocyst	Reference

quality		conditions						operation									log removal by filtration	s
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
1.82-1.89	2.5	Alum/ 23	6.8	CP[9]/ 1.1	C[2]	A[3]/60, S[4]/30	14.6	0.03-0.05	FAC[1] [4]/ 0.05	2.70E+03[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	N/A[7]	100%; treated as 1 oocyst/ EV[24]	>4.69[*]	Edzwald *et al*., 2000
1.36-1.65	2.5	Alum/ 28	6.8	No	C[2]	A[3]/60, S[4]/30	14.6	0.03-0.09	FAC[1] [4]/ 0.06	2.58E+03[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	N/A[7]	100%; treated as 1 oocyst/ EV[24]	>4.77[*]	
0.49-0.76	13.5	Alum/ 19	6.5	CP[9]/ 1.1	C[2]	A[3]/60, S[4]/30	14.6	0.03-0.07	No	1.11E+01[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	N/A[7]	100%; treated as 1 oocyst/ EV[24]	>3[*]	
0.95-1.02	13.5	Alum/ 18	6.6	CP[9]/ 1.1	C[2]	A[3]/60, S[4]/30	14.6	0.02-0.05	FAC[1] [4]/ 0.06	1.96E+02[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	N/A[7]	100%; treated as 1 oocyst/ EV[24]	>4.3[*]	
1.08-1.24	13.5	Alum/ 22	6.4	No	C[2]	A[3]/60, S[4]/30	14.6	0.03-0.07	FAC[1] [4]/ 0.06	7.03E+01[*]	Inactiv--ated	R[13]	IFA[6]	N/A[7]	N/A[7]	100%; treated as 1 oocyst/EV[24]	>3.9[*]	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
1.54	1 to 12.5	PC[15]/4	N/A[7]	N/A[7]	C[2]	A[3]/60, S[4]/30	14.6	0.03	No	154.22	N/A[7]	R[13]	N/A[7]	0.0025	Not applied	N/A[7]	4.1[*]	Cornwell and Macphee, 2001
1.93	1 to 12.5	PC[15]/4	N/A[7]	N/A[7]	C[2]	A[3]/60, S[4]/30	14.6	0.03	No	94.41	N/A[7]	R[13]	N/A[7]	0.0025	Not applied	Treated as DL[25]	>4.62[*]	
0.92	1 to 12.5	PC[15]/4	N/A[7]	N/A[7]	C[2]	A[3]/60, S[4]/30	14.6	0.03	No	67.17	N/A[7]	R[13]	N/A[7]	0.0025	Not applied	Treated as DL[25]	>4.53[*]	
1.76	1 to 12.5	PC[15]/4	N/A[7]	N/A[7]	C[2]	A[3]/60, S[4]/30	14.6	0.03	No	88.41	N/A[7]	R[13]	N/A[7]	0.0025	Not applied	N/A[7]	4.69[*]	
1.13	15.2	Alum/ 80	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.17	No	3.3E+3	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	1.6	Assavasilav--asukul *et al.*, 2008a
1.02	15.2	Alum/ 70	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.16	No	2.3E+2	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	1.2	
1.0	6.7	Alum/ 60	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.08	No	5.7E+3	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	2.1	
1.0	6.7	Alum/ 50	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.05	No	4.1E+2	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	1.0	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log Removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.34	9.4	Alum/ 60	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.04	No	5.9E+2	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	1.5	Assavasilav--asukul *et al.*, 2008a
0.36	9.4	Alum/ 60	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.16	No	Not-detectable	Viable	R[13]	IFA[6]	N/A[7]	Not applied	100% non-detect	N/A[7]	
0.60	7.0	Alum/ 70	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.19	No	Not-detectable	Viable	R[13]	IFA[6]	N/A[7]	Not applied	100% non-detect	N/A[7]	
0.49	7.0	Alum/ 80	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.14	No	1.5E+2	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	0.3	
0.58	12	Alum/ 80	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.09	No	1.7E+4	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	3.0	
0.81	12	Alum/ 70	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.16	No	Not-detectable	Viable	R[13]	IFA[6]	N/A[7]	Not applied	100% non-detect	N/A[7]	
0.79	8	Alum/ 70	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.1	No	Not-detectable	Viable	R[13]	IFA[6]	N/A[7]	Not applied	100% non-detect	N/A[7]	

0.63	8	Alum/ 80	N/A[7]	No	C[2]	A[3]/46, S[4]/30	11.8	0.06	No	1.1E+4	Viable	R[13]	IFA[6]	N/A[7]	Not applied	N/A[7]	1.3	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (℃)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.73	22.9	Alum/ 33.45	N/A[7]	AS[1]/ 0.64	C[2]	A[3]/64, S[4]/41	2.63	0.08	No	3.83E+5	Inactiv--ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.58	Trial 6-Douglas *et al*., 2014
0.73	22.9	Alum/ 33.45	N/A[7]	AS[1]/ 0.64	C[2]	GAC[17] /64, S[4]/41	2.63	0.09	No	4.23E+5	Inactiv--ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.63	
0.73	22.9	Alum/ 33.45	N/A[7]	AS[1]/ 0.64	C[2]	A[3]/64, S[4]/41	2.63	0.06	No	6.6E+5	Inactiv--ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.82	
0.73	22.9	Alum/ 33.45	N/A[7]	AS[1]/ 0.64	C[2]	GAC[17] /64, S[4]/41	2.63	0.07	No	4.9E+5	Inactiv--ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.69	
0.73	22.9	Alum/ 33.45	N/A[7]	AS[1]/ 0.64	C[2]	A[3]/64, S[4]/41	2.63	0.04	No	4.17E+5	Inactiv--ated	FI[5]	N/A[7]	1	N/A[7]	No non-detect	5.62	

0.73	22.9	Alum/ 33.45	N/A[7]	AS[1]/ 0.64	C[2]	GAC[17] /64, S[4]/41	2.63	0.04	No	4.84E+5	Inactiv-- ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.69	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.73	22.9	Alum/ 32.87	5.8	AS[1]/ 0.68	C[2]	A[3]/64, S[4]/41	2.63	0.04	No	4.83E+5	Inactiv-- ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.68	Trial 6-Douglas *et al*., 2014
0.73	22.9	Alum/ 33.45	5.8	AS[1]/ 0.64	C[2]	GAC[17] /64, S[4]/41	2.63	0.04	No	5.08E+5	Inactiv-- ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.71	
0.73	22.9	Alum/ 33.45	5.8	AS[1]/ 0.64	C[2]	A[3]/64, S[4]/41	2.63	0.04	No	3.84E+5	Inactiv-- ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.58	
0.73	22.9	Alum/ 33.45	5.8	AS[1]/ 0.64	C[2]	GAC[17] /64, S[4]/41	2.63	0.04	No	4.03E+5	Inactiv-- ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.61	
0.73	22.9	Alum/	5.8	AS[1]/	C[2]	A[3]/64,	2.63	0.04	No	2.84E+5	Inactiv--	FI[5]	N/A[7]	1	N/A[7]	Treated as	>5.45	

		33.45		0.64		S[4]/41					ated					DL[25]		

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
FI[5] turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst concentration in FI[5] (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.73	22.9	Alum/ 33.45	5.8	AS[1]/ 0.64	C[2]	GAC[17] /64, S[4]/41	2.63	0.04	No	1.97E+5	Inactiv--ated	FI[5]	N/A[7]	1	N/A[7]	Treated as DL[25]	>5.29	Trial 6-Douglas *et al*., 2014
2.45	0.5	Alum/ 35.3	5.71	AS[1]/ 1.7	C[2]	A[3]/64, S[4]/41	6.58	0.03	No	0.1	Inactiv--ated	FI[5]	N/A[7]	0.00417	N/A[7]	N/A[7]	N/A[7]	Trial 7-Douglas *et al*., 2014
2.45	0.5	Alum/ 35.3	5.71	AS[1]/ 1.7	C[2]	A[3]/64, S[4]/41	6.58	0.04	No	1.2E+3	Inactiv--ated	FI[5]	N/A[7]	0.00417	N/A[7]	No non-detect	5.46	
2.45	0.5	Alum/ 35.3	5.71	AS[1]/ 1.7	C[2]	A[3]/64, S[4]/41	6.58	0.05	No	1.42E+6	Inactiv--ated	FI[5]	N/A[7]	0.00417	N/A[7]	No non-detect	5.52	

2.45	0.5	Alum/ 35.6	5.71	AS[1]/ 1.7	C[2]	A[3]/64, S[4]/41	6.58	0.03	No	0.1	Inactiv--ated	FI[5]	N/A[7]	0.0041 7	N/A[7]	N/A[7]	N/A[7]	
2.45	0.5	Alum/ 35.6	5.71	AS[1]/ 1.7	C[2]	A[3]/64, S[4]/41	6.58	0.05	No	2.87E+3	N/A[7]	FI[5]	N/A[7]	0.0041 7	N/A[7]	No non-detect	4.93	
2.45	0.5	Alum/ 35.6	5.71	AS[1]/ 1.7	C[2]	A[3]/64, S[4]/41	6.58	0.06	No	3.31E+6	N/A[7]	FI[5]	N/A[7]	0.0041 7	N/A[7]	No non-detect	4.63	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
Influent water turbidity (NTU)	Temperature (℃)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
N/A[7]	N/A[7]	Alum/5	8	N/A[7]	D[20]	A[3]/50.8, S[4]/20.3	14.7	0.06	P[16]/ 1	A spike of 10^8 oocysts	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	N/A[7]	N/A[7]	3.7[23]	Yates *et al.*, 1997
N/A[7]	N/A[7]	Ferric chloride/ 3	8	N/A[7]	D[20]	A[3]/50.8, S[4]/20.3	14.7	0.06	P[16]/ 1	A spike of 10^8 oocysts	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	N/A[7]	N/A[7]	4.5[23]	
0.45	N/A[7]	Alum/10	6.5	No	D[20]	A[3]/45.7, S[4]/22, G[21]/14.7	12.3	0.03	No	1006	Viable	R[13]	IFA[6]	N/A[7]	Applied	No non-detect	2.9[23]	Ongerth and Pecoraro, 1995
0.38	20	Alum/10	6.5	No	D[20]	A[3]/45.7,S[4] /22, G[21]/14.7	12.3	0.021	No	1296	Viable	R[13]	IFA[6]	N/A[7]	Applied	No non-detect	3.1[23]	

0.41	19.5	Alum/10	6.5	No	D[20]	A[3]/45.7, S[4]/22, G[21]/14.7	12.3	0.0026	No	2764	Viable	R[13]	IFA[6]	N/A[7]	Applied	No non-detect	2.8[23]	
0.43	16.5	Alum/10	6.5	No	D[20]	A[3]/45.7, S[4]/22, G[21]/14.7	12.3	0.09	No	816	Viable	R[13]	IFA[6]	N/A[7]	Applied	No non-detect	2.7[23]	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log Removal by filtration	References
Influent water turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
2.5-28	N/A[7]	N/A[7]	N/A[7]	N/A[7]	D[20](full-scale)	Dual media	11.8	0.15	No	A spike of 10^7oocysts	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	2.88[23]	Nieminski and Ongerth, 1995
2.5-28	N/A[7]	N/A[7]	N/A[7]	N/A[7]	D[20](full-scale)	Dual media	11.8	0.15	No	A spike of 10^7oocysts	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	2.92[23]	
2.5-28	N/A[7]	N/A[7]	N/A[7]	N/A[7]	D[20](full-scale)	Dual media	11.8	0.15	No	A spike of 10^7oocysts	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	2.57[23]	
4-23	N/A[7]	Alum/6	N/A[7]	CP[9]/3	D[20]	A[3]/51, S[4]/61	14.1	0.15	AP[22]	1.53E+4	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	3.60[23]	

4-23	N/A[7]	Alum/6	N/A[7]	CP[9]/3	D[20]	A[3]/51, S[4]/61	14.1	0.15	AP[22]	1.53E+4	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	1.31[23]	
4-23	N/A[7]	Alum/6	N/A[7]	CP[9]/3	D[20]	A[3]/51, S[4]/61	14.1	0.15	AP[22]	1.53E+4	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	3.78[23]	
4-23	N/A[7]	Alum/6	N/A[7]	CP[9]/3	D[20]	A[3]/51, S[4]/61	14.1	0.15	AP[22]	1.53E+4	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	2.90[23]	
4-23	N/A[7]	Alum/6	N/A[7]	CP[9]/3	D[20]	A[3]/51, S[4]/61	14.1	0.15	AP[22]	1.53E+4	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	3.31[23]	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
Influent water turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
4-23	N/A[7]	Alum/6	N/A[7]	CP[9]/3	D[20]	A[3]/51, S[4]/61	14.1	0.15	AP[22]	1.53E+4	Inactiv--ated	R[13]	IFA[6]	N/A[7]	Not applied	No non-detect	2.93[23]	Nieminski and Ongerth, 1995
0.26	20	Alum/20	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.066	No	1.0E+5	Viable	R[13]	SPC[19]	N/A[7]	Not applied	Treated as 1 oocyst/EV[24]	>4.2[23]	Dugan and Williams,

0.26	20	Alum/ 20	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.068	No	1.0E+5	Viable	R[13]	SPC [19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.3[23]	2004
0.26	20	Alum/ 20	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.061	No	1.0E+5	Viable	R[13]	SPC [19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.1[23]	
0.26	20	Alum/ 20	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.063	No	1.0E+5	Viable	R[13]	SPC [19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.1[23]	
0.26	20	Alum/ 20	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.074	No	1.0E+5	Viable	R[13]	SPC [19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.2[23]	
0.26	20	Alum/ 20	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.061	No	1.0E+5	Viable	R[13]	SPC [19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.2[23]	
0.26	20	Alum/ 20	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.064	No	1.0E+5	Viable	R[13]	SPC [19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4[23]	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
Influent water turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
0.20	20	Ferric chloride/10	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.062	No	1.0E+5	Viable	R[13]	SPC [19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.1[23]	Dugan and Williams,

0.20	20	Ferric chloride/10	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.075	No	1.0E+5	Viable	R[13]	SPC[19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.2[23]	2004
0.20	20	Ferric chloride/10	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.067	No	1.0E+5	Viable	R[13]	SPC[19]	N/A[7]	Not applied	No non-detect	4.0[23]	
0.20	20	Ferric chloride/10	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.068	No	1.0E+5	Viable	R[13]	SPC[19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.2[23]	
0.20	20	Ferric chloride/10	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.078	No	1.0E+5	Viable	R[13]	SPC[19]	N/A[7]	Not applied	No non-detect	4.2[23]	
0.20	20	Ferric chloride/10	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.079	No	1.0E+5	Viable	R[13]	SPC[19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.1[23]	
0.20	20	Ferric chloride/10	7.4	No	I[18]	A[3]/51, S[4]/25	5	0.073	No	1.0E+5	Viable	R[13]	SPC[19]	N/A[7]	Not applied	Treated as 1 oocyst/ EV[24]	>4.2[23]	

(Continued)

Table A1 Summary of *Cryptosporidium* Log Removal Data by Pilot-scale Rapid Granular Filtration Experiments

Raw water quality		Coagulation conditions			Filter design			Filter operation		Experimental differences			Analytical differences				Oocyst log removal by filtration	References
Influent water turbidity (NTU)	Temperature (°C)	Coagulant type / dosage (mg/L)	Coagulation pH	Coagulation aid	Type of filtration	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Filter aid	Oocyst spiked concentration (oocysts/L)	*Cryptosporidium* condition	Seeding location	Detection methods	Detection limits (oocysts/L)	Recovery efficiency	Occurrence and handling of non-detects		
3.55	20	Alum/5	7.4	No	I[18]	A[3]/52, S[4]/20	10.4	0.058	No	1.0E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	N/A[7]	4.4	Brown and Emelko,

3.52	20	Ferric chloride/ 3	7.4	No	I[18]	A[3]/52, S[4]/20	10.4	0.0673	No	1.0E+5	Inactiv--ated	FI[5]	IFA[6]	N/A[7]	Not applied	N/A[7]	4.1	2009

Table A2 Summary of *Cryptosporidium* Log Removal Data by full-scale Water Treatment Plant with Naturally Occurring Oocysts

Raw water quality		Coagulation conditions	Filter design		Filter operation	Plant configuration	Analytical differences			Oocyst log removal by entire plant	References
Raw water turbidity (NTU)	Naturally occurring *Cryptosporidium* concentration (Oocysts/100L)	Coagulant type	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Treatment process before filtration	Detection limits (oocysts/100L)	Recovery efficiency	Occurrence and handling of non-detects		

N/A[7]	31	Ferric chloride	A[3]/46, S[4]/30	2.45	<0.1	Coagulation; Flocculation; Sedimentation	0.6	Not applied	Treated as DL[25]	>1.49	States *et al.*, 1997
N/A[7]	N/A[7]	Ferric or Alum or Polymer	Sand or Dual media or Mixed media or GAC	N/A[7]	0.19	66 full-scale Plants	N/A[7]	N/A[7]	No non-detect	Average 2.38	Lechevallier *et al.*, 1991
					0.18				Non-detect	Average >2.2	
High	480	Ferric	Dual media	N/A[7]	N/A[7]	Conventional Plant with lime s	N/A[7]	Not applied	Non-detect	>2.38	Lechevallier and Norton (1992)
Moderate	250	Alum	GAC[17]/S[4]	N/A[7]	N/A[7]	Coagulation; In-line mixing; Sedimentation	N/A[7]	Not applied	Non-detect	>2.45	
Low	250	Alum	Dual media	N/A[7]	N/A[7]	Coagulation; Flocculation; Sedimentation	N/A[7]	Not applied	Non-detect	>2.30	

(Continued)

Table A2 Summary of *Cryptosporidium* Log Removal Data by full-scale Water Treatment Plant with Naturally Occurring Oocysts

Raw water quality	Coagulation conditions	Filter design	Filter operation	Plant configuration	Analytical differences	Oocyst log	References

Raw water turbidity (NTU)	Naturally occurring *Cryptosporidium* concentration (oocysts/100L)	Coagulant type	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Treatment process before filtration	Detection limits (oocysts/100L)	Recovery efficiency	Occurrence and handling of non-detects	removal by entire plant	
N/A[7]	60	Alum	Sand Filter	N/A[7]	Average 0.097	Coagulation; Lime softening; Sedimentation	N/A[7]	Not applied	Non-detect	>1.78; >0.98 (filtration only)	Kelly *et al*.,1995
N/A[7]	53	Alum	Sand Filter	N/A[7]	Average 0.103	Coagulation; Flocculation; Sedimentation	N/A[7]	Not applied	Non-detect	>1.4; >0.9 (filtration only)	
1	3.4	WAC	PS/S[4]	10	<0.1 (55-70%); <0.2 (97-99%)	Direct filtration	N/A[7]	N/A[7]	N/A[7]	>4 (filtration only)	Baudin and Laîné, 1998
15	137.5	Polyaluminium chloride	GAC[17]/ 80	7	<0.1 (99%)	Conventional plant	N/A[7]	N/A[7]	N/A[7]	2-3 (filtration only)	

(Continued)

Table A2 Summary of *Cryptosporidium* Log Removal Data by full-scale Water Treatment Plant with Naturally Occurring Oocysts

Raw water quality		Coagulation conditions	Filter design		Filter operation	Plant configuration	Analytical differences			Oocyst log removal by entire plant	References
Raw water turbidity (NTU)	Naturally occurring *Cryptosporidium* concentration (Oocysts/100L)	Coagulant type	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Treatment process before filtration	Detection limits (oocysts/100L)	Recovery efficiency	Occurrence and handling of non-detects		
<50 most of time	30	Alum	Mono-media	N/A[7]	N/A[7]	Coagulation; Clarification; Lime softening	0.1	Not applied	Non-detect	>2.4	Gammie *et al.*, 1998
<50 most of time	22	Alum	Dual media	N/A[7]	N/A[7]	Coagulation; Clarification; Lime softening	0.1	Not applied	Non-detect	>2.2	
<50 most of time	45	Alum	Mono-media	N/A[7]	N/A[7]	Coagulation; Clarification; Lime softening	0.1	Not applied	Non-detect	>2.4	
<50 most of time	23	Alum	Dual media	N/A[7]	N/A[7]	Coagulation; Clarification; Lime softening	0.1	Not applied	Non-detect	>2.1	

<50 most of time	228	Alum	Mono-media	N/A[7]	N/A[7]	Coagulation; Clarification; Lime softening	0.1	Not applied	No non-detect	3	

Table A2 Summary of *Cryptosporidium* Log Removal Data by full-scale Water Treatment Plant with Naturally Occurring Oocysts

Raw water quality		Coagulation conditions	Filter design		Filter operation	Plant configuration	Analytical differences			Oocyst log removal by entire plant	References
Raw water turbidity (NTU)	Naturally occurring *Cryptosporidium* concentration (Oocysts/100L)	Coagulant type	Filter media /depth (cm)	Hydraulic loading rate (m/h)	Filter effluent turbidity (NTU)	Treatment process before filtration	Detection limits (oocysts/100L)	Recovery efficiency	Occurrence and handling of non-detects		
<50 most of time	130	Alum	Dual media	N/A[7]	N/A[7]	Coagulation, Clarification, Lime softening	0.1	Not applied	No non-detect	3.1	Gammie *et al.*, 1998
<50 most of time	77	Alum	Mono-media	N/A[7]	N/A[7]	Coagulation, Clarification, Lime softening	0.1	Not applied	Non-detect	>2.9	
<50 most of time	31	Alum	Dual media	N/A[7]	N/A[7]	Coagulation, Clarification, Lime softening	0.1	Not applied	Non-detect	>2.6	

1. AS: activated silica; 2. C: conventional filtration (i.e., raw water go through coagulation, flocculation, clarification before entering into granular media filters); 3. A: anthracite; 4. S: sand; 5. FI: filter influent; 6. IFA: immunofluorescence assay; 7. N/A: information not available; 8. RM: rapid mixer; 9. CP: cationic polymer; 11. F:

$Fe_2(SO_4)_3$; 12. FC: flow cytometry; 13. R: raw water; 14. FAC: floc aid polymer; 15. PC: polyaluminum chloride; 16. P: polydiallyl dimethylammonium chloride (PolyDADMAC);

17. GAC: granular activated carbon; 18. I: inline filtration (filtration with coagulation); 19. SPC: solid-phase cytometry;

20. D: direct filtration (filtration with coagulation, flocculation); 21. G: garnet; 22. FE: filter effluent; 22. AP: anionic polymer; 23. The *Cryptosporidium* removals are based on raw water; 24. EV: Effective volume; 25. DL: detection limit; *: data estimated by subtracting log removal by clarification

Appendix B

Questionnaire Cover Letter for Drinking Water Professionals who have conducted research on *Cryptosporidium* removal

I am a Master's student in the Department of Civil and Environmental Engineering at University of Waterloo (Ontario, Canada) under the supervision of Drs. Peter Huck and Bill Anderson (with input from Dr. Mohamed Hamouda, a former PhD student and postdoc in our group, who is now at the Australian College of Kuwait). I am contacting you to seek your assistance in a research project **examining factors accounting for the reported variability in *Cryptosporidium* oocyst removals by granular media filtration processes**. A qualitative analysis of published data to-date continues to show that there is wide variation among reported oocyst log removals in various studies, and the reasons for these differences are still not readily apparent.

You are receiving this questionnaire because it is our understanding that you have conducted investigations on *Cryptosporidium* or surrogate removal through granular media filtration. We hope to be able to benefit from your experience and insights that you may have gained that were not necessarily reflected in published reports or papers.

Attached is a **simple tick box type of questionnaire** that you, or a designate, are kindly requested to complete, save, and then attach it to a response to this e-mail (we're estimating it'll take about 15 minutes of your time). We recognize that in some cases investigations were conducted a number of years ago, and as such it may be difficult for you to respond to some questions. Please feel free to indicate "do not know" for any questions you do not feel comfortable answering.

The information gathered from this questionnaire will be used in my Master's thesis as well as a potential manuscript and conference presentation. Your name and those of other participants will be kept confidential. Your responses will be analyzed as group data only (individual responses will not be shown). Please feel free to contact me to discuss any questions about the questionnaire's content/purpose.

My supervisors are copied on this e-mail if you wish to contact them directly. For information on our research group (NSERC Industrial Research Chair in Water Treatment) including researchers, mission, publications, etc. please click on the link below.
http://www.civil.uwaterloo.ca/watertreatment/

I would very much appreciate your assistance and feedback. It would be helpful if you could respond by **Thursday, July 23rd, 2015.**

If you have suggestions for other interested individuals or experts whom you think could be helpful and would like to participate in this activity please let me know.

Thanks!

Questionnaire Cover Letter for Drinking Water Professionals Involved in Full-scale Treatment Facilities

I am a Master's student in the Department of Civil and Environmental Engineering at University of Waterloo (Ontario, Canada) under the supervision of Drs. Peter Huck and Bill Anderson (with input from Dr. Mohamed Hamouda, a former PhD student and postdoc in our group, who is now at the Australian College of Kuwait). I am contacting you to seek your assistance in a research project **examining factors accounting for the reported variability in *Cryptosporidium* oocyst removals by granular media filtration processes**. I have completed an analysis of published data to-date which continues to show that there is wide variation among reported oocyst removals in various studies, and the reasons for these differences are still not readily apparent.

You are receiving this questionnaire because it is our understanding that you are involved with the design, operation, or management of full-scale treatment drinking water treatment facilities. As part of the study, we would therefore like to benefit from your experience by asking you to indicate, what factors you consider are likely to be important for removals. Although you may not have been involved in investigations specifically targeting *Cryptosporidium* or surrogate removal, we feel that your experience with drinking water treatment processes and conditions under which they are challenged may provide you with valuable insights as to factors that might be important for such removals.

Attached is a **simple tick box type of questionnaire** that you, or a designate, are kindly requested to complete, save, and then attach it to a response to this e-mail (we're estimating it'll take about 15 minutes of your time). Depending on the nature of your experience, it may be difficult to respond to some questions, so please feel free to indicate "do not know" for any questions you do not feel comfortable answering.

The information gathered from the questionnaire will be used in my Master's thesis as well as a potential manuscript and conference presentation. Your name and those of other participants will be kept confidential. Your responses will be analyzed as group data only (individual responses will not be shown). Please feel free to contact me to discuss any questions about the questionnaire's content/purpose.

My supervisors are copied on this e-mail if you wish to contact them directly. For information on our research group (NSERC Industrial Research Chair in Water Treatment) including researchers, mission, publications, etc. please click on the link below.
http://www.civil.uwaterloo.ca/watertreatment/

I would very much appreciate your assistance and feedback. It would be helpful if you could respond by **Thursday, July 23rd, 2015.**

If you have suggestions for other interested individuals or experts whom you think could be helpful and would like to participate in this activity please let me know.

Thanks!

Questionnaire #1 (test version)
Expert Assessment of List of Potential Factors Influencing *Cryptosporidium* Removal by Rapid Granular Filtration

Name:
Affiliation:
Email:
Date:

Affiliation category:
Full-scale plant operator
Full-scale plant manager
Researcher
Filter manufacturer
Water consultant
Regulator
Public health professional
Other

Background: *Cryptosporidium* are protozoan parasites associated with gastrointestinal illness and have been responsible for some major disease outbreaks attributable to public drinking water supplies. Due to the ineffectiveness of common chlorine-based disinfectants, conventional treatment plants not employing UV (or in some cases, ozone) rely primarily on rapid granular filtration processes as the major barrier against oocysts.

The USEPA and Health Canada have concluded that a 3-log *Cryptosporidium* oocyst removal credit can be reliably attributed to conventional filtration processes (with optimized coagulation/flocculation/sedimentation). However, various full- and pilot-scale experiments have reported variable oocyst removals averaging from 1.4 log to 5.8 log by granular media filters with coagulation pretreatment (Figure 1).

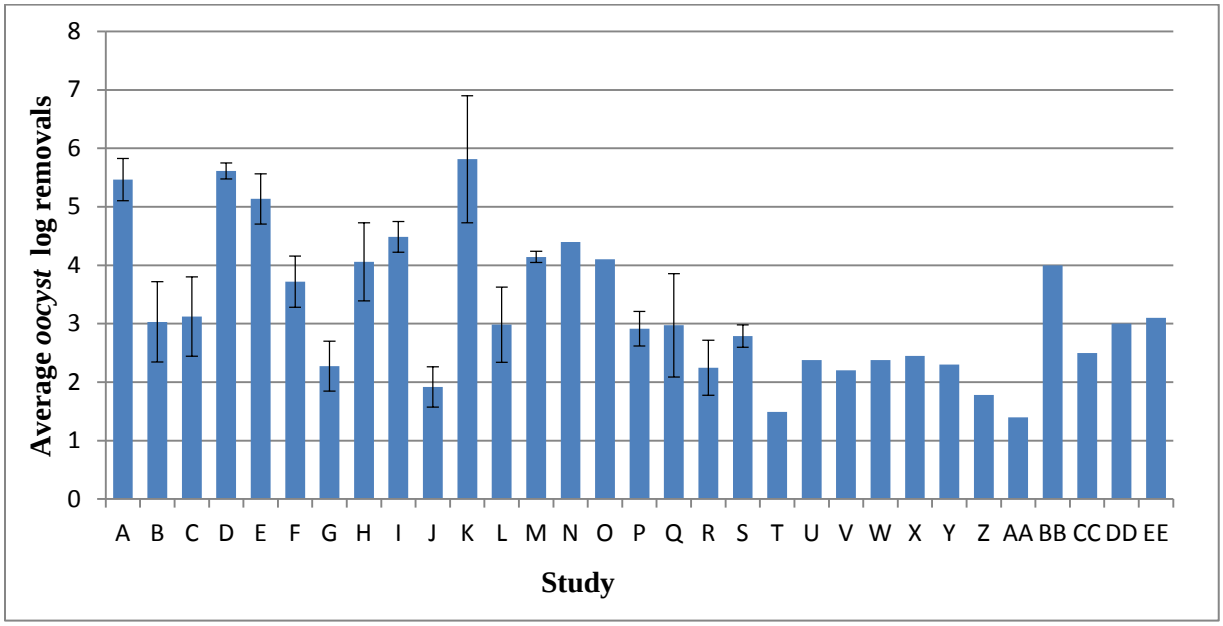


Figure 1 Average *Cryptosporidium* log removals reported in published studies

The reasons behind the substantial variability in removals are not fully understood. Previous studies have attributed the differences in removals to analytical reliability, processed sample volume, detection limit, influent microorganism concentration, microorganism type (environmental vs. pre-cultured), raw water characteristics, temperature, process set-up, and process operation (e.g. Huck *et al*., 2002; Hijnen and Medema, 2010). We have conducted a qualitative analysis of published data to evaluate important influencing factors. As part of the study, it was felt that expert opinion on the factors which may have an impact on oocyst removal by **granular media filters would enhance our research into this important topic**. The six groups of potential influencing factors and some examples of each are shown in Figure 2.

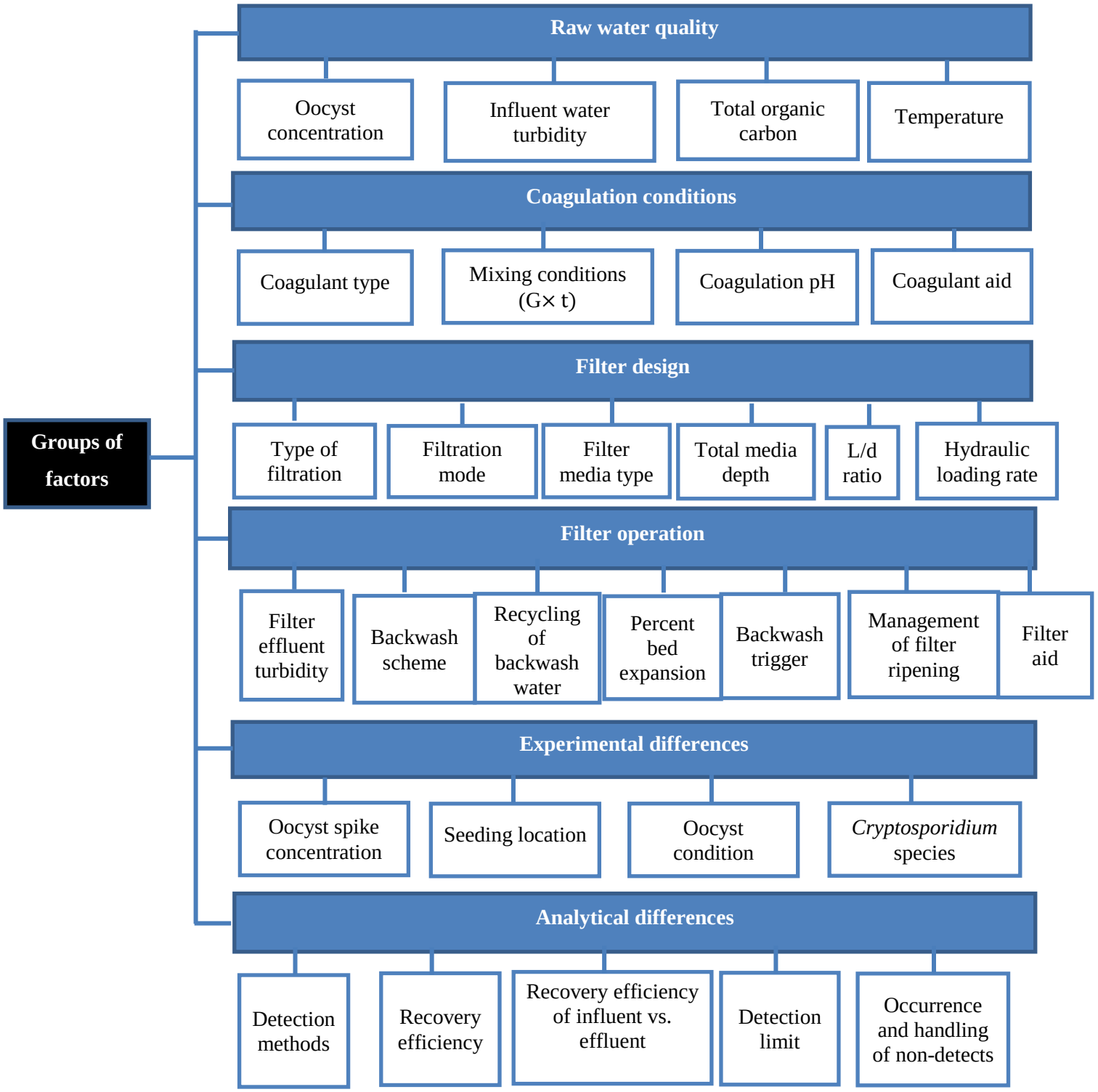

Groups of factors
Raw water quality
Oocyst concentration
Influent water turbidity
Total organic carbon
Temperature
Coagulation conditions
Coagulant type
Mixing conditions (G× t)
Coagulation pH
Coagulant aid
Filter design
Type of filtration
Filtration mode
Filter media type
Total media depth
L/d ratio
Hydraulic loading rate
Filter operation
Filter effluent turbidity
Backwash scheme
Recycling of backwash water
Percent bed expansion
Backwash trigger
Management of filter ripening
Filter aid
Experimental differences
Oocyst spike concentration
Seeding location
Oocyst condition
Cryptosporidium species
Analytical differences
Detection methods
Recovery efficiency
Recovery efficiency of influent vs. effluent
Detection limit
Occurrence and handling of non-detects

Figure 2 List of potential factors influencing oocyst removal by granular media filtration

Objective: The aim of Questionnaire #1 is to seek expert opinion on refining the factor list and developing applicable levels/options used to assess the effect of each factor. We are also considering a second questionnaire which will ask questions about comparisons between groups and factors, as well as ask for suggested weights to assign to levels/options of each factor. Responses from Questionnaire #2 will be analyzed using pairwise comparison, with the expected outcome being a structured weighted list that could help identify the most significant factors. The outcome of this work is not to predict removal or replace the need for pilot-scale studies. It is to provide guidance to water industrial professionals addressing filter design and operation in the context of *Cryptosporidium* removal. The information gathered from questionnaire will be used as part of my Master's thesis as well as other publications. The names of participants will be kept confidential. Your responses will only be grouped with other respondents who share your area of expertise (e.g. full-scale plant operators, filter manufacturer, researcher, etc.).

The following is a simple questionnaire seeking your opinion on:

(1) The relevance of identified factors as they likely pertain to *Cryptosporidium* removal by granular media filter during stable operation
(2) If a factor is relevant, what are the applicable ranges and options to assess/rank its effect on removals

References

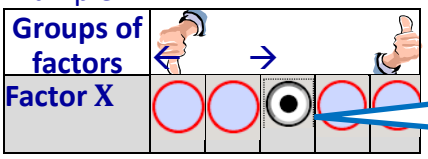
Hijnen, W.A.M., & Medema, G.J. (2010). *Elimination of Micro-organisms by Water Treatment Processes*. London, UK: IWA Publishing.

Huck, P.M., Coffey, B.M., Emelko, M.B., Maurizio, D.D., Slawson, R.M., Anderson, W.B., Oever, J.V.D., Douglas, I.P., & O'Melia, C.R. (2002). Effects of Filter Operation on *Cryptosporidium* Removal. *Journal of American Water Works Association*, *94*(6), 97-111.

How to answer the questionnaire:

Click the button below the "thumbs up " (strongly influence) and "thumbs down "(no influence) to indicate if you think the factor **does not influence, very mildly influences**, **mildly** influences, **moderately** influences, or **strongly** influences oocyst removal by granular media filtration. A comment section for the proposed levels or options is provided for each question.

Example:



This respondent indicates that Factor X **mildly influences** oocyst removal by granular

1) What is the relevance of factors under "**Raw Water Quality**" in influencing oocyst removals? If you believe a factor is relevant, are the suggested options applicable for ranking its effect?

Raw Water Quality	← →	Suggested levels/options	Comments
Oocyst concentration		Low (1-10 oocysts/100L) Medium (10-100 oocysts/100L) High (>100 oocysts/100L)	The suggested levels are appropriate for assessing the influence of **oocyst concentration**: Applicable Not applicable, my suggested levels are _____ Other comment:_____
Influent water turbidity		Low (<5 NTU) Medium (5-50 NTU) High (>50 NTU)	The suggested levels are appropriate for assessing the influence of **influent water turbidity**: Applicable Not applicable, my suggested levels are _____ Other comment:_____
Total organic carbon (TOC)		Low (<2 mg/L) Medium (2-5 mg/L) High (>5 mg/L)	The suggested levels are appropriate for assessing the influence of **TOC**: Applicable Not applicable, my suggested levels are _____ Other comment:_____
Temperature		Low (<4℃)	The suggested levels are appropriate for assessing

						Medium (4-15℃) High (>15℃)	the influence of **temperature**: Applicable Not applicable, my suggested levels are _____ Other comment:

(Continued)

Other comments for factors under "**Raw Water Quality**": _____ _____

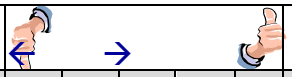
2) What is the relevance of factors under "**Coagulation conditions**" in influencing oocyst removals? If a factor is relevant, are the suggested options applicable for ranking its effect?

Coagulation Conditions	← →	**Suggested levels/options**	**Comments**
Coagulant type		Polyaluminium chloride (PACl) Alum Ferric compounds Other	The suggested **coagulant types** are: Applicable Not applicable, my suggested coagulant types are _____ Other comment:_____
Mixing conditions (hydraulic detention time× velocity gradient-G×t)		No levels suggested at this point in time	Comment: _____ _____
Coagulation pH		pH<6.5 6.5<pH<8 pH>8	The suggested levels are appropriate for assessing the influence of **coagulation pH**: Applicable Not applicable, my suggested levels are _____ Other comment:_____
Coagulant aid		No coagulant aid Activated silica	The suggested **coagulant aid** types are: Applicable Not applicable, my suggested coagulant aid types are _____

						Cationic silica	Other comment:_____
Other comments for factors under "**Coagulation conditions**": _____							

*Coagulant dose is not listed in the above table because it overlaps with other factors such as influent turbidity, TOC, and effluent turbidity (and is accounted for in those categories)

3) What is the relevance of factors under "**Filter design**" in influencing oocyst removals? If a factor is relevant, are the suggested options applicable for ranking its effect?

Filter Design		Suggested levels/options	Comments
Type of filtration		Conventional filtration (preceded by sedimentation) Conventional filtration (preceded by dissolved air flotation) Direct filtration (including flocculation) Inline filtration	The suggested **types of filtration** are: Applicable Not applicable, my suggested filtration types are _____ Other comment:_____
Filter media type		Monomedia filter (sand) Monomedia filter (anthracite) Monomedia filter Dual-media filter (anthracite/sand) Dual-media filter (GAC/sand) Tri-media filter (anthracite/sand/garnet)	The suggested **filter media types** are: Applicable Not applicable, my suggested filter media types are _____ Other comment:_____ _____
Total filter media depth		<75 cm 75-125 cm >125 cm	The suggested levels are appropriate for assessing the influence of **total filter media depth**: Applicable Not applicable, my suggested levels are _____ Other comment:_____

L/d ratio (depth of a granular media filter bed over media effective size)						<1000 1000-1200 >1200	The suggested levels are appropriate for assessing the influence of **L/d ratio**: Applicable Not applicable, my suggested levels are _____ Other comment:_____

(Continued)

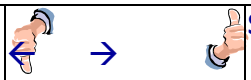
Filter Design	←				→	**Suggested levels/options**	**Comments**
Hydraulic loading rate						< 5 m/h (2 gpm/ft^2) 5-10 m/h (2-4 gpm/ft^2) >10 m/h (4 gpm/ft^2)	The suggested levels are appropriate for assessing the influence of **hydraulic loading rate**: Applicable Not applicable, my suggested levels are _____ Other comment:_____
Filtration mode						Constant rate filters Declining rate filters	The suggested **filtration modes** are: Applicable Not applicable, my suggested filtration modes are _____ Other comment:_____
Other comments for factors under "**Filter design**": _____ _____							

4) What is the relevance of factors under "**Filter operation**" in influencing oocyst removals? If a factor is relevant, are the suggested options applicable for ranking its effect?

Filter Operation	←				→	**Suggested levels/options**	**Comments**
Filter effluent turbidity (at least 95% measurement)						<0.05 NTU <0.1 NTU <0.3 NTU <1 NTU	The suggested levels are appropriate for assessing the influence of **filter effluent turbidity**: Applicable Not applicable, my suggested levels are _____ Other comment:_____

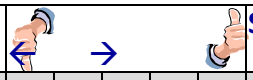
						>1 NTU	
Backwash scheme						Water Air Scour Collapse pulsing (air and water flow concurrently)	The suggested **backwash schemes** are: Applicable Not applicable, my suggested levels are _____ Other comment:_____

(Continued)

Filter Operation		**Suggested levels/options**	**Comments**
Recycling of backwash water		No recycling of filter backwash water Recycling of untreated backwash water to plant influent water	The suggested **recycling of backwash water** schemes are: Applicable Not applicable, my suggested backwash water recycling schemes are _____ Other comment: _____
Percent bed expansion (after backwash)		<15% 15-30% >30%	The suggested levels are appropriate for assessing the influence of **percent bed expansion**: Applicable Not applicable, my suggested levels are _____ Other comment: _____
Backwash trigger		Time Turbidity Headloss	The suggested **backwash trigger** types are: Applicable Not applicable, my suggested backwash trigger types are _____ Other comment: _____
Management of filter ripening		No filter-to-waste Filter-to-waste	The suggested types of **filter ripening management** are: Applicable Not applicable, my suggested types of filter ripening management are

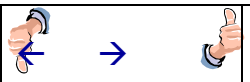
						Extended Terminal Subfluidization Wash (ETSW)	_____ Other comment: _____
Filter aid						No filter aid	The suggested **filter aid** types are: Applicable Not applicable, my suggested filter aid types are _____ Other comment: _____
						Iron or ferric salts	
						Anionic polymer	
						Cationic polymer	
						Nonionic polymer	
Other comments for factors under "**Filter operation**": _____ _____							

5) Based on your experience working on **filtration experiments** where oocysts are spiked ahead of filters (bench-scale, pilot-scale, full-scale), what is your opinion on the relevance of factors under "**Experimental differences**" in influencing oocyst removals? If a factor is relevant, are the suggested options applicable for ranking its effect?

Experimental differences		Suggested levels/options	Comments
Oocyst spike concentration		10-10^2oocysts/L and lower 10^2-10^4 oocysts/L 10^4-10^6 oocysts/L and higher	The suggested levels are appropriate for assessing the influence of **oocyst spike concentration**: Applicable Not applicable, my suggested levels are _____ Other comment_____
Seeding location		Rapid mix Filter influent water (pre-coagulated oocysts) Filter influent water (oocysts not pre-coagulated)	The suggested **seeding locations** are: Applicable Not applicable, my suggested seeding locations are _____ Other comment _____
Oocysts conditions		Viable (with appropriate precautions to avoid contamination of potable water) Formalin-inactivated	The suggested levels are appropriate for assessing the influence of **oocyst conditions**: Applicable Not applicable, my suggested oocyst conditions are _____

						Heat-inactivated	Other comment _____
***Cryptosporidium* species**						*Cryptosporidium hominis* *Cryptosporidium parvum*	The suggested ***Cryptosporidium* species** are: Applicable Not applicable, my suggested *Cryptosporidium* species are _____ Other comment: _____
Other comments for factors under "**Experimental differences**": _____ _____							

6) What is the relevance of factors under "**Analytical differences**" in influencing oocyst removals? If a factor is relevant, are the suggested options applicable for ranking its effect?

Analytical differences						**Suggested levels/options**	**Comments**
Detection methods						Immunofluorescence assay (IFA) Flow cytometry Molecular methods	The suggested **detection methods** are: Applicable Not applicable, my suggested detection methods are _____ Other comment: _____
Recovery efficiency						<40% 40%-60% >60%	The suggested levels are appropriate for assessing the influence of **recovery efficiency**: Applicable Not applicable, my suggested recovery efficiencies are _____ Other comment: _____
Recovery efficiency of influent vs. filter effluent water						Equal Influent recovery> Filter effluent recovery Influent recovery< Filter effluent recovery	The suggested levels are: Applicable Not applicable, my suggested levels are _____ Other comment: _____

Detection limit						10^{-3} oocysts/L and lower 10^{-3}-1 oocysts/L >1 oocyst/L	The suggested levels are appropriate for assessing the influence of **detection limits**: Applicable Not applicable, my suggested levels are _____ Other comment: _____
Occurrence and handling of non-detects						No non-detect Non-detects treated as detection limit Non-detects treated as 1/2 of detection limit	The suggested **occurrence and handling of non-detects** are: Applicable Not applicable, my suggested levels are _____ Other comment: _____
Other comments for factors under "**Analytical differences**": _____							

Your identity will be kept confidential. Only your affiliation category will be indicated. Thank you very much!

Questionnaire (final version)
Drinking Water Professionals Assessment of List of Potential Factors Influencing *Cryptosporidium* Removal by Rapid Granular Filtration

Name:
Affiliation:
Email:
Date:
Affiliation category: Filter manufacturer
Full-scale plant manager
Full-scale plant operator
Public health professional
Regulator
Researcher
Water consultant
Other

Rate your understanding of *Cryptosporidium* removal/assessment in the context of drinking water treatment:
Minimal Moderate Extensive

Have you ever been directly involved in research on *Cryptosporidium* removal by filtration?

Yes, please specify (as many as apply):
I have been involved in experiments with *Cryptosporidium*
I have been involved in experiments with *Cryptosporidium* surrogates (Please specify surrogate type:_____)
I have conducted review studies on *Cryptosporidium* removal
No

Background: *Cryptosporidium* are protozoan parasites associated with gastrointestinal illness, and have been responsible for major disease outbreaks attributable to public drinking water supplies. Due to the ineffectiveness of common chlorine-based disinfectants, conventional drinking water treatment plants not employing UV (or in some cases, ozone) rely primarily on rapid granular filtration processes as the major barrier against *Cryptosporidium* oocysts.

The USEPA and Health Canada have concluded that a 3-log *Cryptosporidium* oocyst removal credit can be reliably attributed to conventional filtration processes (with optimized coagulation/flocculation/sedimentation). However, various full- and pilot-scale experiments have reported variable *Cryptosporidium* removals averaging from 1.4 log (96% reduction) to 5.8 log (>99.999% reduction) by granular media filters (or including removals due to pretreatment) with coagulation pretreatment. The wide variation is evident in Figure 1 where *Cryptosporidium* removals in various studies are shown in descending order.

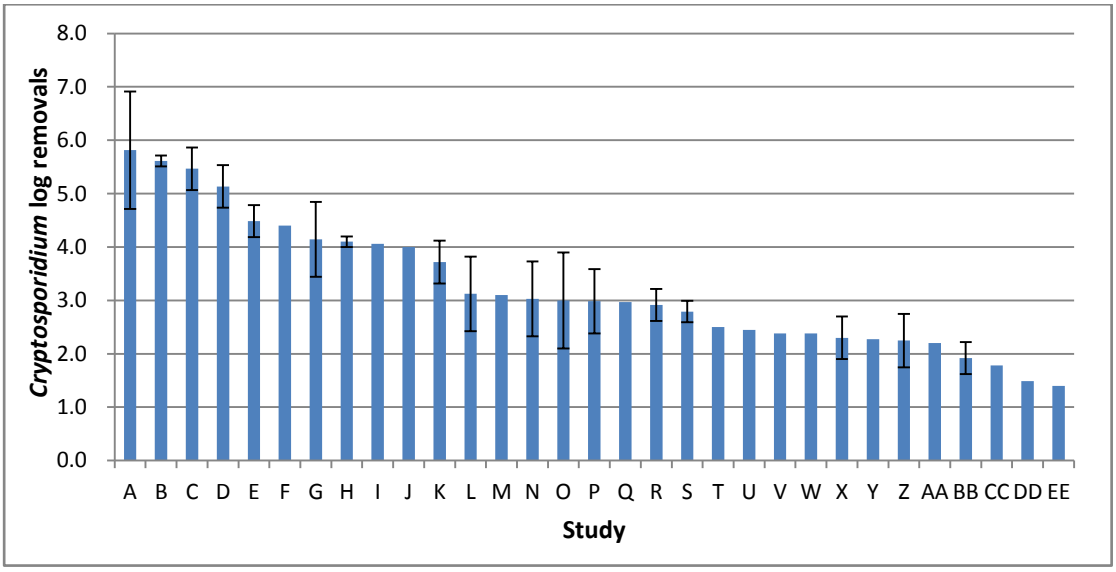


Figure 1 Average *Cryptosporidium* log removals reported in published studies

The reasons behind the substantial variability in removals are not fully understood. Previous studies have attributed the differences in removals to analytical reliability, processed sample

volume, detection limit, influent microorganism concentration, microorganism type, raw water characteristics, temperature, process set-up, and process operation (e.g. Huck *et al*., 2002; Hijnen and Medema, 2010).

We have recently reviewed published data to evaluate important influencing factors. Based on this analysis, six groups of influencing factors were identified including raw water quality, coagulation conditions, filter design, filter operation, experimental differences, and analytical differences (Figure 2).

As part of the study, it was felt that opinions from drinking water professionals on the factors which may have an impact on reported *Cryptosporidium* removals by granular media filters would enhance our research into this important topic.

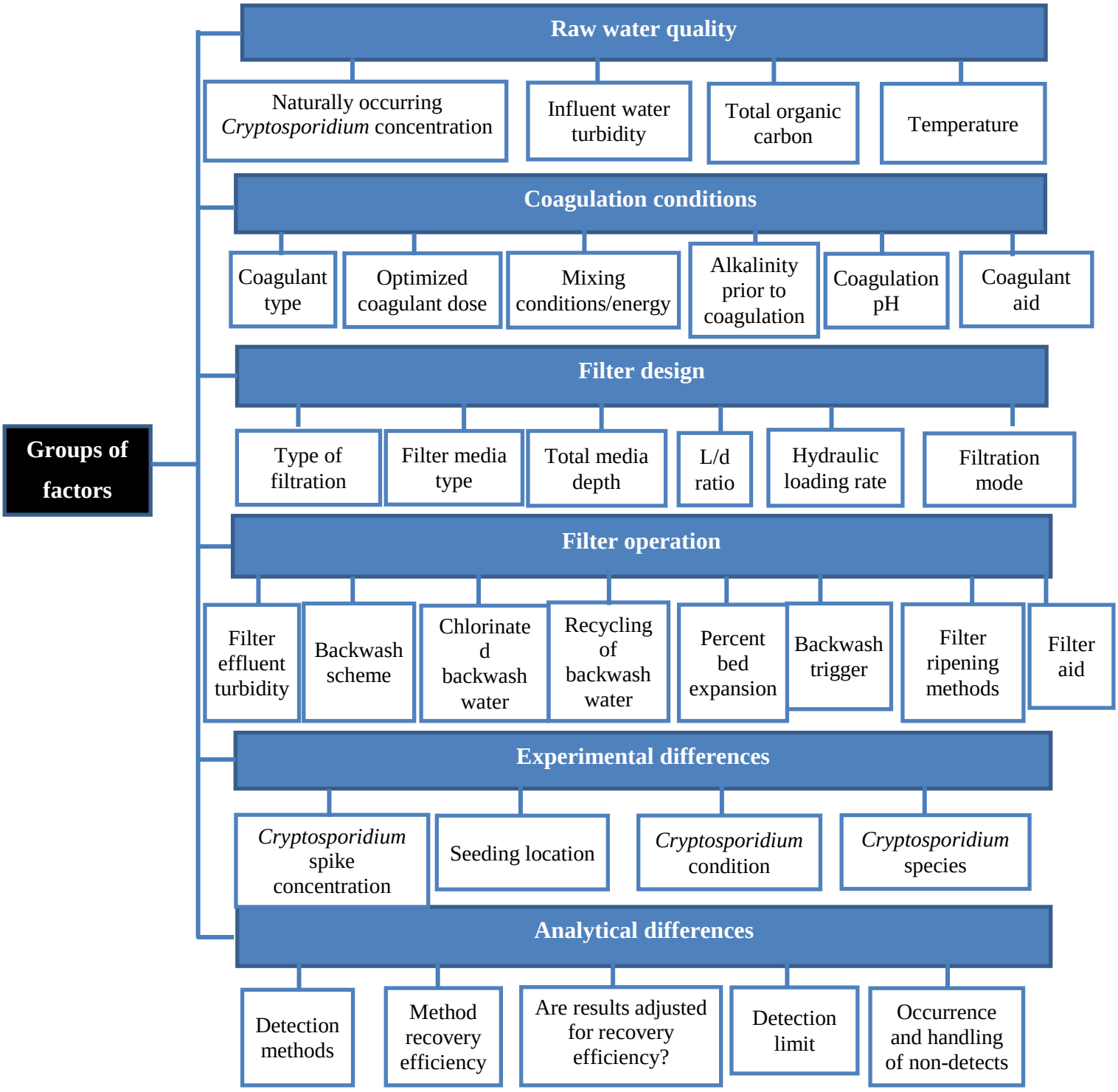


Figure 2 List of potential factors influencing reported *Cryptosporidium* removal by granular

media filtration

Objective: The aim of questionnaire is to collect and understand opinions from drinking water professionals on the relevance of identified factors in influencing *Cryptosporidium* removal by granular media filtration. Based on your responses, relevant factors which may have an impact on *Cryptosporidium* removal by granular media filtration will be selected and a refined factor list will be developed.

The overall goal of this research is to identify the most influential factors and their relative effect with respect to *Cryptosporidium* removals, which help provide guidance to water industrial professionals addressing their granular media filter design and operation. The information gathered from the questionnaire will be included in my Master's thesis as well as a manuscript and conference presentation. The names of participants will be kept confidential, with results shown as grouped data only (individual responses will not be shown).

References

Hijnen, W.A.M., & Medema, G.J. (2010). *Elimination of Micro-organisms by Water Treatment Processes*. London, UK: IWA Publishing.

Huck, P.M., Coffey, B.M., Emelko, M.B., Maurizio, D.D., Slawson, R.M., Anderson, W.B., Oever, J.V.D., Douglas, I.P., & O'Melia, C.R. (2002). Effects of Filter Operation on *Cryptosporidium* Removal. *Journal of American Water Works Association*, *94*(6), 97-111.

How to answer the questionnaire:

Select your response to indicate if you think the factor has **no influence, some influence**, or **strong influence** on *Cryptosporidium* removal by granular media filtration. Please feel free to indicate "do not know" if you prefer not to answer this question. A comment section is provided for each question, but is not required.

Example:

Groups of factors	No influence	Some influence	Strong influence	Do not know
Factor X		●		

This respondent indicates that Factor X has **some influence on** *Cryptosporidium* removal by

1) For the factors under "**Raw Water Quality**", what is the relevance of the following variables in influencing *Cryptosporidium* removal by granular media filtration? Indicate what perspective your response is based on.

Raw Water Quality	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments
Naturally occurring *Cryptosporidium* concentration					I rate the relevance of **naturally occurred *Cryptosporidium* concentration** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Influent water turbidity					I rate the relevance of **influent water turbidity** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____

Total organic carbon (TOC)					I rate the relevance of **total organic carbon** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____

(Continued)

Raw Water Quality	**No influence**	**Some influence**	**Strong influence**	**Do not know**	**Basis for response**	**Comments**
Temperature					I rate the relevance of **temperature** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____ ___
Other comments for factors under "**Raw Water Quality**": _____ _____						

2) For the factors under "**Coagulation conditions**", what is the relevance of the following variables in influencing *Cryptosporidium* removal by granular media filtration? Indicate what perspective your response is based on.

Coagulation Conditions	**No influence**	**Some influence**	**Strong influence**	**Do not know**	**Basis for response**	**Comments**

Coagulant type (e.g., PACl vs. alum vs. ferric compounds)					I rate the relevance of **coagulant type** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Importance of optimized coagulant dose					I rate the relevance of **optimized coagulant dose** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____

(Continued)

Coagulation Conditions	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments
Mixing conditions /energy (hydraulic detention time× velocity gradient-G×t)					I rate the relevance of **mixing conditions/energy** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____ ___
Alkalinity (prior to coagulation)					I rate the relevance of **alkalinity** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____ ___
Coagulation pH					I rate the relevance of **coagulation pH** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____ ___

Coagulant aid (e.g., no coagulant aid vs. activated silica vs. polymer)					I rate the relevance of **coagulation aid** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____ ___
Other comments for factors under "**Coagulation conditions**": _____ _____						

3) For the factors under "**Filter design**", what is the relevance of the following variables in influencing *Cryptosporidium* removal by granular media filtration? Indicate what perspective your response is based on.

Filter design	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments
Type of filtration (Conventional vs. direct vs. inline)					I rate the relevance of **type of filtration** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Filter media type (e.g., monomedia vs. dual media vs. tri-media of different material)					I rate the relevance of **filter media type** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____

Total filter media depth					I rate the relevance of **total media depth** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
L/d ratio (depth of a granular media filter bed over media effective size)					I rate the relevance of **L/d ratio** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Hydraulic loading rate					I rate the relevance of **hydraulic loading rate** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____

(Continued)

Filter design	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments
Filtration mode (declining vs. constant rate)					I rate the relevance of **filtration mode** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Other comments for factors under "**Filter design**": _____ _____ ____						

4) For the factors under "**Filter Operation**", what is the relevance of the following variables in influencing *Cryptosporidium* removal by granular media filtration? Indicate what perspective your response is based on.

Filter Operation	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments
Filter effluent turbidity					I rate the relevance of **filter effluent turbidity** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Backwash scheme (water vs. air scour vs. collapse pulsing vs. water with surface scour)					I rate the relevance of **backwash scheme** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Chlorinated backwash water (chlorinated vs. non-chlorinated)					I rate the relevance of **chlorinated backwash water** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Recycling of backwash water (to an upstream process)					I rate the relevance of **recycling of backwash water** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Percent bed expansion (during backwash)					I rate the relevance of **percent bed expansion** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement	_____ _____ _____

					Other_____	
Backwash trigger (time vs. turbidity vs. headloss)					I rate the relevance of **backwash trigger** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Filter ripening methods—effect on removal during overall filter cycle (e.g. no filter-to-waste vs. filter-to-waste vs. extended terminal subfluidization wash)					I rate the relevance of **filter ripening methods** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Filter aid (e.g., no filter aid vs. iron or ferric salts vs. polymer)					I rate the relevance of **filter aid** in influencing *Cryptosporidium* removals based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Other comments for factors under "**Filter operation**": _____ _____						

5) Based on your experience working on **filtration experiments** where *Cryptosporidium* oocysts are **spiked** ahead of filters (bench-scale, pilot-scale, full-scale), 1) what is the relevance of the following variables under "**Experimental differences**" in influencing the calculation/determination of *Cryptosporidium* removals? Indicate what perspective your response is based on.

Experimental differences	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments

***Cryptosporidium* spike concentration**					I rate the relevance of ***Cryptosporidium* spike concentration** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Seeding location (e.g. source water vs. rapid mixer vs. filter influent with pre-coagulated *Cryptosporidium* vs. filter influent with *Cryptosporidium* not pre-coagulated)					I rate the relevance of **seeding location** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
***Cryptosporidium* condition (e.g. viable vs. heat-inactivated vs. formalin-inactivated)**					I rate the relevance of ***Cryptosporidium* condition** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
***Cryptosporidium* species (e.g. *Cryptosporidium parvum* vs. *Cryptosporidium hominis*)**					I rate the relevance of ***Cryptosporidium* species** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Other comments for factors under "**Experimental differences**": _____ _____						

6) For the factors under "**Analytical differences**", 1) what is the relevance of the following variables in influencing the calculation/determination of *Cryptosporidium* removals? Indicate what perspective your response is based on.

Analytical differences	No influence	Some influence	Strong influence	Do not know	Basis for response	Comments

Detection methods (immunofluorescence assay vs. flow cytometry vs. molecular method)					I rate the relevance of **detection methods** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Method recovery efficiency (in percentage)					I rate the relevance of **recovery efficiency** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Are results adjusted for recovery efficiency					I rate the relevance of **adjusting recovery efficiency** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Detection limit					I rate the relevance of **detection limit** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Occurrence and handling of non-detects (e.g., no non-detect vs. non-detects treated as detection limit)					I rate the relevance of **occurrence and handling of non-detects** in influencing removal determination based on my: Past research experience Operational perspective/experience General engineering judgement Other_____	_____ _____ _____
Other comments for factors under **"Analytical differences"**: _____ _____						

Your identity will be kept confidential. Only your affiliation category will be indicated. Thank you very much

Appendix C

Opinions and Insight on the Influence of Identified Factors from Questionnaire Participants

Note: while these comments have been paraphrased to make the responses more concise and protect the confidentiality of respondents, no attempt has been made to identify or correct statements which may not be accurate.

Raw water quality-Naturally occurring *Cryptosporidium* oocyst concentrations	
Summary of opinions	Original comments from respondents (paraphrased)
1. Influent *Cryptosporidium* concentration affects analytical accuracy and precision in filtered samples thus influencing oocyst log removal calculation	• If *Cryptosporidium* concentrations are low in raw water, it is difficult to accurately measure their removal through treatment • If *Cryptosporidium* concentrations are low in raw water, log removal calculation is affected • Must have an accurate and measureable number of *Cryptosporidium* oocysts in settled or/and filter effluent to accurately determine log removal performance; otherwise, only minimum log removal performance can be determined; for example, a greater than 2 log removal has been reported in several studies • Reliable concentration data are required to calculate reliable log removals • Analytical precision in filtered samples improves when counts are higher. *Cryptosporidium* oocysts are only detected when raw water concentration is relatively high • Influent *Cryptosporidium* concentration is one of the most important factors in explaining high log removal results; naturally-occurring levels are typically too low to see more than 2 log removal

2. High influent *Cryptosporidium* concentrations pose a challenge for treatment	• Raw water with high *Cryptosporidium* oocyst concentrations requires more robust treatment including granular media filtration • Higher influent concentrations increase statistical chance of breakthrough • Ontario Reg. 170 requires a minimum 2 log *Cryptosporidium* removal and influent concentration is significant determinant
3. When influent oocyst concentration increases, *Cryptosporidium* removals through filtration increase as well	• Based on published findings (Assavasilavasukul *et al*., 2008), increased *Cryptosporidium* removals have been observed with higher seeding concentration • From general engineering knowledge, less *Cryptosporidium* in influent water leads to less log removal through processes

Raw water quality-Influent water turbidity	
Summary of opinions	Original comments from respondents (paraphrased)
1. Influent water turbidity plays a role in filtration theory	• Co-aggregation enhances *Cryptosporidium* removal • Influent water turbidity is related to particle numbers, which influences filtration theory • *Cryptosporidium* associated with solids/turbidity affects treatment processes differently than unassociated *Cryptosporidium* in raw water
2. Turbidity can challenge treatment process effectiveness	• Have not measured removal results at varying turbidities; utilities with variable source water turbidities might be more at risk of *Cryptosporidium* passage • Rapid changes in turbidity require treatment adjustment (coagulation chemistry); if the adjustment is not done in a timely fashion or rapidly, filter performance can be compromised (*Cryptosporidium* removal is assumed to be affected as well) • Raw water with very low water turbidity is hard to treat properly, more care is required to appropriately pretreatment • Higher influent water turbidity will increase the loading on filters which can contribute

	to *Cryptosporidium* breakthrough • High levels of turbidity make plant operation more difficult
3. Turbidity interferes with *Cryptosporidium* detection and thus potentially influences removals	• Turbidity influences analytical methods evaluating *Cryptosporidium* concentration • High turbidity levels impede the effectiveness of detection methods • High levels of turbidity make *Cryptosporidium* analysis more difficult, with detection being overestimated
4. *Cryptosporidium* removal is higher at increased turbidity levels	• Oocyst removal is better at higher turbidity levels • Based on published findings (Assavasilavasukul *et al*., 2008), higher raw water turbidity seems to lead to higher *Cryptosporidium* removals • Increased coagulant doses to control turbidity can have a positive effect on oocyst removal
5. The type of turbidity rather than the absolute turbidity may play a role	• The presence of kaolinite or bentonite clay may alter the zeta potential of sand media and influence the interaction between pathogen and media; in this regard, the type of turbidity may be more important than the quantity of turbidity, which cannot be measured by a turbidimeter

Raw water quality-Total organic carbon (TOC)	
Summary of opinions	Original comments from respondents (paraphrased)
1. TOC affects coagulation performance and requires coagulant dose adjustment	• With high TOC, utilities tend to use sweep coagulation which is more effective at *Cryptosporidium* removal • TOC might affect coagulation performance which in turn affects oocyst removals via filtration • TOC impacts coagulation effectiveness which plays a role in *Cryptosporidium* removal • If coagulant dose is insufficient to control TOC, oocyst removal performance is compromised • Coagulant demand of TOC must be satisfied in order to attain effective coagulation • TOC has no direct influence on *Cryptosporidium* removals except that it has an impact on coagulant dose which might affect *Cryptosporidium* removals • The effect of TOC is important only in the context that high TOC makes plant operation more difficult and requires higher coagulant dosing • Based on published findings (Xagoraraki and Harrington, 2004), NOM (measured as TOC surrogate) has been reported to influence the interaction between oocysts and aluminum hydroxide precipitate when alum is used as coagulant • The characteristics and fractions of TOC may be relevant to the surface chemistry of naturally occurring oocysts • NOM (measured as TOC surrogate) determines size, structure, and strength of flocs formed
2. Other	• TOC can be an indicator of the level of *Cryptosporidium* contamination as spikes in concentration can be the result of events occurring upstream or in the vicinity of a water intake • TOC has less impact on *Cryptosporidium* removal than does turbidity • TOC has some effect on oocyst method recovery

Raw water quality-Temperature	
Summary of opinions	Original comments from respondents (paraphrased)
1. Temperature influences treatment processes, primarily coagulation/ flocculation/sedimentation; little impact on filtration	• Temperature affects treatment efficiency • Temperature strongly affects coagulation/settling performance • Temperature has an effect on coagulation processes • In cold water, the coagulation-flocculation-clarification can be much less efficient if coagulant dosages are not adjusted • Particle removal is more efficient at warmer water temperature; if *Cryptosporidium* removal is proportional to the removal of particles, similar conclusions can be drawn • Filtration performance is poorer in cold vs. warm water conditions • Cold water is harder to treat when alum is used as coagulant • Temperature has less impact on filtration than it does on clarification • Not much effect of temperature on *Cryptosporidium* removal by filtration has been observed
2. *Cryptosporidium* concentrations can be associated with water temperature	• Depending on the events leading to *Cryptosporidium* in raw water, water temperature could be linked with their concentration • Higher *Cryptosporidium* concentrations are found in colder water compared to warm water • *Cryptosporidium* concentrations can be higher in winter (cold temperature), which is the case at our water treatment plant
3. Temperature influences biological activity/predation but it does not substantially impact *Cryptosporidium* removal by filtration	• Temperature has an effect on biological activity/predation. Compared to other variables though, it has little impact on *Cryptosporidium* removal

Additional comments for factors in the "Raw water quality" category
• Other water quality conditions affecting attachment to granular materials include pH and the presence of other natural coagulants (e.g. organic polymers from algae) • pH and alkalinity are additional influencing factors as they play a role in coagulation chemistry • In our full-scale plant, high *Cryptosporidium* levels are associated with high turbidity and TOC, which leads to rapid change in conditions and difficulty in terms of operational responses • Filter clogging algae substantially affect *Cryptosporidium* removal by granular media filtration • Optimizing coagulation conditions to reduce filter effluent turbidity to less than 0.1 NTU is essential to ensure *Cryptosporidium* removal. Care must be taken for water with turbidity, TOC, and temperature challenges to achieve optimal coagulation

Coagulation conditions-Coagulant type	
Summary of opinions	Original comments from respondents (paraphrased)
1. The effect of coagulant type is site specific	• The effects of different coagulant types are site-specific • Coagulant type should be assessed in terms of raw water quality and season • Milwaukee outbreak occurred when coagulant type switched from alum to polyaluminum chloride (PACl) • Based on previous research (Harrington et al., 2001), treatment trains (coagulation/sedimentation/filtration) using alum have demonstrated superior *Cryptosporidium* removal performance than trains applying ferric chloride and polyaluminum hydroxychlorosulfate when treating Lake Mendota water • Pilot-scale work has demonstrated superiority of alum over other coagulants

2. Similar filtration performance can be achieved with different coagulant types	• If coagulation chemistry is optimized, there is little effect on *Cryptosporidium* removal among different coagulant types • There is no substantial difference in *Cryptosporidium* removal between the use of alum and ferric chloride

Coagulation conditions-Importance of optimized coagulant dose	
Summary of opinions	Original comments from respondents (paraphrased)
Optimized coagulant dose is very important for *Cryptosporidium* removal by filtration	• Besides optimized coagulant dose, optimized coagulation conditions are very important for *Cryptosporidium* removal • Optimized coagulant dose improves granular media filtration performance; even sub-optimal coagulation is far superior to no coagulation • Optimized coagulant dose based on raw water properties is beneficial for removal of protozoans

Coagulation conditions-Mixing conditions	
Summary of opinions	Original comments from respondents (paraphrased)
1. Mixing conditions influence coagulation conditions	• Utilities have reported that mixing conditions affect coagulation processes • The effect of mixing condition depends on the type of coagulation performed, i.e., very important for charge neutralization and less so for sweep coagulation • Proper mixing improves coagulation performance • Mixing is relevant in ensuring coagulation effectiveness and general filtration performance
2. The effect of mixing conditions is site specific	• Based on particle removal results in my pilot plant with one source water and about 100 jar tests, the influence of mixing condition on particle removal is more significant for water with low turbidity and low DOC, and is less for water with high DOC and high turbidity • The effect of mixing condition depends on the type of coagulation performed, i.e., very important for charge neutralization and less relevant for sweep coagulation
3. The effect of mixing condition is not significant	• Some utilities have reported low filtered water turbidity regardless of less than optimal rapid mixing conditions • Chemistry of coagulation is more important than the physics of mixing

Coagulation conditions-Alkalinity prior to coagulation	
Summary of opinions	Original comments from respondents (paraphrased)
Alkalinity plays a minor role in coagulation processes	• When alkalinity affects coagulation efficiency, it will influence *Cryptosporidium* removal in downstream processes • Coagulants consume alkalinity, and sufficient alkalinity is required to form floc; otherwise, aside from this condition there should be no effect of alkalinity on coagulation • Raw water alkalinity influences coagulant dosage • Coagulation requires alkalinity and low alkalinity will induce suboptimal coagulation which will impair *Cryptosporidium* removals during filtration • Alkalinity has an effect on coagulation pH • Alkalinity helps buffer or resist pH changes • Coagulation pH is an important variable, and alkalinity influences coagulation to the extent that it affects coagulation pH • The influence of alkalinity is only related to the extent that it is related to coagulation pH • The effect of alkalinity lies only in the fact that coagulation needs alkalinity to work efficiently • The effect is considerable when alkalinity limits coagulation • Alkalinity does not make a difference for *Cryptosporidium* removal by filtration if the coagulant dose and pH are optimized

Coagulation conditions-Coagulation pH	
Summary of opinions	Original comments from respondents (paraphrased)
1. Optimized coagulation pH is crucial for coagulation	• Optimal coagulation is crucial and is site specific • Optimized coagulation depends on both optimized coagulant dose and optimized coagulation pH • Coagulation pH significantly affects coagulation effectiveness
2. Lower coagulation pH may lead to higher *Cryptosporidium* removals	• Based on reported findings (Harrington *et al*., 2001), a treatment train with a pH of 5.7 achieved significantly higher *Cryptosporidium* removal by sedimentation and filtration processes than that with a pH of 7.0

Coagulation conditions-Coagulant aid	
Summary of opinions	Original comments from respondents (paraphrased)
Addition of coagulant aid can be beneficial but may be site specific	• Coagulant aids improve particle attachment to filter grains • Polymer dose significantly influences particle removal efficiency of both pretreatment and filtration; optimal polymer dose makes floc less prone to breakage, which increases robustness of filtration performance; polymer type also needs to be taken into consideration as it relates to surface charge conditioning and filterability • Coagulant aids can be important for floc stability • Dosing adequate cationic polymer to achieve near-neutral zeta potential can be crucial for controlling particle breakthrough and filter ripening time • Depending on water quality and pretreatment type, coagulant aids can substantially affect coagulation and filtration performance • Coagulant aids can improve filtration performance in some waters, but not others • Coagulant aids are critical for coagulation and particle removal at low temperature • The use of coagulant aids is very important in cold water conditions, but will be site-specific • Anionic polymers are required for good filtration performance in our full-scale plant

Additional comments for factors in the "Coagulation condition" category
• The goal of coagulation optimization is to improve turbidity and particle removal, and as such improved *Cryptosporidiu*m removal is expected • Factors that influence coagulation effectiveness will impact *Cryptosporidium* removals by granular media filtration processes • Coagulation conditions are crucial for particle removal, but may not serve as the most important factor accounting for the high end of *Cryptosporidium* log removals reported

Filter design-Type of filtration	
Summary of opinions	Original comments from respondents (paraphrased)
1. Conventional treatment performs better for the removal of *Cryptosporidium* than does direct and inline filtration	• Conventional treatment processes provide better *Cryptosporidium* log removal performance than direct and in-line coagulation • As *Cryptosporidium* oocysts are colloidal particles, improved removal performance of *Cryptosporidium* should be expected for conventional filtration treatment over direct or inline filtration; same conclusion can be drawn for the superiority of direct over inline filtration • Based on the data from our plants, no oocysts have been detected in filter effluent when the plant has operated in conventional mode. Occasional positives have been observed in filter effluent during direct filtration • In conventional treatment processes, the effect of pretreatment on particle removal is significant, which is not the case for direct and inline filtration • Sedimentation achieves additional *Cryptosporidium* removal in conventional treatment compared to that achieved by direct and inline filtration
2. Other	• Without clarification, as is the case with direct or inline filtration, filters are less likely to achieve high levels of *Cryptosporidium* removal • In direct filtration plants, filters experience higher oocyst loadings and assume more responsibility for the removal of oocysts than filters in conventional plants with upstream sedimentation processes • Coagulant dose is critical for all three type of filters
Filter design-Filter media type	
Summary of opinions	Original comments from respondents (paraphrased)
1. There are no substantial effects of filter media type on *Cryptosporidium* removal	• There are no substantial changes in *Cryptosporidium* removal efficacy among different media types as long as optimal coagulation is practiced • As long as filters are performing normally, GAC, anthracite, sand filters can all function

	well • Based on results from pilot-scale experiments (Harrington *et al*., 2001), no significant difference in *Cryptosporidium* removals were reported for mono-media, dual-media, and tri-media filters
2. Headloss build-up may be an issue mono-media filters	• If filter media depth is sufficient, mono-media can work well; but mono-media filters operate at higher headloss and shorter filter run length • Headloss might be an issue in certain mono-media filters vs. dual- or tri- media filters
3. Dual-media filtration provides an advantage in terms of removing particles	• Dual media filters better • Fine particle breakthrough is better controlled by dual-media filtration than by mono-media filtration as demonstrated at pilot-scale

Filter design-Total filter media depth	
Summary of opinions	Original comments from respondents (paraphrased)
1. Deep filters perform better	• Deep filters perform better for *Cryptosporidium* removal • Fine particle breakthrough has been controlled better by deep bed filters, however, ensuring adequate coagulation become more important when deep bed filtration is employed • Deep filter can hold more particles with more throughput
2. Filter media depth has no significant effect on *Cryptosporidium* removal efficacy	• Filter media depth affects run time but should not affect *Cryptosporidium* removal efficacy
3. A minimum filter media depth is needed, but its effect on oocyst log removal is otherwise not clearly linked	• A certain amount of media is necessary, but doubling filter media depth does not double *Cryptosporidium* log removal

Filter design-L/d ratio	
Summary of opinions	Original comments from respondents (paraphrased)
L/d ratio is a useful parameter for sizing filter media, but its effect on *Cryptosporidium* removal is not clear	• L/d ratio has some effect, but D_{60} is more important • As both filter depth and media size are important, L/d ratio can serve as a useful index parameter • L/d ratio is of minor importance for *Cryptosporidium* removal; this parameter is more important for filter run length and overall filter performance • L/d ratio has no subtantial impact on *Cryptosporidium* removal by filtration

Filter design-Hydraulic loading rate	
Summary of opinions	Original comments from respondents (paraphrased)
1. Filters with lower hydraulic loading rates have demonstrated improved filter performance	• In past pilot-scale filtration experiments, we have applied very low filtration rates which contribute to excellent log removal performance (more than 5 log) • Operating filters at higher hydraulic loading rates leads to reduced particle removal due to increased hydraulic sheer • By reducing hydraulic loading rate, fine particle breakthrough can be delayed. *Cryptosporidium* surrogates have demonstrated increased removal by filters at lower hydraulic loading rates • Poorer filter performance is expected for filters at higher hydraulic loading rate if the overall media depth is insufficient
2. No systematic difference in *Cryptosporidium* removal performance for filtration rate at various hydraulic loading rates	• Pilot-scale experiments have demonstrated no apparent difference in *Cryptosporidium* removals for ripened, properly operated filters at various hydraulic loading rates in the range from 2 to 8 US gpm/ft^2 (Harrington et al., 2001),

Filter design-Filtration mode	
Summary of opinions	Original comments from respondents (paraphrased)
There is no consensus as to the effect of filtration mode types on *Cryptosporidium* removal efficacy	• Declining rate filtration should perform marginally better • Declining rate filters perform better for the prevention of end of run breakthrough • Declining rate filtration may provide lower potential for particle breakthrough in the latter stages of a filter run, however, this can be offset by adequate process controls for coagulation optimization and filter run termination criteria for constant rate filters • Declining rate filters may experience step changes in filter loading which could result in more significant particle breakthrough, relative to constant rate filters where approaching breakthrough may be more apparent from online monitoring of particle and turbidity • As long as a filter's effluent valve is properly operated in constant rate mode, and proper coagulation is practiced, *Cryptosporidium* removal is expected to be similar for both filtration modes

Additional comments for factors in the "Filter design" category
• Filter performance is important, but may not be the primary factor accounting for the wide range of *Cryptosporidium* log removals reported • Filter media type, bed depth, media size, and L/d ratio are all interrelated

Filter operation-Filter effluent turbidity	
Summary of opinions	Original comments from respondents (paraphrased)
1. The current regulations for filter effluent turbidity needs to be more stringent to optimize *Cryptosporidium* removals (e.g. 0.1 NTU)	• 0.3 NTU is too high under any circumstances, and less than 0.3 NTU only 95% of time per month poses risk • 0.1 NTU is needed to optimize removals • Confidence in a filter's ability to remove *Cryptosporidium* is highest if filter effluent turbidity is maintained below 0.1 NTU • It is critical to keep turbidity low (preferably less than 0.1 NTU)
2. Particle counts serve as a better indicator for *Cryptosporidium* removal than filter turbidity	• Although turbidity is a useful indicator for removing particles, particle counts are a much more sensitive tool • Particle counts increase before turbidity changes, and the time difference can be substantial; particle counts may be more valuable as an indicator of *Cryptosporidium* removal by filtration • Particle counts are a better indicator of performance at low turbidities • Filter effluent turbidity is a general (coarse) measure of coagulation and filtration optimization, however, it does not allow for the finer optimization that could be achieved compared to online particle counting • Particle breakthrough can occur many hours prior to turbidity breakthrough
3. Filter effluent turbidity is indicative of the effectiveness of filter performance	• Filter effluent turbidity is a direct indication of filter efficiency on a regular basis • Filter effluent turbidity is a good surrogate for optimized coagulation and filter performance • Filter effluent turbidity is a relatively good measure of filter performance
4. A slight rise in turbidity needs to be carefully monitored and/or responded to from an operational perspective	• A slight rise in turbidity can be very significant in with respect to *Cryptosporidium* passage

Filter operation-Backwash scheme	
Summary of opinions	Original comments from respondents (paraphrased)
The effect of different backwash schemes is not clear	• Sludge retention analysis has demonstrated that air/water scour is most effective for cleaning filter media, but its effect on *Cryptosporidium* removal is not clear • Surface scour (water and/or air) at the beginning of the backwash scheme is aimed to make sure the contamination on top of the filter is eliminated efficiently and do not accumulate in the filter bed with time • Filters with surface scour are inferior to filters using air scour or collapse pulsing for particle removal; particle removal is slightly improved when collapse pulsing is applied compared to air scour backwash • The effect of different backwash schemes on *Cryptosporidium* removal is not clear • Inadequate backwash may produce poorer filter effluent or higher risk of breakthrough; however, if operated correctly, all backwash schemes should provide equal effluent quality

Filter operation-Chlorinated backwash water	
Summary of opinions	Original comments from respondents (paraphrased)
1. Since chlorine is ineffective as it pertains to *Cryptosporidium* inactivation, chlorinated backwash water has no influence	• Because *Cryptosporidium* is not inactivated by chlorine and chlorine-related chemicals, this factor (chlorinated back wash water) is not important • This factor likely has no effect on *Cryptosporidium* removal result • Since chlorine is ineffective for *Cryptosporidium* disinfection, its benefit on *Cryptosporidium* removal is not clear
2. Chlorine affects the biological activity in the filter, which may have some influence on *Cryptosporidium* removal	• Biofilm growing on the filter media is beneficial for pathogen removal; chlorinated backwash water will kill off some of the biofilm • If the filter is biological, chlorinated backwash water may have an influence on *Cryptosporidium* removal • This factor is presumably related to the biological activity in the filter which might play role in removing *Cryptosporidium*

Filter operation-Recycling of backwash water	
Summary of opinions	Original comments from respondents (paraphrased)
1. Recycling of backwash water increases *Cryptosporidium* loading on filtration processes	• It artificially increases *Cryptosporidium* concentration • Recycling is known to increase *Cryptosporidium* loading on filtration processes • Need to limit recycle or inactivate *Cryptosporidium* to prevent build-up within treatment processes • It is better to introduce additional treatment to keep *Cryptosporidium* concentrations in backwash water as low as possible • It depends on whether treatment of recycled water is provided to reduce the returning solids and oocyst loads • The stability and equalization of recycle stream loading could be a significant variable that influences *Cryptosporidium* removal efficacy by filtration
2. Recycling of backwash water may influence filter performance	• This factor may impact overall removal in treatment • Recycling of backwash water is not recommended; concern arises especially if polymer is used • Recycling of backwash water is a bad idea
3. The impact of recycling on *Cryptosporidium* by filtration is irrelevant or small if accompanied by well-operated clarification processes	• With well-performing clarification, the recycling of backwash water has little to no effect on filter performance • If filter backwash settling performs well and recycled water makes up less than 5% of total volume, the impact is minimal

Filter operation-Percent bed expansion (during backwash)	
Summary of opinions	Original comments from respondents (paraphrased)
Adequate expansion is important to remove attached oocysts in the filter bed; its effect on *Cryptosporidium* removal is not clear	• The effect of this parameter on *Cryptosporidium* removal is not clear; the percent bed expansion is more of an operational issue • Adequate expansion is necessary to eliminate oocysts trapped in the filter bed • A properly fluidized bed is important to remove attached oocysts; percent bed expansion should be at least 15% • This parameter might be important if backwash water is recycled • This parameter helps to describe the effectiveness of filter bed cleaning

Filter operation-Backwash trigger	
Summary of opinions	Original comments from respondents (paraphrased)
The opinions for selecting a backwash trigger vary	• If waiting until filter effluent turbidity or headloss increases to a threshold, it is possible that oocyst passage has occurred • Turbidity trends need to be monitored as well • It is important to trigger on increases in particle counts • Filter effluent turbidity serves as the best indicator of backwash performance • Dual triggers of incipient particle breakthrough based on continuously monitored turbidity and particle counts work best compared to using headloss as a backwash trigger • Most of the our filters backwash on time • Using headloss and time as the backwash trigger, no breakthrough occurs if filter effluent turbidity is less than 0.15 NTU at the time target headloss or run time is reached • With optimized coagulation and good filter design, the backwash trigger should be headloss • If turbidity breakthrough occurs, *Cryptosporidium* passage is possible • Based on conservative hydraulic designs, turbidity or particle counts should be the primary termination trigger as they typically increase prior to terminal headloss

Filter operation-Filter ripening methods	
Summary of opinions	Original comments from respondents (paraphrased)
1. Opinions on selecting filter ripening configuration vary, extended terminal subfluidization may have a role to play	• Extended terminal subfluidization wash works well; filter ripening may not have pose as much risk as was previously thought. Pilot-scale experiments have demonstrated very similar log removals between filter ripening and early filter run conditions for some colloids • Filter-to-waste is recommended • Based on monitoring filter effluent particle counts, the practice of filter-to-waste seems to be the most robust and guaranteed approach to reduce the risk of oocyst passage • Extended terminal subfluidization, relying on good optimization of backwash sequence and monitoring of filtered water performance, can also provide low filtered water particle counts, comparable to filter-to-waste operation
2. Filter ripening may be a vulnerable period during which *Cryptosporidium* oocysts can be released	• Filter ripening is a vulnerable period for *Cryptosporidium* breakthrough • Filter ripening is a period when oocyst removal can be compromised

Filter operation-Filter aid	
Summary of opinions	Original comments from respondents (paraphrased)
Opinions as to the effect of filter aid vary	• The use of a filter aid is more effective in inline filtration processes • In our pilot--plant, a filter aid has never been used; not sure why a filter aid it should be • In our full-scale plant, polymer is used as the filter aid • In most cases, filter aids can improve *Cryptosporidium* removal during filtration processes; polymers seem to perform best • In pilot-scale experiments, a cationic polymer controlled time-to-breakthrough of fine particles • Filter aids can help filter performance but can be overdosed • A filter aid could clean up particle counts in filter effluent, but this is a making up for sub-optimal pretreatment condition or shearing of floc before entering the filter • Filter aid affects particle attachment

Other comments for factors under "**Filter operation**"
• Intermittent (discontinuous) filtration use may be a factor, especially in small plants where this may be practiced • Flow variation and (sudden) filter flow interruptions are factors to consider • Adjusting filter flow in response to demand is a significant factor in terms of influencing particle removal robustness; bumping filters in the early or later stages of a run can have a different impact; better to make gradual flow changes (ramping) during ripening filter period • Hydraulic changes can significantly affect filtration removals • The most important goal of filter operation is the attainment of very low filter water turbidity from the beginning to the end of the production cycle • Optimization of filtration particle/turbidity performance results in the optimum removal of *Cryptosporidium* by filtration • Optimization of filtration performance results in the optimum removal of *Cryptosporidium* by filtration

Experimental differences-*Cryptosporidium* spike concentration	
Summary of opinions	Original comments from respondents (paraphrased)
1. A sufficiently high *Cryptosporidium* seeding concentration is needed to achieve reliable counts in filter effluent to allow for oocyst log removal through filters to be accurately estimated	• A sufficiently high oocyst spiked concentration is required to ensure an accurate count of *Cryptosporidium* in filter effluent water to determine accurate log removals; Pilot-scale experiments at our water treatment plant have demonstrated very similar *Cryptosporidium* log removals between trials using high and very high spiked concentrations, but the low spiked concentration trials led to the occurrence of non-detects in filter effluent and as such log removal estimates at low concentrations are not attainable • Need sufficiently high *Cryptosporidium* concentration to calculate "real" removal; Otherwise the removal data can only be expressed in the form of ">" • If the spiking concentration is too low, then *Cryptosporidium* can be removed by preceding clarification, when present, resulting in very low numbers reaching filters • Spiking high concentrations of *Cryptosporidium* is the only way to achieve high log removals
2. *Cryptosporidium* log removal increases as influent spiked concentration increases	• Pilot scale experiments demonstrated that *Cryptosporidium* removal increased as spiking concentration increased (Assavasilavasukul *et al*., 2008)
3. Higher spiking concentration results in more rapid breakthrough and impacts removal of a *Cryptosporidium* surrogate	• Using yeast as *Cryptosporidium* surrogate, it was reported that higher spiking concentration results in quicker breakthrough, which in turn impacts removals

Experimental differences-Seeding location	
Summary of opinions	Original comments from respondents (paraphrased)
1. Preferable to spiked oocysts into source water	• Preferable to seed source water, but no significant difference in removals by filtration processes has been observed between seeding source water and seeding into filter influent (pre-coagulated oocysts) • In our experiments, we always spiked *Cryptosporidium* oocysts into source water prior to coagulation • The concern with spiking directly into source water is that high concentrations of *Cryptosporidium* will be needed to ensure concentrations coming into filter are not too low • Oocysts need to go through the whole treatment train
2. The absence of any coagulation is expected to have a substantial effect	• The absence of any coagulation would be expected to be quite significant • If oocysts are seeded after coagulation, then they will not be effectively removed
3. The mixing and transferring of seeded oocysts into water is a source of variability in *Cryptosporidium* removal quantification	• How well the oocysts are transferred and uniformly mixed into the raw water is a source of variability in *Cryptosporidium* log removal results

Experimental differences-*Cryptosporidium* Condition	
Summary of opinions	Original comments from respondents (paraphrased)
1. *Cryptosporidium* condition affects surface charge of oocysts	• Variation includes age of inoculum, storage conditions and detection • All of our experiments have been performed with live *Cryptosporidium*, work by Ongerth and Pecoraro (1996) has demonstrated significant difference in surface charge between inactivated and live oocysts • Condition can affect particle charge (zeta potential) based on findings from bench-scale experiments; particles with similar zeta potentials have been shown to be similarly removed in pilot-scale experiments (e.g. yeast, glycopolymer-coated microspheres) • *Cryptosporidium* condition can alter its surface charge • Surface chemistry (charge and density) of inactivated oocysts should be compared with that of live or naturally occurring oocysts to understand the potential impact of using inactivated oocysts
2. *Cryptosporidium* condition has little to no effect on removal	• Experiments performed by Emelko (2003) demonstrated no significant difference between log removals of viable and formalin-inactivated oocysts • *Cryptosporidium* condition has little effect on removal

Experimental differences-*Cryptosporidium* species	
Summary of opinions	Original comments from respondents (paraphrased)
Limited information available for the effect of *Cryptosporidium* species	• Both are human infectious while it is easier to be infected by *C. parvum* • Based on many discussions with academic experts in the field of *Cryptosporidium* research, there is agreement that there are differences among different Cr*yptosporidiu*m species and strains with respect to surface binding interactions • The effect of *Cryptosporidium* species on removal results is minor

Other comments for factors under "**Experimental differences**"
• Seeding concentration has the greatest impact on achieving high log removals

Analytical differences-Detection methods	
Summary of opinions	Original comments from respondents (paraphrased)
Opinions on the impact of detection methods vary	• Prefer using immunofluorescence assay; we have not attained good results using other methods • Equivalence between these methods cannot be established • Lab methods can influence results when they are not well established • Results have demonstrated no difference between the immunofluorescence assay and flow cytometry; no experience with molecular methods in our experiments • Performance of the overall method is more important that the type of detection methods; although detection methods can have some impact

Analytical differences-Method recovery efficiency	
Summary of opinions	Original comments from respondents (paraphrased)
1. The recovery efficiency provides a reliable estimate of how much *Cryptosporidium* is required for spiking	• Better recoveries suggest fewer *Cryptosporidium* oocysts are required to be spiked; it is important to know what the recovery rate is • Recovery efficiency is related to how many *Cryptosporidium* oocysts need to be spiked to see oocysts in treated water
2. Other	• Very important • Methods of analysis are extremely variable; recovery efficiency provides information on laboratory performance and matrix effects

Analytical differences-Are results adjusted for recovery efficiency	
Summary of opinions	Original comments from respondents (paraphrased)
1. Recovery efficiency should be accounted for to accurately describe *Cryptosporidium* log removals	• Recovery rate has to be accounted for to determine correct pathogen concentration which is used to determine *Cryptosporidium* log removals • It is important to know whether the removals are reported directly or if a factor is used to correct for recovery rate • Recovery efficiency is needed to compare site-specific results with literature results
2. Caution should be exercised when adjusting for recovery efficiency	• Results need to be adjusted for recovery only if the recovery efficiency is dependent on oocyst concentration in a sample; otherwise, the recovery factor becomes effectively irrelevant in the log removal calculation • Adjusting for recovery efficiency is almost never done correctly • Before correcting/adjusting for recoveries, it should be noted that not all *Cryptosporidium* oocysts are recovered at the same rate and therefore adjusting all results based on the recovery of one strain may not be appropriate

Analytical differences-Detection limit	
Summary of opinions	Original comments from respondents (paraphrased)
The detection limit sets the spiked concentration needed; detection limit should always be 1 per volume of water analyzed	• The lower the detection limit the better, but it must be at least one oocyst per volume of water analyzed • Interferences lead to increases in MDL; results are less relevant unless high *Cryptosporidium* levels are encountered • The detection limit is relevant only because it effectively sets the spiked concentration needed • This parameter is important for the detection of high log removals • Detection limit is always 1 per whatever volume filtered and it is critical to ensure high enough volume to provide meaningful information; the 10 L sample volume which is recommended by USEPA may be too low for accurate detection and thus strongly impacts published occurrence of *Cryptosporidium* in US source water

Analytical differences-Occurrence and handling of non-detects	
Summary of opinions	Original comments from respondents (paraphrased)
This factor leads to controversy and discussion; non-detects should be interpreted carefully and be treated in a consistent manner	• A non-detect allows only for the estimation of a minimum log removal based on the concentration spiked into the filter; it indicates the concentration spiked was too low; rounding up to the detection limit is a bad idea and not analytically sound • Non-detects have to be interpreted carefully; duplicates may assist with confirming non-detects • Especially important when working with samples with very low concentration • Should not censor data; a non-detect is a valid result • Only if research quantifies average performance; if research quantifies median performance or 90^{th} percentile, then there is no difference • The handling of non-detects has generated substantial controversy and discussion, a consistent approach is necessary

Additional comments for factors in the "Analytical differences" category
• Analytical differences account for the second most important reason for high log removals (behind only seeding concentration) • Analytical differences may be the reason for the large variability in *Cryptosporidium* oocyst removals reported in the literature • Continuous versus grab sampling may make a difference with regard to analytical differences