Drinking Water Inspectorate

CRYPTOSPORIDIUM - REVIEW OF THE REPORTS OF THE GROUP OF EXPERTS, LITERATURE AND EVENTS.

AUGUST 2025

OFFICIAL

Drinking Water Inspectorate

CRYPTOSPORIDIUM - REVIEW OF THE REPORTS OF THE GROUP OF EXPERTS, LITERATURE AND EVENTS.

TYPE OF DOCUMENT: OFFICIAL

PROJECT NO. 62282760

DATE: AUGUST 2025

WSP

3rd Floor
11 Westferry Circus, Canary Wharf
London
E14 4HD

Phone: +44 20 3215 1610

WSP.com

Copyright and non-disclosure notice

The contents and layout of this report are subject to copyright owned by WSP save to the extent that copyright has been legally assigned by us to another party or is used by WSP under licence. To the extent that we own the copyright in this report, it may not be copied or used without our prior written agreement for any purpose other than the purpose indicated in this report. The methodology (if any) contained in this report is provided to you in confidence and must not be disclosed or copied to third parties without the prior written agreement of WSP. Disclosure of that information may constitute an actionable breach of confidence or may otherwise prejudice our commercial interests. Any third party who obtains access to this report by any means will, in any event, be subject to the Third Party Disclaimer set out below.

Third party disclaimer

Any disclosure of this report to a third party is subject to this disclaimer. The report was prepared by WSP at the instruction of, and for use by, our client named on the front of the report. It does not in any way constitute advice to any third party who is able to access it by any means. WSP excludes to the fullest extent lawfully permitted all liability whatsoever for any loss or damage howsoever arising from reliance on the contents of this report. We do not however exclude our liability (if any) for personal injury or death resulting from our negligence, for fraud or any other matter in relation to which we cannot legally exclude liability.

Management systems

This document has been produced in full compliance with our management systems, which have been certified to ISO 9001, ISO 14001 and ISO 45001 by Lloyd's Register.

QUALITY CONTROL

Issue/revision	First issue	Revision 1	Revision 2
Remarks	Issue 1	Issue 2	Issue 3
Date	27/11/2023	13/03/2024	13/08/2025
Prepared by	Ashleigh Dawson	Ashleigh Dawson	Ashleigh Dawson
Signature	A. Dawson	A. Dawson	A. Dawson
Checked by	Payam Malek	Payam Malek	Payam Malek
Signature	P. Malek	P.Malek	P.Malek
Authorised by	Ashleigh Dawson	Victoria Cherrier	Ashleigh Dawson
Signature	A. Dawson	V. Cherrier	A. Dawson
Project number	62282760	62282760	62282760
Report number	62282760_RP1	62282760_RP1	62282760_RP1
File reference	62282760_231127_RP1_P01	62282760_240313_RP1_P02	62282760_250813_RP1_P03

CONTENTS

EXECUTIVE SUMMARY

Cryptosporidium is a protozoan parasite that can cause the gastrointestinal disease known as cryptosporidiosis. Infection is acquired through the ingestion of *Cryptosporidium* oocysts. Water supplies can become contaminated with *Cryptosporidium* oocysts and act as a vehicle for transmission. Therefore, the effective management of *Cryptosporidium* in water supplies is necessary to prevent cryptosporidiosis outbreaks. Following a series of outbreaks documented in the United Kingdom in the 1980s and 1990s, the government created a Group of Experts on *Cryptosporidium* in Water Supplies to gain insights into the behaviour, prevalence, and movement of *Cryptosporidium* in the environment, as well as its significance as a human pathogen. The Group of Experts published three Reports on *Cryptosporidium* in Water Supplies, the last of which was published in 1998. The reports provided information, guidance and recommendations to safeguard water supplies against *Cryptosporidium* contamination.

Since 1998, academic research and technological advancement has vastly improved both the understanding of *Cryptosporidium* and the availability of options to help safeguard water supplies against it. This report presents an overview of the information in the three Reports of the Group of Experts, a root-cause analysis of *Cryptosporidium* events in England and Wales between 2005 and 2022, and a review of relevant literature since the Third Report of the Group of Experts. The following thematic topics are included: regulation and guidelines, catchment management, network management, *Cryptosporidium* species, detection and monitoring, and treatment technologies.

For *Cryptosporidium* events in England and Wales between 2005 and 2022, there was no single cause that was the most prevalent for causing the events. Insufficient treatment for corresponding catchment risk, faulty assets and poor procedures or staff training were the causes of most *Cryptosporidium* events in this period.

There are various options for the monitoring and detecting of *Cryptosporidium* in water supplies, these include monitoring for surrogates for *Cryptosporidium*, such as turbidity monitoring and particle counters, or using methods to directly detect the organism. Directly detecting *Cryptosporidium* can be undertaken using oocyst count methods, molecular methods and through new options such as miniaturised detection methods. Numerous treatment technologies for *Cryptosporidium* are available, these include solid-liquid separation technologies, traditional disinfection methods, ozone and Ultra-Violet disinfection. Emerging technologies such as ballasted clarification and ceramic membranes have recently had large-scale installations in the UK and show promising results.

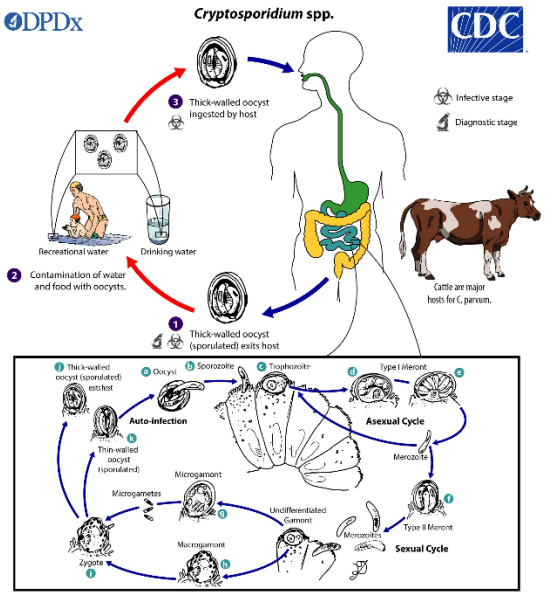
The evidence-base collected in this report will be further developed by undertaking stakeholder engagement to obtain their views and experience of the current guidance and practices for managing *Cryptosporidium* in water supplies.

1 INTRODUTION

1.1 FATE AND PRESENCE OF *CRYPTOSPORIDIUM* IN DRINKING WATER SUPPLY

Cryptosporidium is a protozoan parasite that has garnered increasing attention in recent years due to its significant impact on public health. Of the 48 recognised *Cryptosporidium* species, 23 have been reported to infect humans with *C. parvum* and *C. hominis* being the most predominant species causing disease in humans (Ryan, et al., 2021). The pathogen causes the gastrointestinal infection known as cryptosporidiosis which manifests through a self-limiting diarrhoea lasting for 2-3 weeks (Hunter, et al., 2004). Additional symptoms include nausea, vomiting, and low-grade fever, whereas individuals with compromised immune systems may experience prolonged sickness, which in certain instances can be life-threatening (Innes, et al., 2020). Long term health effects have been documented including gastrointestinal upset have been reported up to 10 years after infection (Carter, et al., 2020), (Boks, et al., 2023). *Cryptosporidium* follows a complex life cycle which can be broadly categorised into three distinct stages which commences through the transmission stage. People can become infected with *Cryptosporidium* through the faecal-oral route. This may be due to recreational exposure, occupational circumstances, through contact with infected animals or people, or via ingestion of contaminated water or food (Innes, et al., 2020). The primary mode of transmission is via the ingestion of contaminated water which contains infective thick-walled oocysts. Upon ingestion by a new host, the oocysts release sporozoites during the process of excystation, initiating infection. A diagram of the life cycle is shown in Figure 1-1 (Centers for Disease Control and Prevention, 2024).

Figure 1-1 – *Cryptosporidium* life cycle



Source: (Centers for Disease Control and Prevention, 2024)

Cryptosporidium oocysts, in particular, present a challenge in mitigating pathogen transmission due to their prolonged survival and effective temperature and chemical resistance. Oocysts can still be viable for 6 to 12 months or more (Jain, et al., 2019). Notably, thermal inactivation of *Cryptosporidium* oocysts only occurs upon exposure to temperatures exceeding approximately 50–60 °C or below -20 °C (Dixon, 2014). At a temperature of 73°C, oocysts would be immediately destroyed (Batt & Tortorello, 2014). Due to this temperature resistance and limited susceptibility to chemical disinfection through chlorine, *Cryptosporidium* can pose a significant challenge in the context of water treatment.

1.2 BRIEF HISTORY OF MAJOR CRYPTOSPORIDIUM INCIDENTS IN THE UK PRE-1998

Cryptosporidium gained notoriety in the United Kingdom prior to 1998 through a series of significant outbreaks, casting a spotlight on the challenges it posed to public health. One such incident was the community outbreak of cryptosporidiosis in the local authority districts of Allerdale and Copeland, North Cumbria from 1992 to 2000. Situated within the Lake District National Park, the region is known for its agricultural and tourism-driven economy. The population of approximately 160,000 relied on diverse water sources, with about one-third receiving water from Ennerdale Lake, another third from Crummock Lake, and the rest from smaller sources. Chlorine disinfection was applied to water from Ennerdale and Crummock Lakes, whilst smaller water sources underwent various conventional treatments, including coagulation, filtration, and chlorination. After the outbreak, the incidence of cryptosporidiosis remained notably higher in Allerdale and Copeland, ranging from 31.2 to 44.2 cases per 100,000 individuals per annum between 1993 and 1995, in contrast to the lower rates observed in neighbouring regions. Subsequent investigations identified un-boiled tap water from public water supplies as a substantial risk factor. The outbreak was primarily attributed to *C. parvum*, with children being mostly affected, leading to many hospitalisations (Goh, et al., 2004).

Other significant outbreaks of waterborne cryptosporidiosis occurred in Swindon and Oxfordshire. Microbiologists noticed a sudden rise in *Cryptosporidium*-positive diarrhoea cases in January 1989 with a total of 516 confirmed cases across a four-month period. The majority of affected individuals were children, and approximately 8 % of cases required hospitalisation, with the illness typically lasting for about three weeks among affected patients. The geographic location of the outbreak led to investigations into water supplies from three treatment works, with subsequent confirmed *Cryptosporidium* oocysts identified within the treated effluent. There may have been an unusually high concentration of oocysts entering the treatment works due to a combination of mild weather, increased grazing and heavy rainfall. The outbreak's cause was attributed to the failure of conventional water treatment processes at the investigated treatment works. There were a large number of oocysts on the filters at the treatment works. However, if the number of oocysts entering the water treatment was unusually high, filtration may not have been sufficient in preventing some oocysts from passing through. Subsequent implementation of mitigation steps was effective in successfully containing the outbreak. Measures included intensive cleaning of the filtration system, changes in procedures for disposal of waters to wash the filters and the removal of sediment from storage tanks and reservoirs. This incident prompted the establishment of a Group of Experts on *Cryptosporidium* in Water Supplies, marking a pivotal step toward improving the management and prevention of *Cryptosporidium*-related waterborne illnesses (Richardson, et al., 1991).

1.3 AN INTRODUCTION TO THE SIR JOHN BADENOCH AND PROFESSOR IAN BOUCHIER REPORTS

In the aftermath of the significant cryptosporidiosis outbreak in Oxfordshire and Swindon in 1989, the government acted by assembling a Group of Experts on *Cryptosporidium* in Water Supplies. Initially, Sir John Badenoch served as the leader of the group, and following his passing, the leadership was taken over by Professor Ian Bouchier. The group had a specific mission: **to gain insights into the behaviour, prevalence, and movement of *Cryptosporidium* in the environment, as well as its significance as a human pathogen.**

Over the course of its work, the Group of Experts produced a series of three reports, with the final one published in 1998. These reports contained a range of recommendations addressing critical aspects such as safeguarding catchment areas, protecting vital assets, refining water treatment processes, enhancing sampling and laboratory analysis, developing strategies for responding to the presence of oocysts in water supplies, managing outbreaks, and formulating emergency plans. The comprehensive findings and guidance provided by this Expert Group played a pivotal role in improving the understanding and management of *Cryptosporidium*-related concerns in water supplies. The three reports produced by the group have served as a standard of good practice for stakeholders within the water industry for the identification, mitigation, and management of *Cryptosporidium*. Nevertheless, recent investigations into *Cryptosporidium* incidents have unveiled certain factors that are not overtly addressed in the three Reports of the Group of Experts (Bridle, et al., 2021).

The second Report of the Group of Experts provided a summary of *Cryptosporidium* risk elements and controls. These topics will be discussed further in this report and an overview is shown below in Table 1.1.

Table 1.1 – Elements contributing to the management of risks identified by the Group of Experts, 1995

Risk element	Components	Controls
Raw water quality	Oocyst numbers Origins	• Careful animal husbandry • Catchment control • Removal from sewage • Monitoring (water quality / concentrations of oocysts in the environment)
Barriers in supply system	Storage Treatment Disinfection	• Type and stages of treatment • Effective operation • Treatment of recycled supernatant • Choice of disinfectant • Disinfectant conditions • Monitoring of treatment e.g. monitoring oocyst removal / inactivation following treatment

Risk element	Components	Controls
Safety of water supplied	Oocyst numbers Viability and species Virulence of oocysts	• Secure storage • Effective mains hygiene • Response to incident
Susceptibility of the consumer	Infective dose Host immunity Quality of water consumed	• Advice to the immune-compromised

1.4 PROJECT OBJECTIVES

The aim of this project is to conduct a comprehensive review of the guidance and recommendations outlined in the existing Reports of the Group of Experts, review up-to-date literature and use expert stakeholder engagement. This will form the basis for the identification of new recommendations for managing *Cryptosporidium* in water treatment. This review aims to assess the recent occurrences of waterborne human cryptosporidiosis and other *Cryptosporidium*-related incidents in water supply systems, considering the following key areas:

I. The occurrence of *Cryptosporidium* in the environment and drinking water safety planning.

II. Species of *Cryptosporidium* that are infective or pathogenic to humans, their occurrence in the environment and concentrations in drinking water likely to cause illness.

III. The impact of raw water storage on the attenuation of *Cryptosporidium*, risks associated with sources of *Cryptosporidium* in catchments (for example human sewage discharges and animal husbandry) and short circuiting in reservoirs.

IV. Water treatment processes that remove or inactivate *Cryptosporidium*, optimisation of these processes and operational good practice. In particular, recent developments in water treatment, for example membrane technology, UV treatment and enhanced coagulation / clarification processes (e.g. CoCoDAF / moving bed / Actiflofilters / cartridge filters).

V. Provision of continuous online monitoring of raw waters, final treated water, and after intermediate stages of water treatment processes for turbidity and other relevant parameters, and triggers for response.

VI. Protection of treated water storage tanks from contamination, taking into account risks present in the environment and risks associated with severe weather events.

VII. Protection of water supply assets, in particular open structures containing partially treated water such as slow sand filters, from avian and mammalian access.

VIII. Sampling methods for *Cryptosporidium* and oocyst recovery for different sampling methods for raw and treated water (with consideration for raw water cartridge clogging). Including good practice for continuous compressed foam filter monitoring

of treated water at treatment works; the impact on oocyst recovery of changing foam pad filters at intervals greater than 24-hourly, and portable monitoring equipment for use during emergencies.

IX. The methodologies employed by Outbreak Control Teams (OCTs) for determining affected populations, the issuing of protective advice to consumers and criteria for lifting protective advice.

This review aims to ensure that the existing guidance remains effective and up-to-date in addressing the evolving challenges associated with *Cryptosporidium* in water supplies.

2 CRYPTOSPORIDIUM INCIDENTS – ROOT CAUSE ANALYSIS

2.1 *CRYPTOSPORIDIUM* EVENTS – THIRD REPORT OF THE GROUP OF EXPERTS BY PROFESSOR IAN BOUCHIER, 1998

The third Report of the Group of Experts by Professor Ian Bouchier, 1998 reviewed 25 UK outbreaks that were associated with public drinking water supplies that occurred between 1988 and 1998. The majority of outbreaks were associated with increases in turbidity, but not necessarily above the regulatory standard for turbidity. Most incidents were reported during the late autumn to early spring period. The majority of the outbreaks of waterborne cryptosporidiosis occurred where the treatment integrity was compromised or the treatment provided was not adequate. Reasons for oocysts entering the supplies included the following:

- Contamination by agricultural slurry;
- Contamination with animal wastes;
- Low river levels with cattle diarrhoea upstream;
- Unfiltered water, point source discharge from sewage treatment works and farm drains and non-point discharge from grazing animals;
- Rapid fluctuations in source water quality;
- Possible link with groundwater turbidity;
- Heavy rainfall and high raw water turbidity;
- Heavy rainfall and run-off from grazing;
- Inadequate treatment, source open to potential contamination;
- Poor operating practices and excessive head on the filters;
- Plant operating above design output, evidence of turbidity peaks in bankside infiltration water;
- Works under strain with excess flow causing solids breakthrough; and
- Breakthrough of solids following inadequate treatment during an algal bloom.

Three out of the 25 incidents were reported to be ‘probably’ associated with groundwater. The reasons for the three groundwater incidents were probable faecal contamination from cattle, possible rapid recharge of surface water contaminated with oocysts and infiltration of surface water containing oocysts.

2.2 DATABASE DEVELOPMENT

A review of the Drinking Water Inspectorate (DWI) water quality incident reports from 2005 to 2022 was completed. Incident reports prior to 2005 were not in a favorable format for effective review and identification of *Cryptosporidium* events. The format of these reports was typically presented as a series of tables with each row representing a specific water quality event. Each event had a corresponding water company, event name, date, classification, affected population, cause (i.e. type of water quality failure) and a brief description. *Cryptosporidium* specific events were able to be extracted from these reports to generate a combined database that contained incidents only where *Cryptosporidium* was detected in the final treated water.

A total of 168 *Cryptosporidium*-related events were identified between 2005 and 2022 in England and Wales (DWI regulated areas). Along with the data already accompanying the events from the DWI reports, each event was also reviewed and assigned within a pre-determined cause and response category.

2.3 EVENT CLASSIFICATION

The DWI has published a 'Guidance on the Notification of Events' which sets out the parameters for drinking water quality event classification. The document is often used by water companies to guide their decision-making process around the notification of water quality incidents.

Notified events are classified by the inspectorate as one of the following:

- Not significant
- Minor
- Significant
- Serious
- Major

These categories are used by the DWI to indicate the time required to assess an event and its complexity, as well as the impact on consumers. Criteria used to classify an event include:

- The number of consumers affected or potentially affected; whether it is a repeat event; whether the company has prolonged the event or exacerbated the consequences through its own actions;
- The presence of faecal indicator organisms;
- The presence of pathogenic or potentially pathogenic microorganisms;
- Whether consumers have been provided with precautionary advice;
- Cases of illness;
- Failure of water treatment, in particular disinfection; and

- The extent of any media interest or national interest.

The Event Risk Index (ERI) is a relatively new metric developed by the DWI designed to quantitatively measure the risk of water quality events, compared to the previous qualitative seriousness category. The ERI score takes into account the seriousness (i.e. Not Significant to Major), the company's performance in managing the event (assessment score) and the consequence (impact score) to obtain an overall numerical rating. For the purpose of the analysis of historical events from 2005 – 2022, only the previous classification method (or seriousness score) was considered.

2.4 DATE OF EVENTS

Figure 2-1 and Figure 2-2 show the progression of *Cryptosporidium* events throughout the time period analysed. Total combined events were found to gradually increase from 2005, peaking in 2016. The period of 2017 to 2022 saw a downwards trend in events, however Figure 2-2 shows a considerable increase in serious and major events in this period.

Figure 2-1 - Bar Chart showing all *Cryptosporidium* Events in England and Wales from 2005 to 2022 by year

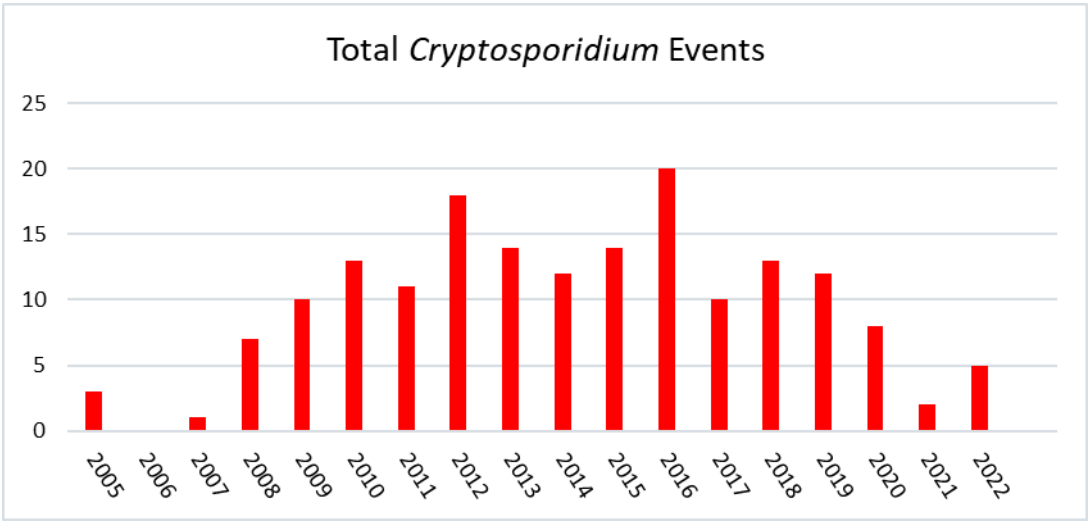
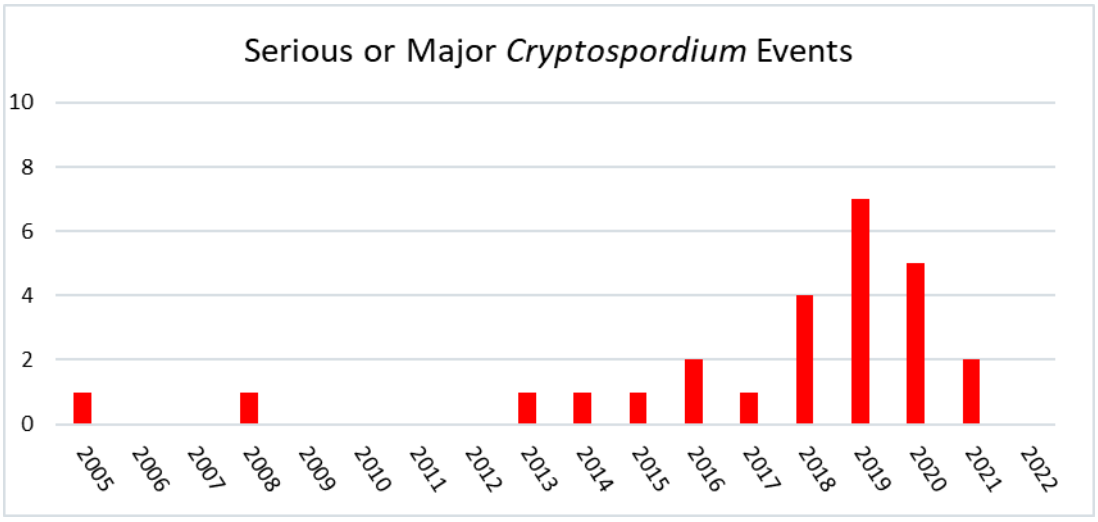


Figure 2-2 - Bar Chart showing all Serious and Major *Cryptosporidium* Events in England and Wales from 2005 to 2022 by year



The increase from 2005 to 2016 could be due to an increase in prevalence of *Cryptosporidium* in the environment. However, it is probably more likely because of an increase in the water companies and regulators' awareness of *Cryptosporidium* due to improved monitoring techniques and the introduction of *Cryptosporidium*-specific risk assessments. The number of events peaks around 2016, which coincides with the time that the highly public Franklaw incident occurred (see section 2.8 for details). A downward trend in events from 2016 onwards shows that water companies have generally improved their *Cryptosporidium* risk management in recent years. This could be as a direct response to the major events such as Pitsford and Franklaw.

The increase in serious and major events from 2017 onwards is difficult to explain, but likely due to an improvement in monitoring and incident reporting. None of the events post-2017 led to large-scale boil water notices being issued as seen with Cwellyn (2005-2006), Pitsford (2008) and Franklaw (2016) (see section 2.8 for details).

2.5 LOCATION OF EVENTS

Figure 2-3 and Figure 2-4 are visual representations of the *Cryptosporidium* event data based on geographical location. Each of the 168 events were assigned a county within the UK which allowed for an event 'heat map' to be generated.

Figure 2-3 - Map depicting the number of *Cryptosporidium* events in each UK county from 2005 to 2022

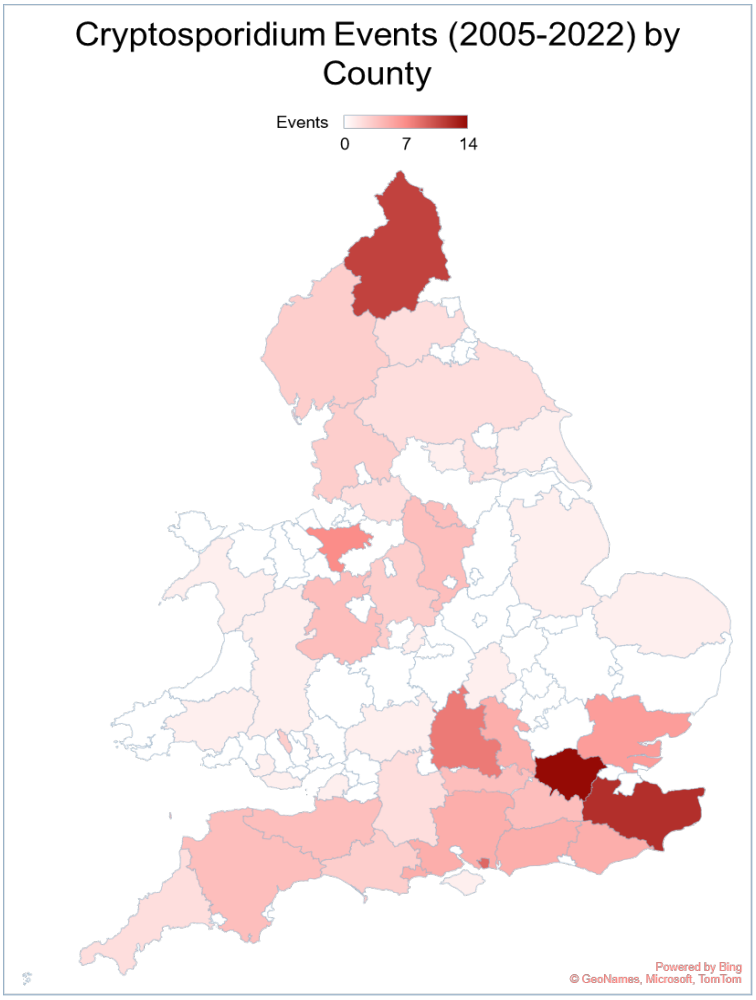


Figure 2-3 shows that *Cryptosporidium* events have occurred across most areas of England and Wales. The counties of Kent and Northumberland have been highlighted as having the highest number of events between 2005 - 2022. The existing database does not reveal a clear and obvious reason for these counties being more vulnerable than the others.

However, the 'heat map' does indicate a significant number of combined events across the southern coast compared to other regions. This could be a trend related to the difference in environmental conditions in the southern coast compared to the rest of the country. Water companies on the south coast have a heavily reliance on groundwater sources compared to other areas. For example, Southern Water and Portsmouth Water source approximately 70 % and 85 % of their water directly from underground aquifers, respectively. These numbers are much higher than the national average of 35 %.

Deep groundwater aquifers are generally considered to be at extremely low risk to *Cryptosporidium* exposure due to extensive ground infiltration that occurs (WHO, 2014). As a result, chlorination-only treatment solutions are often employed for groundwater treatment

works. This risk-based approach to treatment infrastructure does reduce cost and carbon emissions but it does mean there is no barrier or protection if there has been *Cryptosporidium* ingress. Due to the geological makeup of the south coast, many of the groundwater sources are chalk aquifers which are prone to structural fractures, fissures and conduits. These can form pathways for *Cryptosporidium* oocysts to avoid infiltration and pass straight through to the aquifer (WSAA, 2015) (USEPA, 2006).

Figure 2-4 - Map depicting the number of serious and major *Cryptosporidium* events in each UK county from 2005 to 2022

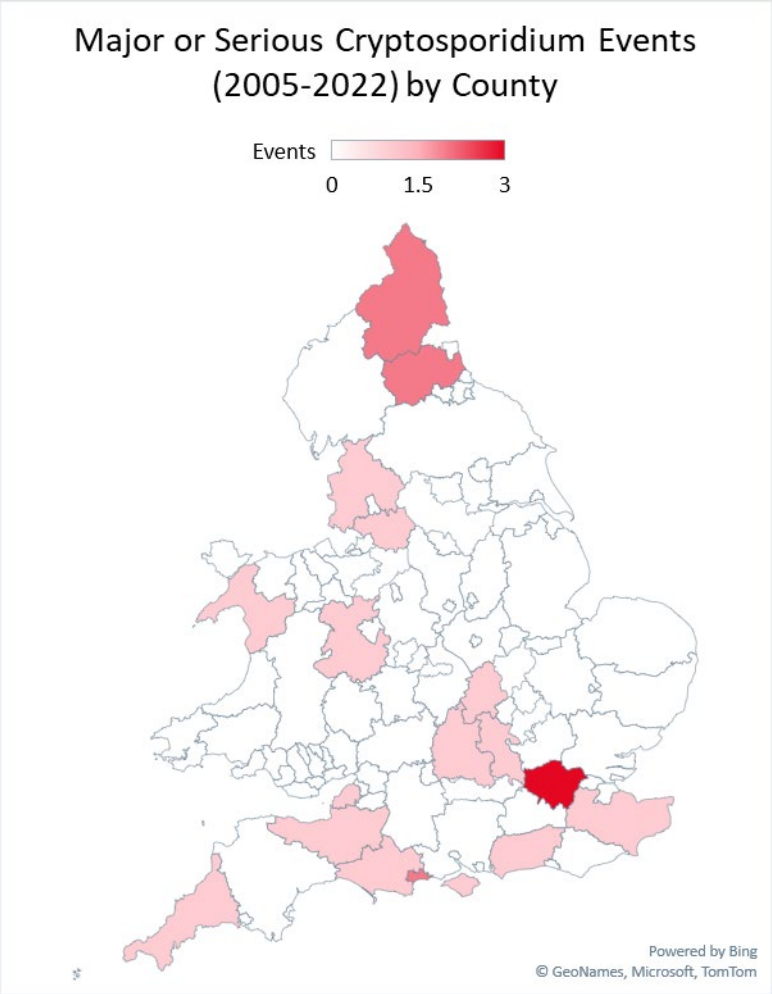
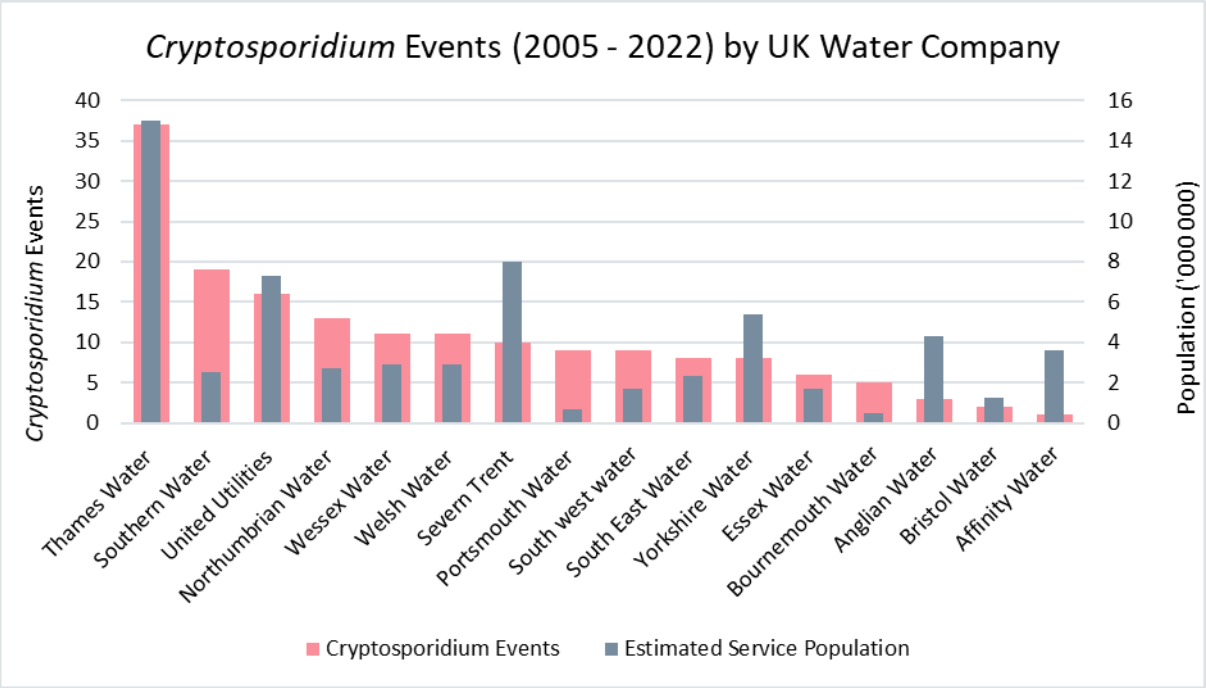


Figure 2-4 shows that serious and major events do not necessarily follow a specific geographical trend. A common factor for these events is that typically highly populated areas are involved (i.e. a population of more than 500,000).

Figure 2-5 splits the *Cryptosporidium* events by the various water companies. It is acknowledged that some water companies have merged or changed names between 2005 – 2022, however the data presented in Figure 2-5 is based on the water company as recorded in the incident reports. The bar chart is ordered from most events to least events and a secondary bar is added to show the relative estimated service population. When comparing the two bars, it can be seen which water companies have a relatively high occurrence of

events per capita. While Thames Water has the most events, Northumbrian Water, Southern Water, Portsmouth Water and Bournemouth Water rank the highest in terms of events per capita. This further reinforces the south coast trend seen in the heat maps.

Figure 2-5 - Bar chart showing the number of *Cryptosporidium* events between 2005 - 2022 for each water company and their respective 2023 service population



2.6 CAUSES OF EVENTS

Following a review of the database, each event was categorised into one of the following causes.

CONTAMINATION OR VERMIN BREACH

Contamination or vermin breach is the introduction of *Cryptosporidium* oocysts from a sudden contamination event downstream of the catchment area (i.e. in the treatment works or in the distribution network).

Typical examples include:

- Animals such as squirrels or rabbits entering into a service reservoir.
- Cross-contamination from a burst sewer main.

This would cause a sudden spike in oocysts rather than gradual increase and it is difficult to anticipate and prevent oocysts from reaching the customer. Boil water notices are often required. This is particularly difficult to manage for *Cryptosporidium* as contamination of other pathogens (e.g. bacteria and viruses) are usually inactivated by a chlorine residual held in the supply. *Cryptosporidium* oocysts are resistant to chlorine. Asset maintenance and adequate security measures are key to prevent events caused by contamination or vermin breach.

Franklaw (2015) and Pitsford (2008) were major and serious events caused by contamination downstream of effective treatment. Others include Playhatch (2020 - ingress of contaminated water into the cascade aerator) and Woodgate Hill (2016 - ingress while the contact tank roof was being repaired).

FAULTY ASSETS

An event caused by faulty assets would be a failure of an asset or assets typically used to prevent or remove *Cryptosporidium* oocysts from the water supply.

Typical examples include:

- Failure of chemical dosing system.
- Short circuiting in filter bed.
- Deterioration of membrane performance.

With reliable monitoring, alarms and interlocks, preventative actions should stop oocysts from reaching the customer. Treatment works and distribution networks with ageing assets were found to be at the highest risk. Timely capital renewals to replace end-of-life assets is critical.

Coppermills WTW *Cryptosporidium* event (2017) was a 'Serious' example but the report was lacking detail - "Repair of faulty equipment" was the only comment provided in the incident report. Other examples include Prescot (issues with polyelectrolyte dosing and associated auto plant shutdown) and Sutton Hall (failure of turbidity analyser in wash water returns).

INSUFFICIENT TREATMENT FOR CORRESPONDING CATCHMENT RISK

An event caused by insufficient treatment would be due to the treatment works being inadequately equipped to remove oocysts present in the catchment / source.

Typical examples include:

- No filtration for relatively high-risk groundwater sources.
- Conventional treatment alone insufficient for high-risk unprotected surface water sources.

Sanitary surveys and monitoring programs can be used to determine the *Cryptosporidium* risk of a particular catchment. If the catchment risk assessment is incorrect or outdated, the treatment works may require additional treatment process units. A multi-barrier approach is often recommended to minimise the risk of pathogen breakthrough should one treatment process fail. With reliable monitoring, preventative measures such as downrating or shutting down a treatment works can be used to prevent oocysts from reaching the customer.

Examples include Swynnerton (2012 – heavy rainfall causing ingress into borehole – UV required) and Huntington (2016 - insufficient treatment of backwash water returning to the head of the works).

OPERATIONAL ISSUES AND / OR LACK OF PROCESS MONITORING

Events caused by sub-optimal performance of treatment works due to operational shortfalls would be placed in this category. The treatment works are sufficiently capable of removing *Cryptosporidium* oocysts but best practice operation is not being applied.

Typical examples include:

- Auto control systems not functioning correctly.
- Lack of turbidity analysers on filter outlets.

Examples include Mosswood (2016 – insufficient in-process monitoring) and Kempton (2015 – sub-optimal operation of slow sand filter).

POOR PROCEDURES OR STAFF TRAINING

Events caused by errors from ill-equipped operational staff that result in a deterioration in water quality would be placed in this category.

Typical examples include:

- Operators not trained on how to optimise chemical dosing for effective treatment.
- Routine maintenance not completed correctly by inexperienced staff due to a lack of procedures.

Site-specific procedures and regular training refreshers are important to prevent *Cryptosporidium* events. *Cryptosporidium* awareness training should be considered particularly for high-risk sites.

Examples include Wendron (2014 - valve not returned to the correct position after routine maintenance) and Huntington (2010 - inadequate start-up procedures).

RARE WEATHER EVENT

Events caused by an extremely rare external event resulting in drastic unforeseen change in raw water quality would be placed in this category.

Typical examples include:

- Once in 20-year flooding leading to surface water ingress into a groundwater source.
- Heavy rain in the catchment leading to a sudden but short-term spike in raw water turbidity.

This is only considered a cause if it was rare and manageable (i.e. treatment works shutdown until raw water quality improves). Additional treatment assets may be required if consistent issues with raw water quality were seen due to weather events.

2.7 SUMMARY OF EVENT CAUSES

Upon review of the individual event descriptions in the database, each event was categorised into one of the causes described above in Section 2.6. In some cases, the

information available was not sufficient to confidently identify a cause, resulting in 16 % of the events being categorised as an 'undetermined' cause. Some complex events could have multiple causes; however, the suspected primary cause was assigned. As a result, this event root-cause analysis and categorisation was heavily reliant on the interpretation of descriptions available in the incident reports.

Figure 2-6 shows the percentage frequency of each cause for the 168 events recorded between 2005 and 2022. The chart shows there is no particular cause that is much more prevalent than the others. 'Insufficient Treatment for Corresponding Catchment Risk', 'Faulty Assets' and 'Poor Procedures or Staff Training' are the most frequent causes with 24 %, 22 % and 20 %, respectively. Events caused by 'Contamination or Vermin Breach' is relatively low at 6 %.

Figure 2-6 - Pie chart showing the various causes of *Cryptosporidium* events in England and Wales from 2005 to 2022

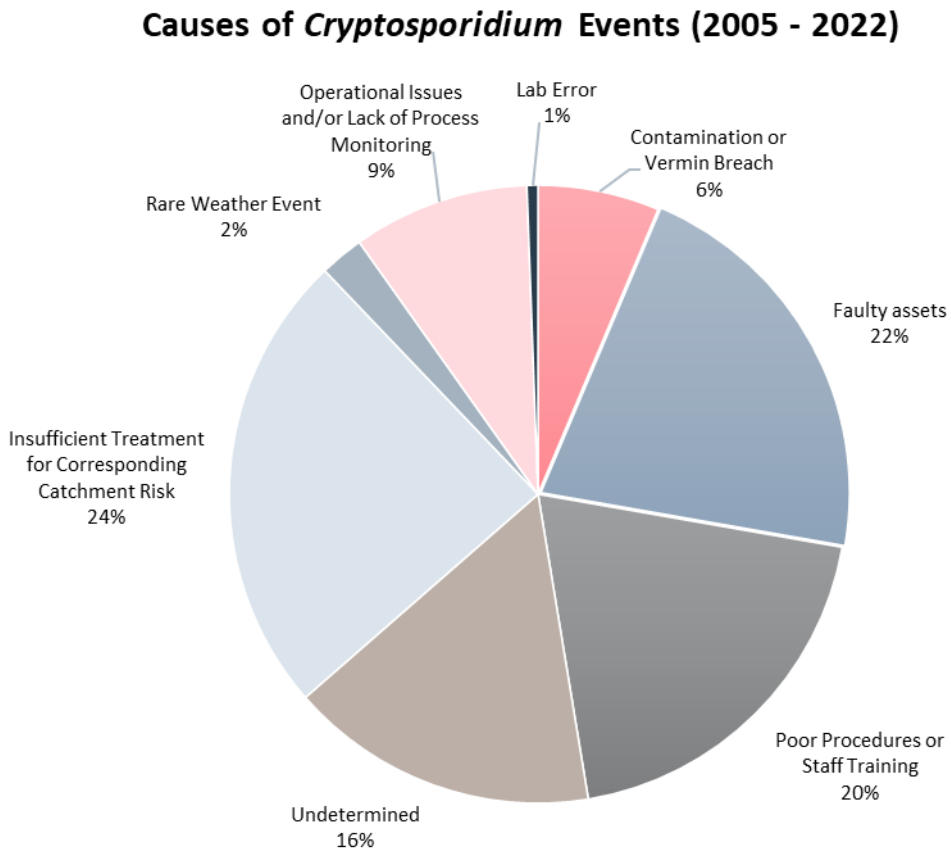
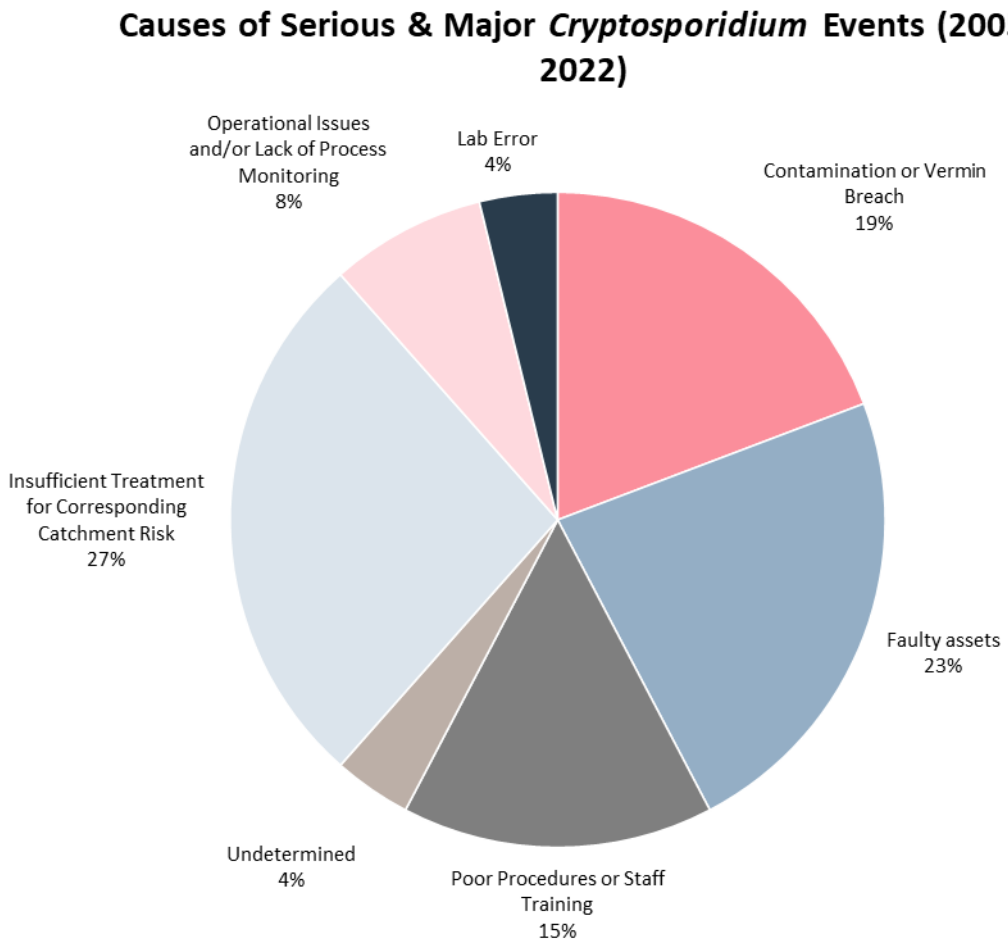


Figure 2-7 shows the causes of the 23 serious and major events between 2005 and 2022. The frequency of the various causes are similar to those shown in Figure 2-6. However, one significant difference is that 'Contamination and Vermin Breach' does increase from 6 % to 19 % in Figure 2-7. This would suggest that while events caused by 'Contamination and

Vermin Breach' (such as a mammal entering a service reservoir) are not particularly common, the likelihood of it resulting in a serious incident is high. This is because the contamination usually occurs downstream of the treatment works and detection may come too late to effectively isolate the contamination by physical intervention. The only major incident (as classified by the DWI) in the period of 2005 – 2022 is the Franklaw incident in 2015 which was caused by contaminated rainwater entering an underground treated water tank. While other causes can also result in severe events, there is generally more time to react and multiple barriers in place to prevent oocysts from reaching the customers taps.

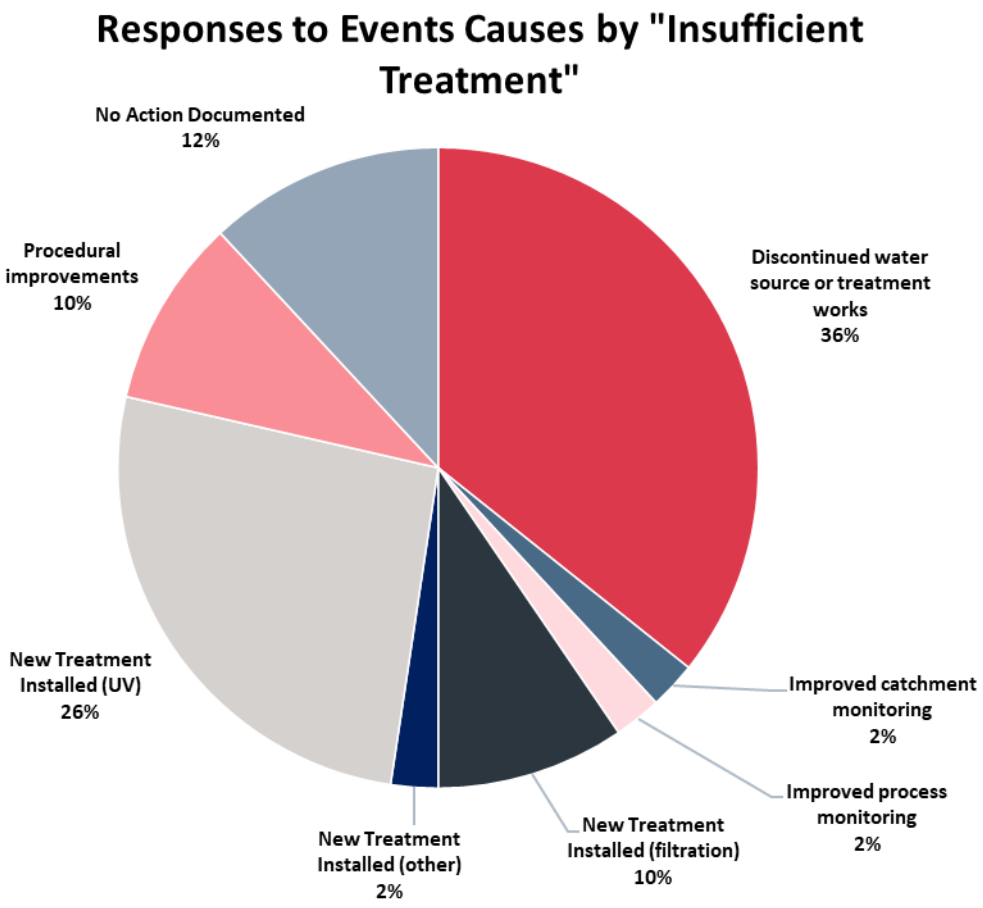
Figure 2-7 - Pie chart showing the various causes of Serious and Major *Cryptosporidium* Events in England and Wales from 2005 to 2022



It should be noted that the event categorisation process was relatively subjective, and some events could have been placed in multiple categories. Each event in the database was assigned a response category. Most of the event causes had a typical or common response e.g., an event caused by a faulty asset typically resulted in the review and repair of that asset. However, responses to events caused by 'insufficient treatment for corresponding catchment risk' was the most varied. Figure 2-8 shows the various responses to these events. It is almost an even split between either deciding to install additional treatment (most

often UV disinfection) or to discontinue the source / treatment works. It is expected that the decision to install additional treatment or not would depend on the availability of other infrastructure within the local supply scheme.

Figure 2-8 - Pie chart showing the responses to *Cryptosporidium* Events in England and Wales that were caused by "Insufficient Treatment" from 2005 to 2022



2.8 MAJOR EVENT CASE STUDIES

CWELLYN 2005-2006

A *Cryptosporidium* outbreak with a total of 231 laboratory confirmed cases was observed in North Wales between October 2005 till January 2006. The local authorities of Gwynedd and Anglesey had the majority of positive cases with an incident management team (IMT) being assembled on 7th November 2005. Preliminary investigations linked the outbreak to a water reservoir in Llyn Cwellyn, located in Snowdonia national park at close proximity to Mount Snowdon. A significant number of affected individuals were adults, suggesting a common community source rather than an acute exposure event. Furthermore, a positive correlation was observed between individuals afflicted with cryptosporidiosis and individuals having consumed mains tap water that had not been boiled. By 29th November, evidence suggested that the primary cause was waterborne infection prompting an outbreak declaration and the

advice to boil mains tap water. Microbiological analysis identified the *C. hominis* strain being responsible with numerous potential transmission routes into the water system. To mitigate further spread, Dwr Cymru who operates the Llyn Cwellyn site installed a new UV treatment unit. Once the performance of the UV unit was validated and deemed appropriate, the boil water advisory was retracted (Lines, 2005). Notably, this incident constituted the largest recorded waterborne outbreak of cryptosporidiosis in Wales, involving 115 laboratory confirmed individuals in a comprehensive four-month investigation.

PITSFORD 2008

In June 2008, Anglian Water's Pitsford WTW detected the presence of *Cryptosporidium* oocysts in a filter cartridge, necessitating immediate action. This was the first recorded outbreak of cryptosporidiosis due to *C. cuniculus* (formerly the rabbit genotype), following a water quality incident. The impact on the public included 23 people being microbiologically linked to the incident although other evidence suggests an excess of 422 cases of cryptosporidiosis above baseline (Puleston, et al., 2014). To safeguard public health, a 'Boil Water' notice was promptly issued at 06:00 on June 25, 2008, affecting approximately 108,000 households. Simultaneously, the DWI was notified to ensure regulatory oversight and coordination. Anglian Water undertook a multi-faceted mitigation strategy, including the distribution of 'Boil Water' cards to affected households, which was implemented by the Royal Mail on 26th June 2008. To increase public awareness, Anglian Water's website was continuously updated, including the implementation of a postcode checker. This tool enabled residents to ascertain whether they resided in an affected area. Furthermore, loud hailers from vans were deployed across the affected localities to distribute information and provide advice to the public. Environmental Health Officers conducted radio interviews, emphasising the importance of using boiled water to mitigate health risks from this outbreak.

After a detailed investigation, including molecular analysis of case, water and animal samples, the source of the outbreak was traced back to a rabbit which gained access to the backwash tank at Pitsford WTW. In an effort to mitigate the contamination at the Pitsford WTW, the installation of three UV lights was undertaken (Malpas, et al., 2008). Furthermore, an extensive flushing regime was implemented across approximately 1,000 miles of mains water supply.

FRANKLAW 2015

In August 2015, a significant public health incident unfolded in North Lancashire, involving the detection of unusually high levels of *Cryptosporidium* in the water supply. Two consecutive water samples from the Franklaw WTW had revealed the presence of *Cryptosporidium*. The incident began on August 4th, 2015, when a filtration unit employed for *Cryptosporidium* capture was removed and sent for analysis. On August 5th, a United Utilities laboratory reported the detection of several oocysts in this filter, with a concentration of 0.031 oocysts per 10 litres. Subsequently, the replacement filter put in place on August 4th was also removed for immediate analysis, which revealed an even higher concentration of oocysts, 0.119 per 10 litres. The results were deemed unnatural for the Franklaw WTW as the site had not previously encountered a *Cryptosporidium* contamination (Rink, 2017).

United Utilities, the responsible water utility company, initially reported this incident to the DWI on August 6th, 2015. In collaboration with Public Health England (PHE), United Utilities issued a boil water notice to all consumers supplied by Franklaw WTW affecting 712,000 people (Rink, 2017). Furthermore, United Utilities initiated an extensive communication campaign through its website, social media, press releases, radio, and written advisories to

affected properties from August 7th. This comprehensive outreach aimed to ensure that consumers were aware of the situation and took appropriate precautions to prevent the spread of cryptosporidiosis.

To manage the emergency response and facilitate investigations, the Scientific and Technical Advisory Cell (STAC) was established, headed by PHE. Although initial investigations were unsuccessful in identifying a root cause, it was concluded that the incident was caused by a number of significant failings in the operation of the Franklaw Water Treatment Works. The existing risk assessment did not take in to account recent changes to the way the process was operated, particularly around the return of contaminated backwash water. In order to ensure a *Cryptosporidium* free water supply, United Utilities took the decision to install UV treatment at service reservoir (SR) outlets. The first UV unit was commissioned on 22nd August at the Warbreck SR, with all water supplied from the Franklaw works being treated with UV by December 2015 (Rink, 2017).

3 REGULATIONS AND GUIDELINES

3.1 REGULATIONS AND GUIDANCE SUMMARY - REPORTS OF THE GROUP OF EXPERTS

This section provides an overview of the guidance and regulations that are included in the three Reports of the Group of Experts. Some of the regulations that are discussed in the Reports of the Group of Experts are now repealed or superseded.

FIRST REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1989

The first Report of the Group of Experts does not discuss any regulations or proposed regulations that include a direct *Cryptosporidium* component. The report discusses the duty of water companies to implement the Water Supply (Water Quality) Regulations 1989. The regulations in place for minimising contamination of water sources are discussed. The report refers to the Water Act 1989 and its legislation of it being an offence for polluting matter to enter water, including groundwater. The report discusses the Sludge (Use in Agriculture) Regulations 1989. Although the report notes that because *Cryptosporidium* oocysts remain viable in the soil for months, adherence to these regulations and the associated Code of Practice for Agricultural Use of Sewage Sludge (1989) will not eliminate the possibility of contamination of water due to sewage sludge application.

SECOND REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1992

At the time of the second Report of the Group of Experts, a repealed EU regulation relating to the quality of water intended for human consumption is described. The legislation contained text stating that “water should not contain parasites, algae and other organisms such as animalcules”. The report notes that the UK Water Supply Regulations contains a clause that precludes the presence of any element, organism or substance at a concentration of value which would be detrimental to public health.

The report considers it an issue that the disposal to land of wastes from agriculture, sewage treatment works, septic tanks and other industries are controlled by different regulators and through different Acts, Statutory Instruments and guidelines. The occurrence of *Cryptosporidium* is not considered in any of them. It identifies a need for some level of harmonisation to control the spread of *Cryptosporidium*.

THIRD REPORT OF THE GROUP OF EXPERTS BY PROFESSOR IAN BOUCHIER, 1998

Proposed regulation

At the time of the third Report of the Group of Experts, the department that proposed regulation for *Cryptosporidium* was the Department of the Environment, Transport and the Regions (DETR). This department has since been replaced by the following departments:

Ministry of Housing, Communities and Local Government (MHCLG), Department for Environment, Food and Rural Affairs (DEFRA), and Department for Transport (DfT). In 1998, DETR issued a consultation document entitled 'Preventing *Cryptosporidium* getting into Public Drinking Water Supplies'. This document stated that Ministers had concluded that water treatment plants at the greatest risk of releasing *Cryptosporidium* into drinking water supplies should implement increased monitoring. The document also proposed amendments to the Water Supply (Water Quality) Regulations 1989 (England and Wales). These included a proposed treatment standard of less than one oocyst in ten litres based on continuously sampling 1,000 litres of treated water per day.

The consultation document was not referred to the Group of Experts for consideration, but the Group of Experts were interested in certain points within the consultation document. These included the following:

The rationale behind the treatment standard.

The report states that the treatment standard was derived from experience of routine sampling in which the concentrations in treated water according to accepted good practice were at least an order of magnitude lower than one oocyst in ten litres and there was no increase in cryptosporidiosis in the community. The report also notes that an infective concentration is at least an order of magnitude greater than one oocyst in ten litres. The report did not identify any other information on which to advise on a different treatment standard to the one proposed.

Whether the proposals cover sources of greatest risk.

The third Report of the Group of Experts identifies river sources as the greatest concern, which would be covered by the proposals presented in the consultation paper. However, the Group of Experts highlighted other high-risk situations (for example groundwaters influenced by surface waters) and wanted to see such sources included on a risk assessment basis.

The use of continuous sampling.

The Group of Experts were not commenting on the proposed regulations, but they did endorse the use of continuous sampling, as random spot sampling for *Cryptosporidium* is ineffective.

Associated regulations

The third Report of the Group of Experts describes some of the regulations in place to protect surface water and groundwater. It discusses these regulations in the context of their role in minimising groundwater contamination. The regulations, statutory management and guidance described in the report are listed below:

- The Water Resources Act 1991 which requires the Environment Agency (EA) to consent to all trade and sewage effluent discharges to controlled waters which includes both surface water and groundwater. The report notes that the situation regarding

groundwater discharges is complex, as indirect discharges such as those to the ground, may not need consent.

- The Control of Pollution (Silage, Slurry and Agricultural Fuel) Regulations 1991 which require that that new or substantially altered silage or slurry storage structures are built to a minimum standard, and that the EA must be notified before they are brought into use.
- The Water Framework Directive[1] is described as possibly providing some additional indirect controls.
- Nitrate Vulnerable Zones may provide reduction in the risk of groundwater contamination by *Cryptosporidium*.
- The Code of Good Agricultural Practice for the Protection of Water which was practical guidance at the time to provide advice to famers and growers to avoid causing pollution of water.
- Landfill sites are required to have a waste management license from the EA.
- The Sludge (Use in Agriculture) Regulations 1989 which set out the treatment requirements of sludge and application rates.
- The Waste Management Licensing Regulations 1994 set out that the EA must be notified of the spreading of exempt waste. If the spreading is taking place within a source protection zone, then the Environment Agency should inform the water company.

Regulations for incidents

The report states that under the Water Supply (Water Quality) Regulations 1989, water companies are required to inform district health authorities (superseded)[2] and local authorities as soon as possible on any event that gives rise to or will likely lead to a significant risk to health of persons residing in the area.

[1] The European Water Framework Directive (2000/60/EC) was transposed prior to the UK's exit from the European Union (EU) into The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017. The regulations have been retained as domestic law following the UK's exit from the EU.

[2] District health authorities were superseded by primary care trusts, then clinical commissioning groups and now integrated care systems.

Reportable disease

The report recommended that cryptosporidiosis should be made a laboratory reportable disease and that consideration should be made to make the disease notifiable.[3]

Public record

The report describes the requirement on water utilities to prepare and maintain information under the Water Supply (Water Quality) Regulations 1989 on Public Record. This includes the following recording of information on water supply zones:

- The name of treatment works supplying the zone;
- Details of any relaxation of water standards;
- Details of any undertakings applying to the zone;
- Results of compliance samples taken from water treatment works,
- Service reservoirs and the distribution system; and
- Annual summary analytical information including, where appropriate, a commentary on water quality.

3.2 NEW GUIDELINES AND REGULATIONS SINCE 1998

The Water Supply (Water Quality) (Amendment) Regulations 1999 (the 1999 Regulations) came into force on 30 June 1999. These have been incorporated into the new Water Supply (Water Quality) Regulations 2000 in England. The 1999 Regulations set a treatment standard of an average of less than one oocyst in 10 litres of water supplied from a treatment works. This has since been deregulated (in 2007) and there is no treatment standard in the regulations. The 1999 regulation also required water companies to conduct specific *Cryptosporidium* risk assessments for each of their water sources. The proposed treatment standard and the *Cryptosporidium*-specific risk assessment are not included in The Water Supply (Water Quality) Regulations 2016, but risk assessments to establish whether there is a significant risk of supplying water that could constitute a potential danger to human health or is likely to be unwholesome are a regulatory requirement. Water companies must design and continuously operate a water treatment process in accordance with the outcomes of that risk assessment. There are different types of risk assessments with varying complexity, however water companies in the UK are strongly recommended to

[3] Currently *Cryptosporidium* is in the list of notifiable organisms but cryptosporidiosis is not on the list of notifiable diseases under the Health Protection (Notification) Regulations 2010.

develop the risk assessment into a comprehensive drinking water safety plan which outline the risk management approach to each specific water supply chain.

The outcome of the risk assessments and drinking water safety plans will determine the type of treatment process required. Where extensive catchment data is available, a treatment process may be designed to provide a pre-determined log-removal of *Cryptosporidium* oocysts. However, this is something that is not currently regulated in the UK and would be assigned by the water company on a case-by-case basis in consultation with the DWI. The Reports of the Group of Experts are used as a benchmark for good practice of design and operation of these water treatment processes.

3.3 DRINKING WATER SAFETY PLANS

The WHO describe drinking water safety plans as “the most effective means of consistently ensuring the safety of a drinking water supply” (WHO, 2023). The DWI strongly supports this initiative from the WHO and have published their own guidance on how to develop a drinking water safety plan.

The primary objectives of a water safety plan (WSP) are:

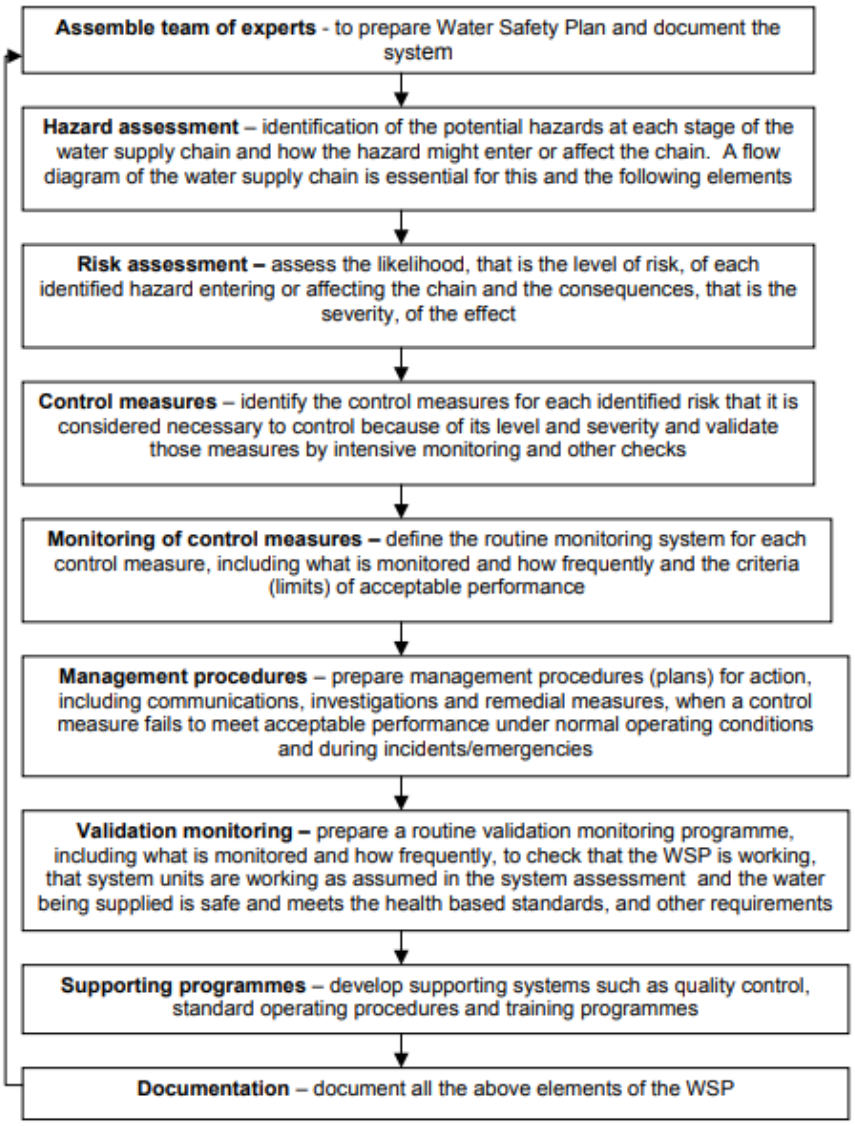
1) the minimisation of contamination at the source;

2) the reduction or removal of contamination through appropriate treatment processes; and

3) the prevention of contamination in the distribution network.

The development of a WSP typically follows the flowchart shown in Figure 3-1, which includes a systems assessment (hazard and risk assessment), operational monitoring programme and documentation of management arrangements. As per regulatory requirements, *Cryptosporidium*-specific risks, controls and monitoring should be considered as a part of the WSP development process. The recommendations outlined in the Reports of the Group of Experts are often used as the benchmark for control measures for *Cryptosporidium* risks identified in the WSP. There have been significant advancements in species identification, monitoring techniques, treatment technologies and general *Cryptosporidium* risk management practices since those reports were published, justifying the need for additional, up-to-date guidance.

Figure 3-1 - Framework guidance for water safety plan development (DWI, 2005)



3.4 INTERNATIONAL EXAMPLES

Other developed countries around the world with varying water supply structures (i.e. publicly and privately owned) have taken a different approach to *Cryptosporidium* risk management with some adopting widespread regulation and guidance to benchmark specific treatment requirements. In particular, providing benchmarked monitoring requirements to quantify *Cryptosporidium* risk and corresponding treatment requirements through log-removal credits. The UK is often considered one of the world leaders for water quality, with relatively low numbers of water quality events and failures. However, the understanding of *Cryptosporidium* risk management is constantly evolving as advancements in species identification, monitoring techniques and treatment technologies continue. Collaboration with

research and industry from other nations and regions around the world will only support the development of effective policy and regulations.

3.4.1 US ENVIRONMENTAL PROTECTION AGENCY LT2 RULE

In 2006, the USEPA introduced the Long Term 2 (LT2) Enhanced Surface Water Treatment Rule aimed to supplement existing regulations by targeting additional *Cryptosporidium* treatment requirements to higher risk systems.

MONITORING

Under the LT2 rule, *Cryptosporidium* monitoring of all water sources was required for an initial 2 year-period to determine the specific treatment requirements. To reduce monitoring costs, small filtered systems could first monitor for *E. coli* and only monitor for *Cryptosporidium* if *E. coli* results exceeded specified concentration levels. Systems were then required to conduct a second round of monitoring six years after completing the initial round to see if the raw water characteristics have changed in that time (USEPA, 2006).

CRYPTOSPORIDIUM TREATMENT

Under the LT2 rule, water sources are placed in one of four treatment categories based on the monitoring results. The majority of systems are classified in the low treatment category where no additional treatment is required. However, filtered systems in one of the higher treatment categories must provide 90 to 99.7 % (1.0 to 2.5-log) of additional treatment of *Cryptosporidium* removal / inactivation. Unfiltered water systems must provide at least 99 or 99.9 % (2 or 3-log) inactivation of *Cryptosporidium* depending on monitoring results.

The USEPA have also provided a series of guidance manuals as a part of the LT2 initiative to support water suppliers in implementing best practice for the operation of *Cryptosporidium* removal inactivation treatment technologies including membrane filtration and UV disinfection. These guidance manuals along with manufacturer testing and validation are used to maintain a consistent log-removal as required under the LT2 rule.

3.4.2 WATER SERVICES ASSOCIATION OF AUSTRALIA HEALTH-BASED TARGETS

Water Services Association of Australia (WSAA) developed a ‘Manual for the application of Health-Based Targets for Drinking Water Safety’ in 2015. From 2015 – 2022, this manual was used as a guidance document for best practice in the design and operation of water treatment systems. In 2022, large portions of the manual were integrated indirectly into the Australian Drinking Water Guidelines (ADWG) which is used as a legislative framework to ensure accountability of drinking water suppliers in Australia.

Similar to the LT2 rule, the Health-Based Targets attempt to split all water sources into four categories based on microbial risk. For surface water, a qualitative vulnerability / sanitary survey which assesses catchment protection and its proximity to widespread human and agricultural activity is conducted to determine the category (WSAA, 2015). The information from the survey is also compared with extensive *E. coli* monitoring to verify the findings (as shown in Figure 3-2).

Figure 3-2 - Excerpt from 'Manual for the application of Health-Based Targets for Drinking Water Safety' (WSAA, 2015) for the comparison of *E. Coli* results to catchment vulnerability assessment

Source category Vulnerability Assessment Category	Microbial indicator concentration category Maximum *E. coli*[†] per 100 ml			
	≤ 20 Category 1	> 20 ≤ 2,000 Category 2 & 3	> 2,000 ≤ 20,000 Category 4	> 20,000 Not suitable for drinking
1	Source = Cat 1	Source = Cat 2	Anomalous	Not suitable
2	Source = Cat 2	Source = Cat 2	Anomalous	Not suitable
3	Anomalous	Source = Cat 3	Source = Cat 4	Not suitable
4	Anomalous	Source = Cat 4	Source = Cat 4	Not suitable

[†] Thermotolerant coliforms can be used for this categorisation if *E. coli* data are not available.

For groundwater sources, the sanitary survey is focused on hydrogeology (i.e. thickness of strata and transmissivity) and whether the aquifer is under the influence of surface water or not.

Once the water source has been categorised, the Health-Based Targets are set which are specific log-removal values (LRV) for bacteria, virus and protozoa (as shown in Figure 3-3). These LRVs are used as a benchmark for all water treatment systems in Australia and are now regulated as a part of the ADWG.

Figure 3-3 - Excerpt from 'Manual for the application of Health-Based Targets for Drinking Water Safety' (WSAA, 2015) for the log-reduction requirements of each source category

Category	Min Pathogen LRV Recommended			Typical Treatment Train
	Bacteria	Viruses	Protozoa	
1	4.0	0	0	Chlorination (possibly following clarification)
2	5.0	3.0	2.5	Direct filtration[1] Chlorination
3	5.0	4.0	3.5	Conventional treatment[2] Chlorination
4	6.0	6.0	5.5	Conventional treatment[2]. UV disinfection Chlorination
Potable reuse	Refer to the stormwater and sewage potable reuse guidance given in the Phase 2 Australian Guidelines for Water Recycling series for water sources that have in excess of the stormwater and/or treatment sewage inflows tolerable for a Category 4 water source.			

Notes: [1] Direct filtration means coagulation, flocculation and filtration.
[2] Conventional treatment means coagulation, flocculation, sedimentation and filtration.

The Health-Based Targets also provide guidance on how treatment processes can be validated to provide a specific log reduction in protozoa / *Cryptosporidium*. For example, for direction filtration - *'Individual filter turbidity ≤ 0.15 NTU for 95 % of month and not > 0.3 NTU for ≥ 15 consecutive minutes'* to achieve a 3.5 log-reduction of protozoa. For UV disinfection – *'UV dose > 40 mJ/cm^2, Turbidity < 1.0 NTU & UVT % > Manufacturer's specification'* to achieve 4 log-reduction of protozoa.

3.5 OVERVIEW TABLE FOR RULES AND REGULATIONS SECTION

Table 3.1 – Overview table for rules and regulations

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
General	No specific *Cryptosporidium* regulations discussed. Water Supply (Water Quality) Regulations 1989 and Water Act 1989 for the prevention of general contamination.	EU regulation contained text stating that "water should not contain parasites, algae and other organisms such as animalcules". The occurrence of *Cryptosporidium* not considered in various water supply Acts, Statutory Instruments and guidelines.	Proposed regulation introduced including the publication of consultation document entitled 'Preventing *Cryptosporidium* getting into Public Drinking Water Supplies'.	Changes to Water Supply (Water Quality) Regulations in 1999 to include *Cryptosporidium*-specific requirements. Each water supply scheme required to complete a specific *Cryptosporidium* risk assessment. Drinking water safety plans endorsed by the WHO in 2009 and strongly supported by the DWI.
Monitoring Standards	N/A	N/A	Monitoring to include continuously sampling 1,000 litres of treated water per day to validate treatment efficacy.	*Cryptosporidium* risk assessments and drinking water safety plans used to develop a monitoring programme. The LT2 rule in the US introduced detailed monitoring requirements in 2006. This included an initial 2-year period of *Cryptosporidium* monitoring to determine risk, followed by a second round of monitoring 6 years later. *E. coli* could be used an indicator for small filtered supplies to reduce cost.
Treatment Standards	N/A	N/A	Proposed amendments to the Water Supply (Water Quality) Regulations 1989 (England and Wales). These included a proposed treatment standard of less than one oocyst in ten litres based on continuously	Amendments to the Water Supply (Water Quality) Regulations in 1999 set a treatment standard of an average of less than one oocyst in 10 litres of water supplied from a treatment works. The LT2 rule in the US and the Manual for Health Based Targets in Australia implement treatment requirements in

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
			sampling 1,000 litres of treated water per day. Accepted good practice was at least an order of magnitude lower than one oocyst in ten litres.	the form of log removal credits for various catchment categories.

4 CATCHMENT MANAGEMENT

4.1 CATCHMENT MANAGEMENT SUMMARY - REPORTS OF THE GROUP OF EXPERTS

This section provides an overview of the approaches to catchment management that are discussed in the three Reports of the Group of Experts.

FIRST REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1989

Catchment risk

The first report states that whilst small numbers of oocysts may occur occasionally in all environmental waters, the risk to health is when an unusually high amount of oocysts occur in the water source. Agricultural sources and products of sewage disposal when infection exists in the community are identified as contamination routes.

The report highlights that evidence shows that there is an increased risk of oocyst contamination following agricultural pollution of source water as well as following a period of heavy rain after a dry spell especially if slurry has recently been spread on agricultural land. Peaks have also been noted in spring and autumn which may be linked to seasonal farming practices.

SECOND REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1992

The importance of catchment control in preventing the contamination of water supplies is emphasised. It states the best way to achieve this control is through the relevant codes of practice (e.g. the Code of Good Agricultural Practice for the Protection of Water).

The second report describes the monitoring programmes undertaken by water utility companies.

THIRD REPORT OF THE GROUP OF EXPERTS BY PROFESSOR IAN BOUCHIER, 1998

The third report provides a summary of suspected *Cryptosporidium* groundwater contamination events in England since 1990. This is shown below in Table 4.1.

Table 4.1 – Suspected *Cryptosporidium* groundwater contamination events in England since 1990

Years of occurrence	Aquifer lithology	Aquifer flow type	Supply source type	Comments
1990-91	River gravels over chalk	Intergranular / dual	Well with adits	Adjacent to river
1992, 1995	River gravels	Intergranular	Collector well Adjacent to river used conjunctively with surface water	Adjacent to river
1992	Sandstone	Dual porosity	Well with adits	Contaminated grazed field runoff to wellhead, possible septic tank leakage in wellhead area
1995	Chalk	Dual porosity	Well with adits	-
1995, 1996	Sandstone	Fissure	Adited spring	-
1997	Chalk	Dual porosity	Single borehole	Grazed catchment, losing stream with sewage effluent discharge close to borehole
1997	Sandstone, karstic limestone	Fissure	Adit of former mine	Possible slurry pit leakage
1997	Chalk	Dual porosity	Well with adits	Adjacent to river
1997	Gravels	Intergranular	Collector well	Very shallow well in thin gravel on flood plain, seasonal flooding and gravel pits adjacent

The report emphasises the vulnerability of groundwater to contamination by *Cryptosporidium*. It states that water companies should be vigilant for the sudden influx of surface water into boreholes, wells and springs. The isolation of oocysts after rainfall recharge is a high-risk circumstance warranting investigation. Water utilities should undertake risk assessments for groundwater contamination to identify where *Cryptosporidium* outbreaks would be more likely to occur. Following the risk assessment, the water utilities should assess options for minimising risks by reviewing catchment controls or by operational improvements to the security of the groundwater source. The risk may be at an extent that treatment installation is necessary. Risk assessments should be regularly reviewed, especially following significant changes in the catchment, the condition of the water supply or the demand of the source. Recommendations regarding groundwater contamination include:

- Risk assessment should assess source, catchment and hydrogeological factors.
- National groundwater vulnerability maps and source protection zoning schemes should be used. Extreme vulnerability should be identified using these.
- Careful attention should be given to the operational aspects of groundwater abstraction.

Risk assessment at the catchment level should include anything that has the potential to allow *Cryptosporidium* into raw water. Risk assessments should be based on a combination of factors and areas for consideration include:

- The degree of exposure of the catchment to oocysts;
- Treatment processes currently in place; and
- History of cryptosporidiosis in the community.

The report includes specific factors that should be considered in the risk assessment of groundwater contamination. These are listed as the type of water source; agricultural activity in the catchment; animals in the catchment and sewage contamination of raw water. The report includes a table providing more specific details on these factors and how the risk can be verified. An adaptation of this table is shown below (Table 4.2).

Table 4.2 - Factors for consideration in the risk assessment of groundwater contamination

Groundwater contamination risk factor		**Verification technique**
Well / raw water source factors	Supply source tapping shallow flow systems e.g. adits, springs, mine galleries	Check site plans, tracing
	Adits with upbores or construction-stage ventilation shafts	Check site plans, site inspection
	Poor casing integrity	CCTV, geophysical logging

Groundwater contamination risk factor		Verification technique
	Masonry linings above pumping water level without additional sanitary seal	CCTV, check site plans
	Sewer / septic tank / slurry pit systems near wellhead or above adits	Site inspection
	Inadequately fenced source especially around spring boxes, catchpits, galleries	Site inspection
	Old, poorly documented well construction	Site plans / BGS National Well Record Archive
Hydrogeological factors	Known or suspected river aquifer connection nearby	Flow gauging, modelling, hydrochemistry
	Unconfined conditions with shallow water table	Well water-level monitoring
	Karst or known rapid macro-fissure flow conditions, especially in shallow groundwater	Field mapping, farm surveys
	Patchy drift cover associated with highly contrasting aquifer intrinsic vulnerabilities	Field mapping, shallow drilling
	Solution features observed or inferred in catchment	Field mapping
	Shallow flow cycles to springs	Tracing, hydrochemistry, water temperature logging
	Fissure-dominant flow (as suggested by high transmissivity or specific capacity)	Downhole fluid / flow logging, pumping test analysis
Catchment factors	High wastewater returns, including sewage effluent to losing river reaches, especially under baseflow conditions	Hydrochemistry, microbiology, hydrometry
	Livestock rearing in inner catchment, especially if intensive	Farm survey
	Likely *Cryptosporidium* – generating activities in catchment e.g. abattoirs	Economic activity survey
	Urbanising catchment	Cadastral survey
	Livestock grazed / housed near wellhead patio / courtyard	Site inspection

Following a drinking water-related *Cryptosporidium* outbreak in London and Hertfordshire 1997, more specific recommendations were made including:

- For water companies to consider the use of tracer tests as a measure of groundwater vulnerability.
- Increase surveillance of water sources vulnerable to fast infiltration of recharge (shaft and adit chalk water sources).
- Review operational sampling programmes.

Catchment control

The report identifies catchment control methods to minimise groundwater contamination. Control is based on the following hierarchy:

1: Prevention – avoiding the development of a hazardous activity within the catchment zone. Statutory methods are identified (Town and Country Planning legislation and pollution control legislation).

2: Elimination - removing, shutting down or banning hazardous activities. It is identified that this option may be limited if the owner of affected land can claim for compensation.

3: Mitigation - adopting measures which reduce the risk associated with hazardous activities. Methods identified are statutory controls; codes of practice; and raising of awareness through education and promotion of good practice.

Training

The report notes that treatment works staff should be trained to be aware of the potential effect on the final water quality of even very small changes in the catchment.

Outbreaks

As a key conclusion, the report states that when there is a cryptosporidiosis outbreak, there is a need for local working partnerships, communications, planning and rehearsals.

Oocysts in the environment

The report notes that UK studies assessing the origin of oocysts in the environment have not detected concentrations high enough to establish the origin of oocysts. However, it states that it is known that farm wastes and domestic effluents are potential sources. Surveys should be carried out on the concentrations of oocysts in sewage effluent. Oocysts occur in low concentrations in surface waters worldwide, but can occur in much higher numbers in waters subject to faecal pollution. It states that sewage effluents and farm wastes have the potential to contribute to large numbers of oocysts in the aquatic environment, but also notes that oocyst viability decreases when in animal faeces and manure.

Groundwater contamination

The report reinforces that borehole linings and seals should be maintained to a high standard to prevent ingress of surface waters and other forms of contamination. The definition of a high standard is not provided in the report.

Catchment control

The importance of catchment control is highlighted to reduce the occurrence of large quantities of oocysts in source water. Point sources of pollution are considered a greater risk of pollution, as point sources can lead to a high spike of oocysts in source water. Catchment control recommendations are regulatory mainly relating to preventing, reducing and controlling contamination of manure and sewage effluent and sludge.

Operational aspects of groundwater abstraction

The report contains a section on guidance for operational aspects of groundwater abstraction. This focuses on the identification of 'at risk' situations where there is the potential for surface-derived pathogens entering groundwater rather than specific operation guidance. The report highlights that there is a research need for the development of operational tools and a general guidance manual for the operation of groundwater abstraction and treatment processes.

The report discusses operational aspects related to flow and level measurement and construction characteristics. Regarding flow and level measurement, the report states that an unexpected rise in groundwater levels should be readily investigated and that the ingress of surface water should be considered. Regarding construction characteristics, current practice for sinking new groundwater abstraction points should present a low risk of contaminated surface water entering the borehole provided that linings and seals are maintained adequately. The report does flag that older abstraction sites may pose a higher risk because of fabric deterioration, a change in the nature of the recharge catchment or because in some cases the facilities were not originally intended for abstraction (for example old mine sites). Shallow water bearing strata present greater risks.

Research needs identified in the third Report of the Group of Experts:

- The development of operational tools and a general guidance manual for the operation of groundwater abstraction and treatment processes;
- Development of operational monitoring tools to improve the detection of rapid influence of surface water sources on the quality of groundwater;
- Transport and fate of *Cryptosporidium* (and other pathogens) in groundwater systems;
- Application of chemical and particulate tracers to investigate the transport and attenuation of pathogens in groundwater;
- Significance and nature of turbidity changes in groundwater and its role as a monitoring tool for rapid surface water ingress; and

- Attenuation rates for *Cryptosporidium* in soils and unsaturated zones following application of farm wastes and sewage sludge to land.

4.2 LITERATURE REVIEW – CATCHMENT MANAGEMENT

4.2.1 GENERAL CATCHMENT MANAGEMENT PRACTICES

The two main risks of *Cryptosporidium* contamination in drinking water sources arise from agricultural activity and nearby wastewater effluent discharge. In recent years, there has been considerable movement towards the increasingly efficient and sustainable operation of both industries to minimise impact on the environment, which also presents opportunities to reduce *Cryptosporidium* contamination.

Research has indicated that by applying measures to prevent and control cryptosporidiosis in livestock, significant benefits can be seen for livestock health and welfare. Measures also increase the efficiency of production bringing economic benefits to livestock farmers (Innes & Wells, 2021). In addition, applying methods on farms to minimise the environmental contamination with faeces containing infective *Cryptosporidium* oocysts will also help to minimise risk to other animals and to people through protection of the environment and water catchments.

The effective management of manure and slurry on farms to reduce viability of *Cryptosporidium* oocysts will have an impact on disease risk in the wider environment and in particular for water catchments. Such on-farm practices include:

- The proper composting of manure as heat (>60^{o}C) will inactivate the oocysts;
- Storage of faecal waste on farms in slurry tanks, as ammonia and low pH will help to inactivate oocysts;
- Fencing of livestock away from streams and watercourses;
- Provision of water troughs; and
- Use of vegetated and riparian buffer strips, which can help to slow down the transfer of *Cryptosporidium* oocysts from livestock faecal matter into watercourses.

It is crucial for water companies to do regular physical inspections of their water catchments and engage with local livestock farmers to instigate these mutually beneficial measures.

In a recent study (Hemati, et al., 2022), a systematic review and meta-analysis was conducted to evaluate the global prevalence of *Giardia* and *Cryptosporidium* in the effluent of municipal wastewater treatment plants. The meta-analysis revealed that the global prevalence of *Cryptosporidium* was 25.90 % in municipal WWTPs effluents. From 11 articles providing information on *Cryptosporidium* oocyst levels in effluents, the globally pooled concentration was also estimated to be 0.13 oocysts/l.

In a case study based in the Louth area in the Anglian Water region, the *Cryptosporidium* vulnerability of the water supply scheme was assessed which involved the impact of performance of a nearby STW (Lamb, 2015). During the sampling period, it was found the STW added 18 oocysts/l to the effluent due to the periodic nature of oocysts and the way they are recycled in the works. It was also found that primary settlement, trickling filters, and humus tanks at the STW removed a lower percentage of oocysts than results in other studies. The trickling filters at the Louth STW had an oocyst removal rate of 17 % and other

studies cited in the paper show removal rates of 56 % (Villacorta-Martinez de Maturana, et al., 1992) and 50 % (Stadterman, et al., 1995). Based on other monitoring results, it was found that Covenham Reservoir and Covenham WTW would receive regular direct contamination from the STW effluent. This demonstrated the need for effective catchment management in the area by either improving oocyst removal at the STW or isolating the drinking water catchment from potential contamination.

4.2.2 RISKS TO GROUNDWATER SOURCES

A review by Morris and Foster (Morris & Foster, 2000) detailed the *Cryptosporidium* contamination risk in UK aquifers. Their review included the summary from the third Report of the Group of Experts of suspected *Cryptosporidium* groundwater contamination events in England since 1990. This is shown previously in Section 4.1, Table 4.1. The review noted the following points on the contamination events:

- All main aquifer types are represented;
- Chalk is the most prominent, the review notes that this may be due to the heavy usage of chalk aquifers as a resource;
- Both rural and part-rural and part-urban catchments are affected, but rural are more affected;
- Adit wells, collectors, springs and former mines with adits are particularly vulnerable;
- Following the implementation of regulations in 1999 that obliged water companies in England and Wales to conduct risk assessments of treatment works for *Cryptosporidium*, Morris and Cunningham reviewed such risk assessments (Morris & Cunningham, 2005). They provided an overview of what water companies identified as being the most at-risk settings in terms of aquifer and type of supply. The review found 332 of the 1,481 treatment works in operation in England and Wales in 1999 as being at significant risk, about one half of which were works treating groundwater. Chalk aquifers presented the greatest risk (Figure 4-1). Springs draining fracture-flow systems were the most common at-risk design type (Table 4.3).

Figure 4-1 - At-risk groundwater treatment works in England and Wales by aquifer and flow type (Morris & Cunningham, 2005)

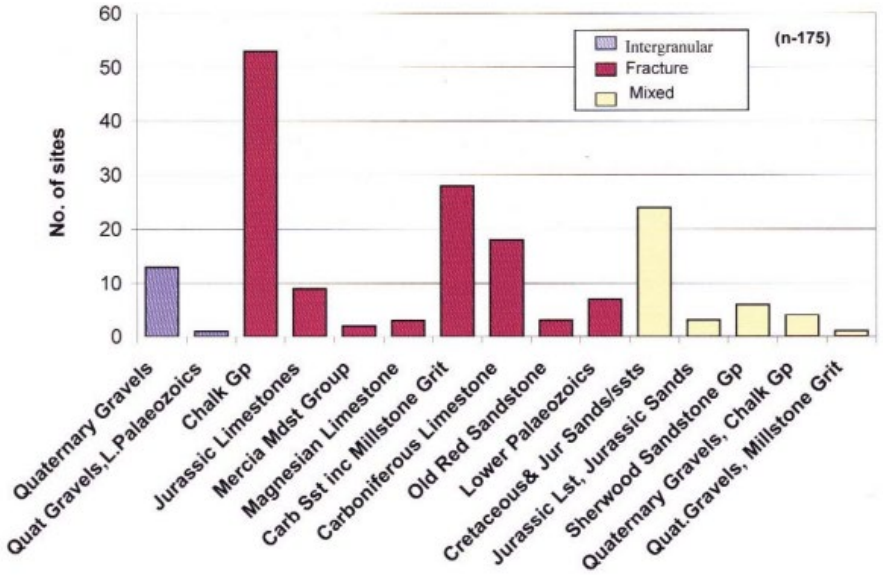


Table 4.3 - At-risk groundwater treatment works in England & Wales by supply type (Morris & Cunningham, 2005)

Class and % of total	Supply type	Number
Drilled well systems 29 %	Borehole(s) alone	50
Borehole-enhanced well or well and adit systems 9 %	Borehole(s) and well(s) Borehole(s), well(s) & adit(s)	6 10
Other systems 62 %	Excavated well(s) (large diameter vertical wellshafts) Well(s) with adit(s) (sub-horizontal excavated shaft or gallery) Spring(s) Spring(s) with well(s) & shallow borehole(s) Mine gallery or adited spring	9 15 76 6 3
	Total	175

International guidance

A manual produced by the Water Services Association of Australia provides information on groundwater vulnerability assessment (WSAA, 2015). It states that groundwater that is not under the influence of surface water will typically have the following characteristics:

- Protected headworks (fenced, above flood level);

- Bore sealed from ingress (including flood events);
- Depth to groundwater >10 m;
- Depth to bore pump >15 m;
- Overlying material homogenous, sand, gravel;
- Total Dissolved Solids (TDS) does not decrease following rainfall, high flow or floods; and
- Turbidity does not increase following rainfall, floods etc.

4.3 OVERVIEW TABLE FOR CATCHMENT MANAGEMENT SECTION

Table 4.4 – Overview table for catchment management

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
General Catchment Risk	Evidence shows that there is an increased risk of oocyst contamination following agricultural pollution of source water as well as following a period of heavy rain after a dry spell.	Best way to achieve catchment control is through the relevant codes of practice (e.g. the Code of Good Agricultural Practice for the Protection of Water). Catchment monitoring programmes are discussed.	Risk assessment at the catchment level should include the following: • The degree of exposure of the catchment to oocysts; • Treatment processes currently in place; and • History of cryptosporidiosis in the community.	Sustainable and environmental drivers in both agriculture and sewage industries present opportunities to reduce *Cryptosporidium* contamination. The effective management of manure and slurry on farms will significantly reduce viability of *Cryptosporidium* oocysts. It is crucial for water companies to do regular physical inspections of their water catchments and engage with local livestock farmers.
Groundwater Sources	N/A	N/A	Summarises suspected groundwater contamination events. Operational best practices for groundwater abstraction are discussed, including the prevention of sudden influx of surface water. Source, hydrological and catchment factors to be considered during risk assessments.	Extensive review of *Cryptosporidium* contamination risk in UK aquifers. Chalk aquifers are the most prominent, but also present the greatest risk. Both rural and part-rural and part-urban catchments are affected, but rural are more affected. Adit wells, collectors, springs and former mines with adits are particularly vulnerable.

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
Surface Water Sources	Small numbers of oocysts may occur occasionally in all environmental waters, the risk to health is when there is an unusually high amount.	N/A	Sewage effluents and farm wastes have the potential to contribute to large numbers of oocysts in the aquatic environment, but also oocyst viability decreases when in animal faeces and manure.	Various research conducted to determine the concentration of oocysts in sewage effluent. A global poled concentration was estimated to be 0.31 oocysts/l with a global prevalence of 25.9 %. Other UK case studies demonstrated the need for effective monitoring and improved STW performance to prevent extensive contamination in high-risk catchments.
Future Research Opportunities	Determine the levels of oocysts occurring in different types of water sources in the UK including groundwater.	N/A	Surveys should be carried out on the concentrations of oocysts in sewage effluent.	N/A

5 NETWORK MANAGEMENT

5.1 NETWORK MANAGEMENT SUMMARY - REPORTS OF THE GROUP OF EXPERTS

FIRST REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1989

The first report discusses the potential contamination of *Cryptosporidium* in the distribution pipe network. It states that normal management of the distribution pipe network should not present a hazard of *Cryptosporidium* oocysts except possibly in emergency conditions. In properly maintained pipe systems, *Cryptosporidium* oocysts are unlikely to be retained in the pipes. Any that have entered from the treatment works will likely be displaced from the pipes by the normal flow conditions. The report also notes that oocysts are dormant in water and will not multiply.

The report states that leaks are inevitable in large networks of distribution pipes. Because of the positive pressure in the pipes, the leaks are normally outwards. However, at times of lower pressure, surrounding water in the ground, which could include sewage, can seep into the pipes. When pipes are repaired, the danger of infection must be recognised.

The report notes that there is a strict protocol[4] for protecting pipes from microbiological contamination during repair or replacement works. However, the chlorine concentration set out in the guidelines is ineffective against *Cryptosporidium* oocysts and the report states that chlorine concentrations of between 8,000 mg/l and 16,000 are needed to kill oocysts. The report notes that there is a need for discussion with the authors of the Operational Guidelines to determine if new protocols of disinfection and sampling in distribution systems should be established if cryptosporidiosis is evident in the population, or oocysts are suspected in the treated water supply from the waterworks.

Service reservoirs

The report discusses the potential contamination of covered service reservoirs in water distribution systems. It states that service reservoirs, particularly roofs, may leak inwards. Poor air vents within these structures can be sources of contamination, but properly constructed and maintained, service reservoirs should not represent a danger to the water supply. The report discourages the use of grazing by livestock on grass covered reservoirs as this can increase the likelihood of contamination. It states that leakage in of oocysts poses a particular risk to the population served by a treated water reservoir, as there is no further barrier to the oocysts reaching consumers' taps.

The report highlights that after commissioning service reservoirs, following construction or maintenance, the disinfection procedures which are recommended to obtain 20 mg/l free chlorine residual do not safeguard if oocyst contamination is suspected. Likewise with the pipe reticulation disinfection described previously, the report notes that there is a need for the revision of the disinfection protocol as disinfection procedures of 20 mg/l chlorine represent no safeguard if oocyst contamination is suspected.

[4] Operational Guidelines for the Protection of Drinking Water Supplies (WAA, September 1988)

Water company plan

The report includes a water company plan which advises on the actions to undertake in the event of an outbreak. This includes remedial actions to remove *Cryptosporidium* oocysts in the network. Specific actions to consider include:

- Contact tanks: inspect, clean out, ensure removal of all sludges.
- Service reservoirs: repair roofs (e.g. by fitment of butyl rubber sheets) if rainwater can seep in.
- Distribution systems: introduce programme of flushing and / or scouring to remove suspect water and any contaminated mains deposits from system.

SECOND REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1992

Service reservoirs

The second report notes that the recommendation of ensuring livestock grazing does not occur on grass-covered service reservoirs is not fully complied with in national parks, areas of natural beauty and common land. It also notes an issue that there is a potential for contamination of service reservoirs through air intakes as a result of grass cutting generating aerosols which contain faecal matter.

THIRD REPORT OF THE GROUP OF EXPERTS BY PROFESSOR IAN BOUCHIER, 1998

The third Report of the Group of Experts does not provide detailed advice or recommendations regarding network management.

5.2 LITERATURE

There are many barriers in the distribution network that prevent *Cryptosporidium* contamination. These include the integrity of the system, the water pressure and backflow prevention in the connections of the network to the domestic plumbing installations (WHO, 2009). Low pressure events, leakage, cross-connections and mains breaks are indicators of the presence of a health risk, even in the presence of a disinfectant residual. Similarly, the construction, maintenance and repair of distribution networks pose a significant risk of contamination if strict hygiene practices are not followed. Workers should be trained appropriately in water hygiene.

A case control study published in 2005 on sporadic cryptosporidiosis in the UK reported an association between gastro-intestinal illness and the loss of water pressure in the distribution network. 28 of 423 controls reported diarrhoea in the two weeks before the questionnaire. Analysis of the risk factors showed a strong association with the loss of water pressure at the household tap. Most of these pressure-losses were associated with reported events in the distribution network, such as a burst of water mains (Hunter & Thompson, 2005).

During August and September 2000, there were 168 laboratory confirmed case of cryptosporidiosis in residents of Belfast. Of these cases, 117 lived within the area supplied by a single treated water pipe constructed approximately 110 years ago. It was found that the pipe was being contaminated by a newly built outflow of a private septic tank (Ainsworth, et al., 2004).

5.3 OVERVIEW TABLE FOR NETWORK MANAGEMENT SECTION

Table 5.1 – Overview table for network management

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
Network management	In properly maintained pipe systems, *Cryptosporidium* oocysts are unlikely to be retained in the pipes. At times of lower pressure or in emergency situations, there could be seepage of surrounding water into pipes. For service reservoirs, poor air vents within these structures can be sources of contamination, but properly constructed and maintained, service reservoirs should not represent a danger to water supply. Livestock grazing on service reservoirs is discouraged.	The recommendation of ensuring livestock grazing does not occur on grass-covered service reservoirs is not always fully complied with in national parks, areas of natural beauty and common land. Contamination of service reservoirs can occur through air intakes as a result of grass cutting generating aerosols containing faecal matter.	n/a	Low pressure events, leakage, cross-connections and mains breaks are indicators of the presence of a health risk, even in the presence of a disinfectant residual. Similarly, the construction, maintenance and repair of distribution networks pose a significant risk of contamination if strict hygiene practices are not followed. Loss of water pressure in the distribution network was associated with gastro-intestinal illness in a case control study published in 2005 on sporadic cryptosporidiosis in the UK.

6 *CRYPTOSPORIDIUM* SPECIES

6.1 *CRYPTOSPORIDIUM* SPECIES SUMMARY - REPORTS OF THE GROUP OF EXPERTS

This section discusses the understanding of *Cryptosporidium* species and their ability to infect humans in the three Reports of the Group of Experts.

FIRST REPORT OF TE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1989

At the time of the first report, the protozoan parasite *Cryptosporidium* was recently recognised as a cause of diarrhoea in humans. *C. parvum* was the species name used for infection in humans, although other species were known to affect mammals, birds, fish and amphibians. At this time there was little known about the identification or pathogenicity differences between different species and genotypes of *Cryptosporidium.*

In the first report, *C. parvum* is described as an important cause of disease in humans and livestock. The report states that transmission has been recorded from human, cattle, sheep and cats. At the time of the first report, it is stated that there is no evidence of avian strains infecting humans. *Cryptosporidium* outbreaks usually involve calves or lambs, and these animals are recognised as important reservoirs of infection for humans. In livestock, there are seasonal peaks of *Cryptosporidium* disease associated with times of high birth rates in spring and autumn.

The report states that the lifecycle of *Cryptosporidium* completes within 1 – 8 days and takes place within the body of a single host. In an infected animal, *Cryptosporidium* multiplies in the digestive tract. The animal then excretes very large numbers of oocysts of the parasites in its faeces. Infected calves excrete approximately 10^{10} oocysts daily for up to 14 days, and the report notes that it is likely that humans shed a similar number. Another animal may ingest the excreted oocysts and then transmission has occurred causing a new cycle of infection. At the time of the first report, the incubation period of *Cryptosporidium* was not known with certainty but refers to estimates of an incubation period of approximately 3 – 7 days.

Children are commonly affected by illness caused by *Cryptosporidium*, but the disease is more serious in immunosuppressed patients or in individuals in countries that are affected by malnutrition.

Water is identified as an important vehicle for the transmission of *Cryptosporidium* and water has been implicated in several outbreaks in the UK. The report states that oocysts are resistant to adverse environmental factors and can survive dormant for months in cool, dark conditions in moist soil or for up to a year in clean water.

SECOND REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1992

Infectivity

The second report refers to a need for understanding the minimum infective dose of *Cryptosporidium* for humans. It refers to a study undertaken in the USA which indicated that

in volunteers without antibodies to *Cryptosporidium*, the dose required for infection can be less than 100 oocysts (Dupont, et al., 1995).

Species identification

At the time of the second report, the development of a monoclonal antibody[5] for identifying *C. parvum* had not yet proved successful. Progress had been made in developing gene probes that could identify different *Cryptosporidium* species. Polymerase Chain Reaction (PCR) is also mentioned as a tool for use in identifying species. It notes that there is not a method in place that could be considered as 'routine' for identifying species.

THIRD REPORT OF THE GROUP OF EXPERTS BY PROFESSOR IAN BOUCHIER, 1998

Cryptosporidium species and subtypes

The only *Cryptosporidium* species discussed in the third report is *C. parvum*. The report acknowledges that there are distinct subtypes of *C. parvum*. It states that *C. parvum* is the only species known to infect both humans and livestock. The report notes that *Cryptosporidium* can spread both by zoonotic (animal to human) and anthroponotic (human to human) transmission.

The report refers to a study undertaken in Warwickshire to understand the prevalence and distribution of *C. parvum* amongst livestock and wild mammals. The study concluded that *C. parvum* is ubiquitous amongst mammals and established a benchmark for the irreducible, minimum background level of *C. parvum* in the UK countryside. The study site was a 190 hectare estate containing different livestock and wild mammal species. The approximate numbers of oocysts generated by the estate was calculated to be between 10^{11} and 10^{12} oocysts. The approximate numbers of oocysts calculated to enter the south-west Warwickshire river system each year from the estate was 10^{9}, a third of which are possibly viable. (Sturdee, et al., 1998).

Distinguishing species and subtypes

The report discusses phenotypic (trait differences) and genotypic (genetic differences) methods to characterise *Cryptosporidium* isolates. Phenotypic methods included distinguishing between *C. parvum* isolates based on their antigenic differences. A further phenotypic method described was to distinguish between *C. parvum* isolates based on isozyme differences. Isozymes are enzymes that catalyse the same reaction but differ from one to another in a range of possible ways. These differences may include having physicochemical, immunochemical and chemical differences. In parasitology, a group of microorganisms that have the same isozymes is known as a zymodeme.

The report discusses genotypic methods available at the time of the report to distinguish *C. parvum* isolates. This includes the use of PCR to amplify genetic polymorphisms to identify

[5] Antibodies are a type of protein that bind to antigens on pathogens and monoclonal antibodies are identical copies of such antibodies.

differences. The report refers to studies that have amplified specific regions of 18S small subunit ribosomal RNA to distinguish between species and 'strains'. The report discusses that the use of PCR has shown differences between isolates found in humans and isolates found in livestock. The report refers to a rapid typing system using the TRAP-C2 gene for which the sequence is available, this method allowed the distinguishing of three genotypes.

Infectivity

The infectivity differences between the different types of *C. parvum* are described. The report speculates that the infective dose for homologous host (same species) transmission is lower than for transmission between different hosts.

Epidemiology

The report states that in waterborne outbreaks, surface-derived water sources are more likely to increase the chance of exposure to a range of *Cryptosporidium* isolates, comprising isolates from both humans and animal sources. This means that an outbreak may not be characterised by a single strain, and that individuals may be infected with more than one isolate. The report refers to studies that characterised *Cryptosporidium* isolates using phenotyping (based on antigenic differences) and genotyping (PCR methods using the COWP gene) from individuals affected by waterborne outbreaks in the UK.

Regarding the pattern that an outbreak might take, a common feature of outbreaks is a start with a marked increase in adults for the primary cases followed by the amplification of the outbreak by secondary propagation, especially by children. This pattern is more likely in areas that have a lower background level of infection prior to the outbreak. It notes that the impact of an outbreak caused by a contamination event may be greater in areas that are supplied from normally high-quality sources compared to areas that are supplied from poorer quality sources.

The report describes the use of serological studies where the sera of subjects that are symptomatic, asymptomatic or part of control group is exposed to *Cryptosporidium* antigens to understand individual's previous exposure to the pathogen.

Cryptosporidiosis

The report describes cryptosporidiosis as a self-limiting diarrhoeal illness in healthy individuals. It states that immunocompromised individuals are more likely to suffer serious disease. It states that the infective dose for humans is not known with confidence but is thought to be quite low.

Research needs identified in the third Report of the Group of Experts

- The need to develop methods for identifying different species and strains of *Cryptosporidium*.
- Further work on typing and understanding host specificity of *Cryptosporidium* oocysts.

6.2 LITERATURE REVIEW – *CRYPTOSPORIDIUM* SPECIES

SPECIES OVERVIEW

There are 48 recognised species and over 120 genotypes of *Cryptosporidium*. The following 23 species have been reported in humans: *C. hominis*, *C. parvum*, *C. meleagridis*, *C. canis*, *C. felis*, *C. ubuiquitum*, *C. cuniculus*, *C. viatorum*, *C. muris*, *C. andersoni*, *C. erinacei*, *C. tyzzeri*, *C. bovis*, *C. suis*, *C. scrofarum*, *C. occultus*, *C. xiaoi*, *C. fayeri, C. ditrichi* (Ryan, et al., 2021), *C. equi* (Huang, et al., 2023), *C. mortiferum* (Kváč, et al., 2025), *C. sciurinum*[6], *and C. wrairi* (Hernández-Castro, et al., 2022). *C. hominis* and *C. parvum* are the two species most frequently reported in humans. The third most common species reported in humans is *C. meleagridis* (Ryan, et al., 2021).

TRANSMISSION

The main host species for *C. hominis* is humans (Zahedi, et al., 2016). The main transmission risk factors for *C. hominis* infection are linked to contact with young children, people with diarrhoea or contamination of water by human waste or wastewater (Cacciò & Chalmers, 2016). Whilst humans are the main host for this *Cryptosporidium* species, it has also been recorded in non-human animals including livestock. Therefore non-human animals could serve as reservoirs for *C. hominis*, however, as previously stated, anthropological rather than zoonotic is the main transmission route for this species (Ryan, et al., 2021), (Xiao & Feng, 2017).

C. parvum has many host species and infects humans, livestock and a broad range of wild animals (Ryan, et al., 2021), (Xiao & Feng, 2017). The main transmission risk factors for *C. parvum* are linked to contact with farm animals (especially young stock for example at petting farms), or consumption of water or food contaminated by their faeces. *C. parvum* can also spread between people (Ryan, et al., 2014).

Birds are the most common host species for *C. meleagridis*, although it can infect humans and other mammals (Ryan, et al., 2021). Zoonotic transmission of this species has been documented at a farm in Sweden (Silverlås, et al., 2012).

A summary of the species that have been reported in humans and the main hosts is shown in Table 6.1.

Table 6.1 - *Cryptosporidium* species recorded in humans and their main hosts

***Cryptosporidium* species**	**Main host(s)**
C. hominis	Humans, non-human primates, donkeys
C. parvum	Ruminants, wildlife, humans

[6] Documented in GenBank

Cryptosporidium species	Main host(s)
C. meleagridis	Birds, mammals
C. canis	Dogs
C. felis	Cats
C. ubiquitum	Ruminants, rodents, carnivores, non-human primates
C. cuniculus	Rabbits
C. viatorum	Rodents
C. muris	Rodents
C. andersoni	Cattle
C. erinacei	Hedgehogs, horses
C. tyzzeri	Rodents
C. bovis	Cattle
C. suis	Pigs, wild boars
C. scrofarum	Pigs, wild boars
C. occultus	Rodents
C. xiaoi	Sheep, goats
C. fayeri	Marsupials
C. ditrichi	Rodents (mainly mice)
C. equi	Equine mammals
C. mortiferum	Squirrels, chipmonks
C. sciurinum	Squirrels
C. wrairi	Guinea pigs

Sources: Ryan *et al* (2021), Zahedi *et al* (2016), Huang *et al* (2023), Kváč, *et al* (2025), Hernández-Castro, *et al* (2022).

CRYPTOSPORIDIOSIS

Infection with *Cryptosporidium* can be asymptomatic or can cause humans to develop a gastroenteritis-type illness called cryptosporidiosis with symptoms that can include diarrhoea, abdominal cramps, nausea, vomiting and low-grade fever (Horne, et al., 2017). *C. hominis* and *C. parvum* are responsible for the vast majority of cases of cryptosporidiosis in Europe

(Ryan, et al., 2014) and globally (Sharma, et al., 2023). In England and Wales, species that have been detected in *Cryptosporidium* patients (from *Cryptosporidium* Reference Unit Data) are *C. parvum*, *C. hominis*, *C. canis*, *C. cuniculus* (rabbit genotype), *C. ditrichi*, *C. equi* (horse genotype), *C. erinaceae*, C. *felis, C. meleagridis*, *C. mortiferum* (Chipmunk genotype 1), *C. occultus* (C.suis-like genotype), *C. sciurinum* (syn ferret genotype), *C. suis*, *C. tyzzeri*, *C. ubiquitum*, *C. viatorum*, Deermouse genotype III, Deermouse genotype IV, Skunk genotype, and novel genotypes.

RISK FACTORS FOR ILLNESS

Cryptosporidiosis symptoms can occur in healthy individuals. Volunteer studies have been undertaken to determine the number of *Cryptosporidium* oocysts associated with cryptosporidiosis. A study undertaken in the USA dosed 21 healthy adults (including both males and females) with either 10, 30, 100 or 500 *C. hominis* oocysts. Enteric symptoms and diarrhoea were present in some of the individuals receiving the lowest dose of oocysts (10 oocysts) although receiving a higher dose of oocysts was associated with a higher risk of developing diarrhoea (Chappell, et al., 2006). A pool of 21 adults is a small sample size meaning the number of individuals in each dose group was small, however, the study does demonstrate that a small number of oocysts can cause cryptosporidiosis. An earlier USA study dosed healthy adults with three geographically distinct isolates of *C. parvum* and found that infection (determined by excreting oocysts and / or developing diarrhoea) can also occur in doses as low as 10 oocysts (Okhuysen, et al., 1999). This study also had low sample numbers in each dose group.

Estimates of average prevalence of human infection have been reported at 4.3 % in high-income countries and 10.4 % in low-income countries (Dong, et al., 2020). Some groups of people may be at a greater risk of developing more serious disease following *Cryptosporidium* exposure. Vulnerable groups include young children and immunocompromised individuals (Innes, et al., 2020). Disease can be particularly severe and prolonged in immunocompromised patients and in children under 5 years in developing countries (Robinson, et al., 2022).

Most studies assessing cryptosporidiosis risk in children have been undertaken in developing countries, as diarrhoeal disease is a major health issue in low-income countries (Kotloff, et al., 2013). There have been some studies assessing cryptosporidiosis risk in children in developed countries. A study in undertaken London in 1992 found that children under two years of age were at greater risk of developing chronic diarrhoea following *C. parvum* infection (Phillips, et al., 1992). A more recent study undertaken in Sweden in 2017 assessed risk factors in children under age 15 following a large waterborne *C. hominis* outbreak. This study did not find younger children to be at a greater risk of developing cryptosporidiosis compared to older children. It did find a higher level of water consumption and being male to be risk factors. The study noted that the male risk factor has also been found in other studies (Widerström, et al., 2014). Immunocompromised individuals most at risk from severe disease are those with profoundly impaired T-cell function and / or T cell deficiency (Hunter & Nichols, 2014). This includes individuals with haematological malignancies and patients with HIV infection with CD4 counts lower than 200mm^3 and especially <50mm^3 (Khorana, 2018).

OUTLINE OF USE OF MOLECULAR TOOLS FOR IDENTIFICATION

Many of the different species within the *Cryptosporidium* genus are morphologically highly similar. This means that molecular techniques are required to identify *Cryptosporidium* at the species level, rather than using microscopy methods. Molecular analysis has also shown intra-species diversity and there are many genotypes and subtypes within *Cryptosporidium* species. Using molecular methods to identify individual species and variants within species (intra-species) allows for tracking of the source and transmission of *Cryptosporidium*.

Tracking infections at the subtype level, can also help in the understanding of subtypes that may cause larger outbreaks and / or are more virulent. To assess intra-species diversity,

sub-typing molecular tools are used. For *Cryptosporidium*, this has mostly been undertaken by analysing differences found at a gene called 60 kDa glycoprotein (*gp60*) (Chalmers, et al., 2019). Within species, there are differences in the number of tri-nucleotide repeats[7] within the *gp60* gene. The number of tri-nucleotide repeats is used to distinguish a subtype (Xiao & Feng, 2017). Using these molecular methods, many gp60 subtypes of *Cryptosporidium* species have been identified. To aid in the categorisation, they have been grouped into families and subtypes. Regarding the two species that most commonly infect humans, there are nine major families identified for *C. hominis* (Ryan, et al., 2014) and over 20 families identified for *C. parvum* (Ryan, et al., 2021). Each family has at least one subtype within, and some families will contain multiple subtypes. There are more subtypes identified for *C. parvum* compared to *C. hominis*. The lower genetic diversity of *C. hominis* compared to *C. parvum* is expected, as it is a more species-specific parasite compared to *C. parvum* which has a broader host range (Hunter, et al., 2007). However, largescale whole genome sequencing may provide further information on the global population genetics of *Cryptosporidium* spp.

Multi-locus genotyping methods can offer more discriminatory power compared to *gp60* sequencing. This can have benefits in epidemiological assessments and help better determine the outbreak strain and understand diversity (Robinson, et al., 2022), (Risby, et al., 2023).

SUBTYPES AND INFECTION

C. parvum and *C. hominis* are responsible for the most infections in humans. Within these species, there are particular subtypes that are responsible for more infections. The three dominant *C. parvum* gp60 families in humans are IIa, IId and IIc. IIa and IId are zoonotic whereas IIc is almost exclusively anthropologically transmitted. IIa is the dominant subtype family in Europe (Ryan, et al., 2021). Within this family, subtype IIaA15G2R1 is the most common in industrialised countries (Ryan, et al., 2021), (Xiao, 2010). For *C. hominis*, family Ib was the most dominant in Europe. Within this family, subtype IbA10G2 largely dominated the outbreaks and sporadic cases in Europe, but other subtypes have recently emerged.

Genotyping studies identifying *Cryptosporidium* species and subtypes following outbreaks have been undertaken in the UK. An analysis of gp60 subtypes linked to cryptosporidiosis outbreaks in England and Wales between 2009 and 2017 was undertaken. The were 178 identified cryptosporidiosis outbreaks. For outbreaks caused by *C. parvum*, gp60 subtype families IIa and IId were recorded. Most *C. parvum* outbreaks were caused by subtype IIaA15G2R1, followed by IIaA17G1R1 and then IIaA19G1R1. There were further subtypes causing small numbers of outbreaks. The *C. parvum* outbreak associated with drinking water (a private water supply) was caused by subtype IIaA15G2R1. For outbreaks caused by *C. hominis*, gp60 subtype families Ia, Ib and Id were recorded. Most *C. hominis* outbreaks were caused by subtype IbA10G2. In the *C. hominis* outbreak associated with drinking water (a

[7] Tri-nucleotide repeats are three nucleotides that are consecutively repeated. In the *gp60* gene in *Cryptosporidium*, the tri-nucleotide repeats are TCA, TCG or TCT. The number of and type of repeats distinguishes a subtype. Some subtypes are distinguished using other regions of the gp60 gene. Subtypes have also been distinguished using other genes.

mains water supply) the consumers were infected with subtypes IbA10G2 and IdA18 (Chalmers, et al., 2019).

Applying genotyping subtyping methods to water samples is challenged by the small numbers of oocysts present.

Species and sub-types responsible for recent outbreaks in England include:

- In May 2024, a cryptosporidiosis outbreak occurred in the Brixham area due to *C. parvum* with the following sub-types: gp60 subtypes IIaA15G1R1 and IIaA20G1R1. Multiple-Locus Variable number tandem repeat Analysis (MLVA) profiles included the alleles 5/6/Ø-12/13/Ø-3/Ø-10/13–18/Ø-9/13-24/25.
- In December 2013, Alderney WTW had consecutive *Cryptosporidium* detections and raw water deterioration due to *C. hominis* with gp60 subtype IbA10G2.
- In June 2008, the outbreak at Pitsford was due to *C. cuniculus* with gp60 subtype VaA18.
- In November 2005, the outbreak at Cwellyn was due to *C. hominis* with gp60 subtype IbA10G2.

6.3 OVERVIEW TABLE FOR *CRYPTOSPORIDIUM* SPECIES SECTION

Table 6.2 – Summary of *Cryptosporidium* species information from the Reports of the Group of Experts and in the literature

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
Species overview	*C. parvum* only species recognised to infect humans. *Cryptosporidium* recognised as an important cause of disease in humans and livestock.	Strain differences recognised between oocysts isolated from humans and animals.	*C. parvum* only species discussed in the report. At the time of the report, *C. parvum* is the only species known to infect both humans and livestock.	48 recognised species and over 120 genotypes of *Cryptosporidium*. 23 species have been reported in humans. *C. hominis* and *C. parvum* are the two species most frequently reported in humans.
Transmission	Water is identified as an important vehicle for the transmission of *Cryptosporidium*	Work in progress to determine importance of person-to-person and zoonotic transmission.	*Cryptosporidium* can spread both by zoonotic (animal to human) and anthroponotic (human to human) transmission.	The main transmission risk factors for *C. hominis* infection are linked to contact with young children, people with diarrhoea or contamination of water by human waste or wastewater. The main transmission risk factors for *C. parvum* are linked to contact with farm animals or consumption of water or food contaminated by their faeces.
Species pathogenicity	Identifies need for understanding minimum infective dose. It is thought to be low though.	Results from a study undertaken in the USA indicate that infective dose is less than 100 oocysts for individuals without *Cryptosporidium* antibodies.	The report speculates that infective dose for homologous host (same species) transmission is lower than for transmission between different hosts.	*C. hominis* and *C. parvum* and responsible for the vast majority of cases of cryptosporidiosis in Europe

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
Risk factors for illness	More serious in immunosuppressed patients or in individuals in countries that are affected by malnutrition.	Immunosuppression, specifically individuals with low CD4 counts.	Immunocompromised individuals are more likely to suffer serious disease. Impact of an outbreak caused by a contamination event may be greater in areas that are supplied from normally high-quality sources	In developing countries: young children and immunocompromised individuals. In developed countries: individuals with profoundly impaired T cell function and / or T cell deficiency. Possible male risk factor (confounded by male linked underlying conditions, and risk).
Molecular tools	Acknowledges that gene probes will be developed in the future to aid in identifying different species.	Progress had been made in developing gene probes which could identify different *Cryptosporidium* species.	PCR used to amplify genetic polymorphisms and typing used to distinguish *C. parvum* isolates.	Molecular tools are used to understand both inter and intra-species diversity. To assess intra-species diversity, this has mostly been undertaken by analysing differences found at a gene called 60 kDa glycoprotein (gp60). Whole genome sequencing emerging for application to *Cryptosporidium*.
Subtypes and infection	Insufficient data to understand subtypes at the time of this report.	Limited understanding of subtypes and host-specificity. Identified as a research need.	Recognises that there are distinct subtypes and one that is more restricted to humans.	Subtypes have been identified for *Cryptosporidium* species by analysing the gp60 gene. These are then grouped into families and subtypes. For *C. parvum*, the three dominant *C. parvum* gp60 families in humans are IIa, IId and IIc. Subtype IIaA15G2R1 is the most common in industrialised countries. For *C. hominis*, family Ib is the most dominant subtype family in Europe but others are emerging. Within this family, subtype IbA10G2 largely dominates the outbreaks and sporadic cases in Europe.

7 DETECTION AND MONITORING SYSTEMS

7.1 DETECTION AND MONITORING SUMMARY - REPORTS OF THE GROUP OF EXPERTS

This section provides an overview of the detection and monitoring systems that are discussed in the three Reports of the Group of Experts.

FIRST REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1989

Monitoring

In the first report, it is noted that most water companies do not undertake routine monitoring of treated water supplies for *Cryptosporidium* oocysts. The report advises on a monitoring strategy for *Cryptosporidium* which outlines when monitoring should be undertaken:

- Following significant contamination of water sources by agricultural pollution or sewage;
- During transitional periods during changes in the treatment process;
- If treatment processes are operating abnormally;
- If turbidity readings or indicator organism levels deviate from normal ranges; and / or
- If an outbreak of cryptosporidiosis in the community is suspected as being linked to a water supply. If a waterborne outbreak is suspected, water companies will need to implement investigative monitoring for oocysts covering source waters, the water treatment works and the distribution system.

Recovery and detection

The recovery and detection method discussed in the first report is the use of a cartridge filter for recovery followed by fluorescently labelled monoclonal antibodies for detection.

SECOND REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1992

Detection

At the time of the second Report of the Group of Experts, as stated in the report, a rapid method for the isolation, identification and enumeration of oocysts was not in place. Progress was in place to improve initial separation and concentration techniques, such as cross-flow filtration, magnetisable particles and calcium carbonate flocculation. Progress was also in place for enumeration techniques such as by using flow cytometry, electro-rotation assays and computer-enhanced image analysers. The use of PCR was highlighted as a promising tool for detecting low numbers in environmental samples.

Particle monitoring

The report reinforces the importance of monitoring the passage of particles. This can be detected using turbidity monitoring or particle count monitors. The latter are more sensitive but at the time of the second report, their role in plant control was not yet developed. The report describes two categories of particle monitor, one which detects particles using a light

beam and another which detects changes in electrical field when particles pass through an orifice. The report notes that particle monitors can provide an indication of a filter which is not working properly. The report references a guide on the application of particle counters which was prepared for the American Water Works Association (Hargesheimer & Lewis, 1995).

Oocyst monitoring

The report states that each treatment plant should develop its own appropriate monitoring strategy for *Cryptosporidium* oocysts based on the recommendations listed in the first Report of the Group of Experts. This should be related to catchment risks and the nature of the treatment provided at the individual site.

THIRD REPORT OF THE GROUP OF EXPERTS BY PROFESSOR IAN BOUCHIER, 1998

Groundwater monitoring

The report discusses the role of monitoring of groundwater sources in assessing *Cryptosporidium* risk. It states that monitoring can vary from minimal surveillance for a few determinants to much more detailed investigations with automatic samplers and online continuous measurement. A table is included in the report showing how monitoring outcomes can indicate contamination (Table 7.1). The report notes that regular detection of *E. coli* does warrant investigation for *Cryptosporidium*.

Table 7.1 - Monitoring outcomes and their significance

Evidence for *Cryptosporidium* risk to groundwater	**Significance**
Detection of *Cryptosporidium* oocysts in source water.	Direct evidence of contamination.
Detection of *Cryptosporidium* oocysts in distribution system sediments.	Evidence of recent or historic contamination.
Regular detection of *E.coli* in source water.	Indication of faecal contamination.
Detection of *Clostridium perfringens* in source water.	Possible surrogate for *Cryptosporidium*.
Transient changes in turbidity of source water.	Possible rapid influence of surface water.
Micro-temperature or conductivity changes detected by down-well logging.	May reveal influence of major inflows at shallow depths.
Concentrations of certain characteristic dissolved inorganic species.	May indicate recent surface water inflow.

Monitoring within treatment works

The report states that in waterborne outbreaks, often there was a significant increase in turbidity at the time that the contaminated water was estimated to enter the supply. Monitoring recommendations are included which are summarised below:

- Process monitoring systems should be appropriate to the risk at each source.
- For high-risk sites, there should be continuous turbidity measuring on the outlet of each filter and on the final water using instruments capable of detecting changes of less than 0.1 Nephelometric Turbidity Units (NTU).
- Also, for high-risk sites, continuous sampling for *Cryptosporidium* with analysis times linked to turbidity monitoring results; or sampling triggered by turbidity events.
- Particle count monitors are encouraged to provide additional information to that provided by turbidity measurements.

The report notes that random spot sampling is unlikely to be effective for operational monitoring.

The report includes recommendations related to the operational aspects of water monitoring:

- Water utilities should define for each treatment works the value and duration that constitutes a significant deviation in turbidity of the final treated water for which alarms will be triggered by.
- Appropriate action procedures are to be in place to react immediately to turbidity alarms.

Recovery and detection of *Cryptosporidium* in water

The report includes a section summarising research developments in *Cryptosporidium* recovery and detection since the previous (second) Report of the Group of Experts. For *Cryptosporidium* recovery, membrane filtration, cartridge filtration and chemical flocculation are discussed. Research assessing various filtration methods such as using filtration with vortex flow, Gelman Envirocheck capsule filters, Costar 5-inch filters, open cell reticulated foam filter and Filterite negatively-charged filter are described. Other approaches described include Immunomagnetic Separation (IMS), hydrocyclones, magnetically stabilised fluidised beds and dynamic membranes. The report highlights that the combination of improved cartridge or membrane filters and concentration on immuno-magnetic beads has significantly improved the level and precision of recovery.

The report discusses identification methods for *Cryptosporidium*. These include microscopy, flow cytometry and the use of antibodies. The use of flow cytometry and laser scanning techniques are highlighted as methods with the potential to automate processes of sorting, detection and confirmation of *Cryptosporidium*. Molecular techniques using Polymerase Chain Reaction (PCR) are also discussed. A series of studies are discussed that were published since the first Report of the Group of Experts detailing molecular techniques. The fast rate of progress in this area is acknowledged.

Research needs identified in the third Report of the Group of Experts

The report highlights that advances have been made in detection due to new filter technologies, immunomagnetic separation, flow cytometry, nucleic acid probes and viability testing. However, the need for a standard protocol for all water types is recognised.

7.2 LITERATURE REVIEW – DETECTION AND MONITORING

This section presents monitoring and detection options for *Cryptosporidium*. One option is monitoring for surrogates for *Cryptosporidium*, using methods such as turbidity monitoring and particle counters. Direct detection of *Cryptosporidium* can be undertaken using oocyst count methods or through using various molecular techniques.

This section will explore the advances in methods since the Reports of the Group of Experts. In the interest of understanding the practical application of such methods and technologies, they have been divided into the following categories:

- Tier 1 - methods which offer rapid (~1 hr or less) monitoring with online capability.
- Tier 2 - methods which can be performed on-site and with a time to result under a working day.
- Tier 3 - methods which require specialist lab facilities and operators. These methods enable direct detection of pathogens, and can give more detailed information, e.g. exact number of pathogens, viability status, species / strain investigation.

The below tables summarise monitoring and detection methods in the three described tiers. The tables have been sourced from a report previously produced by WSP (previously Wood) entitled ‘Maximising the safe return of recovered process water’ (Bridle, et al., 2021).

Table 7.2 - Tier 1 monitoring methods for in water / wastewater

Measurement Principle	Method	Description	Merits	Limitations
Rapid Online Methods – Low accuracy (since done indirectly through surrogates)				
Turbidity	Nephelometric Sensors	These devices utilise light scattering to give a turbidity reading. Incident light is passed through a sight glass with the sample water. Refracted light is detected by the sensor and this gives a quantification of the turbidity. Total Suspended Solids (TSS) and turbidity have a linear relationship, as demonstrated for both fresh water and wastewater systems in the literature, (Hannouche, et al., 2011) (West & Scott, 2016), although it is important to note that the relationship between the NTU and TSS is not linear (Rügner, et al., 2013). The more solids which are suspended within the water, the greater the scattering of light within. Oocysts will contribute to the turbidity, thus turbidity can be used as a surrogate in monitoring for oocysts.	This method will return instantaneous turbidity readings with a high degree of accuracy. Nephelometric sensors can be either handheld and taken by operators or can be easily placed online in order to record turbidity at intervals. Online turbidity meters allow operators to measure the turbidity without coming into contact with the water. Equipment is generally easy to operate and allows for saving of values to monitor turbidity over time.	Some nephelometric turbidity sensors will be in contact with the water, presenting a risk of fouling the sensor. Nephelometric sensors require servicing and calibration in order to maintain their accuracy. Operators must be trained to use handheld equipment. Turbidity readings returned by these sensors will not be indicative of what is the cause e.g. whether suspended solids or oocysts are causing an elevation in turbidity.

Measurement Principle	Method	Description	Merits	Limitations
Particle Counting	Particle counters	Particle counters determine the size and quantity of each single particle in the particle flow using a particle counting sensor, e.g. breaking a laser beam, and flow set-up. They can cope with a range of particle sizes from 1-100 µm. Examples include systems from Detectronic, PAMAS and SetaAnalytics.	Variety of automated online options available. Rapid and easy to use; include integrated cleaning steps. Can be multiplexed.	Correlation of counts with actual pathogen number to be established - can depend on the treatment technology used.
Particle Counting	Flow cytometry	Flow cytometry measures the physicochemical properties of particles as they pass through an observation channel.	Fully automated process. Diversity indices give an indication of microbial community changes.	Sample preparation techniques, and cleaning protocols, impact the response and need to be optimised.

Table 7.3 - Tier 2 monitoring methods in water / wastewater

Measurement Principle	Method	Description	Merits	Limitations
Intermediate Methods – Medium accuracy and capable of being performed on-site (results less than 24hrs)				

Measurement Principle	Method	Description	Merits	Limitations
Turbidity	Tube Testing	Turbidity can be approximated visually by using an apparatus called a transparency testing tube. A tube with a sealed bottom and a reference marker at the bottom is slowly filled with a sample of the water to be tested. The operator will continue to fill this tube until the reference marker is no longer legible, the height of the water is measured and using a conversion table an NTU value can be determined using this method.	Very easy method of determining the turbidity, operators will not require extensive training. Low-cost method of measuring turbidity, once equipment has been procured there is no cost for an individual test.	Tube testing will not give an exact reading of the turbidity and thus a margin of error will exist when using this method. This method requires operators to be in contact with the water, thus precautions must be taken when conducting this test. Not an online measurement method. Highly coloured waters will give false high readings of turbidity. Fouling on tubes or insufficient light can affect the calculation of the NTU.
Turbidity	Secchi Disk	A marked disc with a length of wire is lowered into the water, this is lowered until the reference marker is no longer legible. At this depth (the 'Secchi Depth') the height of the water is measured and using a conversion table, an NTU value can be determined using this method.	Very simple and quick means of determining the turbidity of the water.	The margin of error will exist when using this method. Secchi disks require significant submergence as well as light exposure so this is a method best suited to open tanks. This method requires operators to be in contact with the water, thus precautions must be taken when conducting this test. Highly coloured waters will give false high readings of turbidity. Not an online measurement method.

Table 7.4 - Tier 3 monitoring methods for in water / wastewater

Measurement Principle	Method	Description	Merits	Limitations
High Accuracy Methods – Slow (result take more than 24 hours) and require expert lab analysis				
Oocyst count	EPA 1623 or blue-book method Filtration / IMS / FA (U. S. Environmental Protection Agency (EPA), 2005)	This is achieved via filtration, centrifugation, and immunomagnetic separation (IMS) followed by staining with fluorescent monoclonal antibodies. These are then observed via fluorescence and differential interference contrast (DIC) microscopy.	This is a standard practice and is extensively employed in the water industry.	Time consuming, requires lab and trained operators. Can be significant losses of oocysts during the sample processing steps. (Bridle, 2021) such as in centrifugation and in IMS (Centers for Disease Control and Prevention, 2011). The degree of oocyst seeding for a positive test showed that the amount of *Cryptosporidium* in the sample directly correlates with a better recovery rate. For example, 100,000 or 1,000,000 will yield high recovery rates or high system efficiencies; this is not always the case when the sample contains 100 or less oocysts. Therefore, the recommendation is to assess any system or procedure with a low level of seeding.
Cryptosporidium	PCR testing	PCR testing is a longstanding method used to determine the presence of pathogenic species within water. Prior to PCR tests the first step is to extract the DNA (various	It provides accurate and detailed results of the pathogens present, e.g. species or strain level information.	It does not quantify the amount of oocysts present, only detects or identifies them (unless qPCR or digital droplet PCR is used). No measure of viability (unless additional steps are added to the

Measurement Principle	Method	Description	Merits	Limitations
		protocols and kits exist). The DNA is amplified and used to identify the pathogens which are present. In addition to PCR, isothermal amplification methods are emerging which offer advantages of reducing analysis time and the potential of simplifying molecular techniques to the extent that this approach could move to Tier 2 and be achievable on-site. (Martzy, et al., 2019)		protocol to inhibit amplification of DNA from non-viable pathogens). Different conditions are needed for processing protozoa, viruses and bacteria, so it can be challenging to achieve multiplexed detection. It is very sensitive and PCR testing must be done under very controlled conditions to avoid sample contamination. LAMP can be especially prone to false positives. It requires trained operators. Access to a microbiology lab with DNA extraction and PCR testing apparatus / technicians is required and specific reagents are required. This makes PCR testing an expensive method of detection.
Cryptosporidium	DNA Microarray	DNA Microarrays are used to identify pathogens by using microbial source tracking (MST) markers to indicate which species are present. Extracted nucleic acids are introduced onto an array with biochemical markers which bind with the corresponding DNA / RNA. The array is taken for analysis where the different species are identified (Hagedorn, et al., 2011).	It is highly accurate and can provide a full analysis of the species present. It is highly specific. Arrays can work on both viable and non-viable cells.	It has a slow turnaround, taking around 24 – >48 hours. It requires trained operators. It requires access to a lab with filtration unit, bead beater, centrifuge, vortex, Qubit / nanodrop, reagents and consumables. A custom microarray must be produced specific for this testing. This will need to be developed / analysed by specialists trained in this means of detection.

Measurement Principle	Method	Description	Merits	Limitations
				DNA extraction required, suitable for *Cryptosporidium* as well as other targets.

DETECTION – TRADITIONAL METHOD AND NEWER METHODS

Traditional detection

The process for the direct detection of *Cryptosporidium* in water can be broken down into three main steps as listed below (Hassan, et al., 2020).

1. Particle concentration;
2. Selective concentration (separation of target organisms); and
3. Detection, identification and enumeration.

The standard practice and a commonly used traditional detection method for *Cryptosporidium* is the USEPA Method 1623 (U. S. Environmental Protection Agency (EPA), 2012) described previously in Table 7.4 The USEPA Method 1623 is not discussed in the 3rd Report of the Group of Experts. In the UK, water companies tend to follow the method described in The Microbiology of Drinking Water - Part 14 - Methods for the isolation, identification and enumeration of *Cryptosporidium* oocysts and *Giardia* cysts ('blue-book method') (The Envionment Agency, 2010). This method is very similar to that of the USEPA method. There is also an ISO Standard method: 'Water quality - Isolation and identification of *Cryptosporidium* oocysts and Giardia cysts from water' (ISO 15553:2006).

Molecular detection methods

As introduced in Table 7.4 , there are various molecular methods that can be used for the direct detection of *Cryptosporidium*. An overview of DNA amplification and sequencing methods are described below.

DNA Amplification

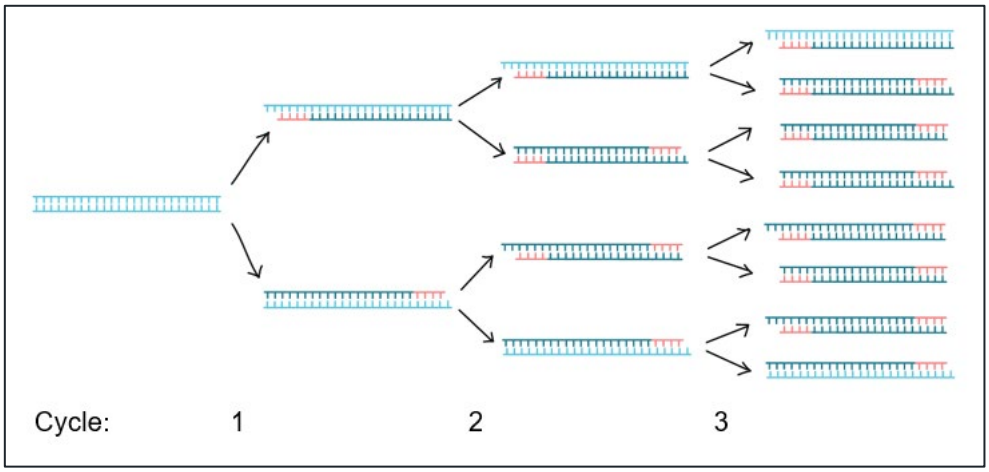
PCR

PCR is a process used to rapidly amplify specific segments of DNA. DNA needs to first be extracted which for *Cryptosporidium* means disrupting the oocysts and then extracting. The resultant amplified DNA can be used for a wide range of applications such as DNA sequencing and genotyping. There are three main stages to the PCR:

1. Denaturing: DNA is heated to separate into two single strands.
2. Annealing: The temperature is lowered to allow a pair of primers to attach to the region to be amplified.
3. Extending: The temperature is raised which allows a polymerase enzyme to add nucleotides making a new double strand of DNA.

This process is repeated which doubles the number of DNA copies in each cycle as shown in Figure 7-1.

Figure 7-1 – Exponential growth of target DNA in PCR



Source: (Khan Academy, 2023)

Quantitative (qPCR) is a method widely used in the detection of pathogens in both environmental and clinical settings. It is a PCR method that allows real-time monitoring of the amplification alongside quantified standards against which the Ct values can be measured for quantification of gene copies. It has been used to detect *C. parvum* and *C. hominis* (Hassan, et al., 2020), (Robinson, et al., 2023).

Various molecular methods, utilising different amplification approaches and / or gene targets / primers etc., have been developed and trialled. Conclusions are that qPCR is best for quantification with consideration needed to be given to removing inhibitors either through additional purification steps or through the addition of anti-inhibitory compounds. Droplet digital PCR is at present quite costly but has potential for future use. Loop-mediated Isothermal Amplification (LAMP) is considered the most suitable for presence / absence confirmation as it is the least sensitive to inhibitors and the isothermal amplification offers advantages in terms of equipment and potential miniaturisation (Fradette, et al., 2022). LAMP can detect the *C. parvum* (GP60 gene) and the entire *Cryptosporidium* genus (SAM gene) from environmental samples with high-specificity and no cross-reactivity (Mthethwa, et al., 2022). Multiplex LAMP offers a significantly simpler and less time-consuming method compared to the traditional USEPA Method 1623 and is a realistically practical option for water monitoring (Ongerth & Saaed, 2020). A kit that can be used to sensitively, rapidly and simply detect *Cryptosporidium* spp. in environmental water is the Loopamp *Cryptosporidium* Detection Kit.[8] LAMP can be prone to false positives so rigorous lab practices are needed to prevent this. Recombinase Polymerase Amplification (RPA) is another useful isothermal approach which is gaining in popularity (Liu, et al., 2023). Clustered regularly interspaced short palindromic repeats (CRISPR) and CRISPR-associated (Cas) technologies have also been used in faecal samples and water (Yu, et al., 2021), (Li, et al., 2021). None have been validated and accredited for routine application for water monitoring.

[8] Further information available at: https://loopamp.eiken.co.jp/en/product/cat-101/cry_e.html

DNA Sequencing

Restriction Fragment Length Polymorphism (RFLP) can be used to differentiate between organisms. This is achieved by using restriction enzymes to cut the DNA to form DNA restriction fragments. The resultant fragments will differ in length between different species. The fragments can be separated by length using gel electrophoresis. Some *Cryptosporidium* species may be hard to differentiate. The use of RFLP in molecular biology is mostly being replaced by more advanced DNA sequencing technologies. These include Sanger sequencing and high-throughput next generation methods such as the Illumina next-generation platform or long read Nanopore technology.

Multi-locus genotyping is becoming established for *Cryptosporidium* (Chalmers, et al., 2018). GP60 subtyping applied to investigation of outbreaks in England and Wales from 2009 to 2017 was shown to offer two advantages, i.e. identifying epidemiologic links between cases and indicating possible exposures and sources to inform outbreak management but a multi-locus approach applied nationwide systematically would offer further benefits (Chalmers, et al., 2019), (Risby, et al., 2023).

Summary of USEPA and molecular methods

An overview of the advantages and disadvantages of the USEPA method and molecular methods is shown in Table 7.5 (Fradette, et al., 2022).

Table 7.5 - Advantages and disadvantages of the USEPA method and molecular methods

Technique	Advantages	Disadvantages
USEPA Method	Possibility of concentrating large volumes of water (up to 100 L); Detection limit of one oocyst per 100 L; No PCR amplification biases; Simultaneous use of several fluorescent dyes for more confidence in the identification; and Quantification (enumeration) possible.	Time consuming and high costs associated with this analysis; Low recovery and possibility of cross-reaction; Requirement of intact parasitic cells for identification; Little information can be obtained about the microorganisms (such as no species identification[9] and no viability assessment); and Identification biased by the skills of the microscopist.
Molecular methods	No growth of microorganisms required; No intact cells of the microorganisms required;	Susceptible to contamination by external sources of DNA; Not distinguishing DNA from live or dead cells;

[9] Note that species identification can be undertaken afterwards by slide genotyping.

	Identification not biased by the skills of the manipulator (less subjective); and Capable of giving complementary information about the microorganisms according to the technique chosen (including: species identification and viability assessment).	Depending on primers, which need to be carefully designed to prevent amplification of DNA from other eukaryotes; Susceptible to the efficiency of the oocyst disruption / lysis method chosen; Susceptible to PCR inhibitory substances; and No standard method and not accessible to all laboratories. Can provide presence / absence but reliability of quantification needs to be established, particularly at low levels.

Source: Fradette, *et al.*, 2022

Table 7.6 - Advantages and disadvantages of the blue-book method

Technique	Advantages	Disadvantages
UK standard blue-book method	Sample volume can be up to 1000 L; Quantification (enumeration) possible; and No PCR amplification biases.	Time consuming; Expensive; Has low specificity; Does not inform on viability or human infectivity; Potential for a number of other contaminants ending up on the microscope slide; Multiple opportunities for loss of oocysts; and Requires highly-skilled microscopy.

Source: The Microbiology of Drinking Water - Part 14, The Envionment Agency, 2010; Robinson, et al., 2023

New trends

Miniaturised systems available for the detection of *Cryptosporidium* oocysts in water

Detection techniques that are rapid, provide more information and are automatable are highly sought after. To address this, a range of miniaturised devices have been developed, some of which can enable point of use testing (Luka, et al., 2022). Methods are summarised in Table 7.7 (Bridle, et al., 2012). Some of these techniques utilise immunorecognition approaches, and

advances in this area include the development of aptamers[10] for improved target capture (Hassan, et al., 2020) and can be enhanced by nanotechnology (Luka, et al., 2022).

[10] Aptamers are artificial oligonucleuotide (short, single- or double-stranded DNA or RNA) molecules that bind to a specific target.

Table 7.7 – Miniaturised detection methods for *Cryptosporidium*

Technique type	Method	Overview	Detection limit	Total Volumetric throughput in 24 hrs
Optical detection techniques	Hydrodynamic trapping combined with immunofluorescence detection	A method that can be undertaken by two modes (A) trapping in wells and (B) trapping in filters.	10^6	7.2 – 28.8 ml depending on method
	Microscopy techniques	A portable microscope method was developed (Mudanyali, et al., 2010). A portable holographic microscope was built and a rapid image reconstruction algorithm and an automated counting method was developed.	380 (*G Lambia* cysts)[1]	Not applicable
	Raman spectroscopy techniques	This is a detection method that is based on light scattering.	Not calculated	Not applicable
	Fibre-optic based sensor	This is a method that uses optical fibre for sensing or to convey optical signals.	10^5	57.6 ml
Mass-based detection techniques	Quartz crystal microbalance sensing	Quartz crystal microbalance (QCM) biosensors work by detecting mass changes.	10^5	72 ml
	Cantilevers based sensing	Piezoelectric-excited millimetre-sized cantilevers (PEMC) are made up of two layers, one acts as an actuator and a sensor and the other functions to bond the target organism.	5	1.44 L

Technique type	Method	Overview	Detection limit	Total Volumetric throughput in 24 hrs
Surface plasmon resonance	Surface plasmon resonance	This measures changes of the refractive index at the interface between a planar metal surface and a dielectric material.	100	7.2 ml
Molecular diagnostics and existing total analysis systems	DNA / RNA amplification and sequencing methods	These include the mRNA amplification technique Nucleic-Acid-Sequence-Based Amplification (NASBA) plus electrochemical or fluorescent detection, NASBA plus lateral flow assay and DNA microarrays.	Varies depending on method. Can detect very low quantities.	Varied depending on method.
Electrical methods	Bioimpedance method	This is also known as Electrochemical Impedance Spectroscopy (EIS) for biological applications. This is a method that detects and quantifies the presence of analytes in liquids.	10^4	14.4 ml
	Dielectrophoresis	This is an electrokinetic phenomenon and can be used as a tool to separate and concentrate biological particles and cells.	Not calculated	Batch testing 1.45 mL in 10 min

Source: (Bridle, et al., 2012)

[1] *G Lambia* is also referred to as *G. duodenalis or G. intestinalis*

7.3 OVERVIEW TABLE FOR DETECTION AND MONITORING SECTION

Table 7.8 – Summary of monitoring and detection information from the Reports of the Group of Experts and in the literature

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
Turbidity and particle monitoring	The report advises that turbidity readings that deviate from the normal range should be followed by *Cryptosporidium* oocyst monitoring.	The report reinforces the importance of monitoring the passage of particles. This can be detected using turbidity monitoring or particle count monitors.	For high-risk sites, there should be continuous turbidity measurement on the outlet of each filter and on the final water using instruments capable of detecting changes of less than 0.1 NTU. Particle count monitors are encouraged to provide additional information to that provided by turbidity measurements.	For turbidity monitoring, nephelometric sensors can be used. These can be handheld or can be used as online monitoring systems. They will not indicate what the cause of the change is but can indicate if further investigation is needed. Tube testing and secchi disks are other options for turbidity monitoring. For particle monitoring, particle counters and flow cytometry are two options. Particle counters can be automated, are rapid and easy to use and can be multiplexed. Flow cytometry is fully automated and diversity indices give an indication of microbial community changes.
Oocyst monitoring	The report advises that monitoring for oocysts should be undertaken following significant agricultural contamination, during transitional periods in the treatment processes, if treatment is operating abnormally, if turbidity readings or indicator organism levels deviate from normal ranges and / or if an outbreak of cryptosporidiosis in the community is suspected as being linked to a water supply.	Each treatment plant should develop its own appropriate monitoring strategy for *Cryptosporidium* oocysts This should be related to catchment risks and the nature of the treatment provided at the individual site.	For high-risk sites, continuous sampling for *Cryptosporidium* with analysis times linked to turbidity monitoring results; or sampling triggered by turbidity events.	The blue-book method outlines the purposes for which sampling for oocysts is usually undertaken: • Water treatment process control; • Monitoring of catchment areas and water sources; • Risk assessment; • Incident management; • Water-borne or swimming pool outbreak investigations; and • Regulatory or statutory purposes. It also states that the introduction of a new treatment process, or the modification of an existing one, may require water quality monitoring to assess the effectiveness of the new or modified process to remove *Cryptosporidium* oocysts.

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of Experts (1998)	Literature
Recovery and detection	Cartridge filter for recovery followed by fluorescently labelled monoclonal antibodies for detection.	Progress is described to improve initial separation and concentration techniques, such as cross-flow filtration, magnetisable particles and calcium carbonate flocculation. Enumeration techniques such as using flow cytometry, electro-rotation assays and computer-enhanced image analysers are also progressing. The use of PCR is highlighted as a promising tool for detecting low numbers in environmental samples.	For *Cryptosporidium* recovery, membrane filtration, cartridge filtration and chemical flocculation are methods described in the report. For identification, microscopy, flow cytometry and the use of antibodies are described.	The traditional oocyst count method is the USEPA 1623 or blue-book method. This is a standard practice and is extensively employed in the water industry. The limitations are that it is time consuming, requires trained operators and that there can be significant losses of oocysts during the sample processing steps. Molecular detection methods are a further direct detection option. Methods for DNA amplification include qPCR, ddPCR and LAMP. Methods for sequencing include RFLP and Sanger or high-throughput next generation sequencing. Sequencing has mostly replaced RFLP. Long read e.g. nanopore sequencing. New trends include the use of miniaturised detection methods. These can be rapid and automatable. Various options are optical detection techniques, mass-based detection techniques, surface plasmon resonance, molecular diagnostics and existing total analysis systems, and electrical methods.

8 TREAMENT TECHNOLOGIES AND PROCESSES

8.1 TREATMENT TECHNOLOGIES AND PROCESSES SUMMARY – REPORTS OF THE GROUP OF EXPERTS

This section provides an overview of the treatment technologies and processes that are discussed in the three Reports of the Group of Experts.

FIRST REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1989

Groundwater treatment

The first report states that groundwater treatment processes such as chlorine, aeration and filtration through sand will not deactivate or fully remove oocysts. At the time of the first report, the risk of contamination to groundwater supplies was not fully assessed.

Lowland surface water

The two principal forms of treatment presented in the report for lowland water are chemical coagulation with rapid filtration and pre-filtration followed by slow sand filtration. The report notes that the removal of oocysts from water by slow sand filters is expected to be more efficient than with rapid filters. However, rapid filters are assisted by prior chemical flocculation. For chemical coagulation, the report states that aluminium and ferric salts are equally effective in retaining oocysts. Flocs generated can be improved by adding coagulant aids (organic polymers), however this is not especially the case for oocysts. Opportunity for polymers to be used as filter aids are identified.

Disinfection

The report states that concentrations of between 8,000 and 16,000 mg/l of chlorine are required to deactivate oocysts. It identifies ozone as an option that could be applied in treatment processes for *Cryptosporidium* disinfection. The report notes that although further research regarding the use of ozone is required, it does have disadvantages. These include that it may encourage bacterial growth in the water mains, and it can create toxic organic by-products. Other disinfectants such as chlorine dioxide, hydrogen peroxide and the use of ultraviolet radiation may be technically feasible, but expensive for large-scale supplies.

Operational aspects of water treatment

The report highlights certain practices which should be avoided that increase the likelihood of the passage of oocysts through a water treatment works. Examples included are the shutdown of filters and their restart without being backwashed which can contribute to the oocyst load in the treated water supply. The report refers to the partial by-passing of the slow sand filters in relation to a suspected waterborne outbreak in North Humberside in December 1989. By the end of May 1990, when the outbreak was over, *Cryptosporidium* oocysts had been detected in the faeces of 477 people. The report says that conclusions could not be drawn on the significance of this by-passing, but notes that changes in normal operations at a water treatment works increase the risk of the transfer of oocysts if they are present in the source water. The report reiterates that water supplies may be more susceptible to oocyst contamination when there has been a major planned

change in a water treatment process or when a normal treatment process has to be by-passed for operational reasons. In these situations, the report states that water treatment works can be considered to be working sub-optimally.

The report includes a water company plan that sets out responsibilities and actions to be taken by the water company in the event of a suspected outbreak. This includes instructions to establish whether any significant operational changes have taken place at the water treatment works such as by-passing a treatment element or a change in the coagulant used. It also instructs to examine records to determine if there have been any unusual variations from normal operation conditions and lists the following examples:

- Changes in raw water, for example, high turbidity, high colour, unusually high or low pH or changes in its microbiological quality.
- Coagulation control lost or difficult.
- Higher than usual turbidity of filtrate.
- Filter runs of abnormal length.
- Unusually high throughputs, or unusually rapid changes in throughput.
- Changes in the microbiological quality of treated water.
- Unusually high demands for chlorine.

SECOND REPORT OF THE GROUP OF EXPERTS BY SIR JOHN BADENOCH, 1992

Water treatment processes

The second Report of the Group of Experts emphasises the importance of not by-passing key stages in treatment. The information and advice on treatment processes provided in the second report are listed below:

- There is a tendency for particles to be released from filters during flow changes and following the reinstatement of filters after backwashing. Strategies should be in place to minimise rapid changes in flows. Whilst the limits which should be placed on changes of flowrate depend on filter flowrate and floc quality, the report states that changes between 1.5 % and 5 % per minute have been shown to control problems.
- Breakthrough of particles into treated water can still occur when using a slow start period when a filter is reintroduced to service after backwashing. Although the concentration of particles is lower, it extends over a longer period. The report notes that investing in a more complex system is likely not justified for this purpose alone. However, where systems are already installed, they can provide a benefit of reducing the likelihood of oocysts entering the supply.
- Diverting or recycling the initial filtrate provides a benefit of reducing particulate matter into supply. The addition of a coagulant aid at the end of a backwash cycle may reduce the particle count in the treated water when the filter is brought back into use.
- The importance of effective ripening of slow sand filters before water is put into supply after a filter has been cleaned is emphasised.
- Good coagulation control is a key factor in the removal of oocysts in chemical treatment plants.

Treatment options

Different filter types are discussed. Activated carbon filters have been shown to remove oocysts to a similar extent as other filter types of the same size. Variable performance has been shown with textile filters. Membrane filters have been shown to be effective.

Treatment studies

The report highlights that care must be taken when assessing the results of treatment studies. The method of oocyst measurement should be considered. The use of percentage or log removal can be challenged, as it is the number of oocysts remaining in the water after treatment which is the key factor in terms of health risk.

Disinfection

Research into disinfection options for *Cryptosporidium* are discussed in the report. It notes that chlorine dioxide is more effective than chlorine, but there may be safety issues associated with the dose levels that are required. Ozone has been shown to be more effective than other disinfection options, but the required dose and contact times are likely to be outside of the normal design range. Ozone efficacy as a disinfectant is also temperature dependant. UV has been shown to be effective, but at the time of the second report, the energy levels required are likely higher than what is achievable under normal operating conditions. Ultrasound has been explored as an option, but results had not been published at the time of the second report.

Operational aspects of water treatment

The progress in ensuring treatment plants are effectively operated is discussed. Water utility companies reviewed their operation practices and these were inspected by the DWI. The importance of not by-passing key treatment stages was emphasised by the DWI and water utilities accepted this advice.

The report notes that studies at treatment plants have further demonstrated the tendency for particles to be released from filters during flow changes and following the reinstatement of filters. Strategies should be in place to minimise rapid changes in flow.

THIRD REPORT OF THE GROUP OF EXPERTS BY PROFESSOR IAN BOUCHIER, 1998

Overview

The third report begins its discussion of treatment technologies by highlighting the challenge posed by *Cryptosporidium* in that oocysts are resistant to the standard chlorine disinfection regimens used for drinking water treatment. The report also states that *Cryptosporidium* can be present in treated water in the absence of bacterial indicators that are normally used to assess the efficiency of disinfection.

Based on the examination of incidents, the report concludes that water-related cryptosporidiosis outbreaks do not just ‘happen’. The report highlights correlations between inadequate treatment, inadequacy in the operation of the treatment or overloading of the treatment process.

The report states that conventional physical and chemical water treatment processes such as coagulation, sedimentation, dissolved air flotation (DAF), rapid gravity filtration and slow sand

filtration were not designed specifically for *Cryptosporidium* oocyst removal. However, these treatments can provide an effective barrier provided that the appropriate level of treatment for the raw water source is in place and is operating properly. If the treatment is compromised or inadequate, a significant quantity of oocysts can pass into the treated water supply. Bypassing of treatment can also lead to waterborne outbreaks. The report notes that the use of membrane technologies can further improve oocyst removal.

Risk Assessment

The report outlines factors that should be considered when undertaking *Cryptosporidium* risk assessments at the water treatment works. These are listed below and should be considered in the context of *Cryptosporidium* being able to break through:

- Full physical-chemical treatment;
- Partial physical-chemical treatment;
- Disinfection only;
- Whether the treatment process is not used fully on every occasion;
- Whether the process is known to be problematic;
- Whether filter flow changes suddenly;
- Whether there is a significant increase in turbidity before or after filter wash;
- Whether are there significant blips in turbidity during treatment runs;
- Whether there are signs of significant media loss or severe cracks in the filter surface;
- Whether backwash and / or sludge supernatant water is recycled;
- Whether turbidity meters are on individual filters;
- Whether turbidity alarms are based on individual works performance; and
- Whether turbidity meters are connected to alarm systems.

Treatment standard

As discussed in the section on regulation, the third report refers to the treatment standard proposed in the Water Supply (Water Quality) Regulations 1989 (England and Wales). These proposed a treatment standard of less than one oocyst in ten litres based on continuously sampling 1,000 litres of treated water per day. In the third report, it was stated that the Group of Experts did not have any additional information on which to offer a different treatment standard to that proposed.

Treatments

The report discusses chemical coagulation-based treatment for oocyst removal. It states that for oocyst removal it is reliant on the ability to maintain a suitable coagulant dose, which is governed by the raw water quality, in particular colour and turbidity. There is then a requirement for a high degree of removal of the coagulant solids during the subsequent solids-liquid separation

processes. The report reiterates that if these processes are impaired, not operating within the design capacity or bypassed, the plant performance for oocyst removal is compromised. The report notes that some unit processes are not designed for coagulant solids removal and overloading or by-passing of these (for example second stage filters for manganese removal or post-filtration granular activated carbon adsorbers) should not compromise performance for oocyst removal. The report notes that the performance of filters is poorest just after restart, even when an effective backwash has been applied. The report advises that efforts should be made to reduce the impact of increased turbidity on final water quality after start-up. The report lists some options to achieve this:

- Disposal of the first flush (this being the most effective);
- Recycling to the head of the works;
- Improved backwash; or
- Delayed start.

The report refers to a guidance manual published by UKWIR (UKWIR, 1998) which supports the recommendations from the first and second Reports of the Group of Experts. The Group of Experts endorses the general approach to water treatment set out in the 1998 UKWIR manual.

The recommendations for water treatment set out in the report are listed below:

- Water treatment works should be designed to handle the typical peak turbidity and colour loadings in the source water.
- Water treatment works should be operated at all times in a manner that minimises turbidity in the final water, with attention given to other parameters which reflect the performance of chemical coagulation (coagulant metal concentration and colour).
- Water treatment works should normally be operated within the design capacity without by-passing the solids-liquid separation processes. Coagulation should never be by-passed or compromised.
- In the event of an emergency, if it is necessary to overload or bypass solid-liquid separation processes, a stringent monitoring regimen should be implemented to ensure turbidity targets are not exceeded. If there is an indication that turbidity targets will not be achieved, an immediate advice to boil notice should be issued.
- For high-risk sites, if reducing the effects that filter start-up has on final water quality cannot be achieved through more easily implemented changes (for example improved backwash or delayed start after backwash), modifications to the works should be made to allow the first flush to be run to waste or recycled to the works inlet.
- Coagulation / flocculation processes should be checked regularly to meet changing conditions of source water quality and other environmental factors.
- Only dedicated washwater mains should be used to carry the returned washwater flow.
- Filters should be operated and maintained under optimum conditions with attention to the quality and depth of media and to the operation of the backwashing / air scouring system.
- Treatment staff should be trained to be aware of the effects that even very small changes in the catchment or the treatment stream can have on the final water quality.

Research

The report summarises key research findings since the publication of the second Report of the Group of Experts. For water treatment, the report highlights that the key to minimising exposure to *Cryptosporidium* is the consistent production of low turbidity water and the avoidance of peaks in turbidity. Focal points of the research have been the optimisation of turbidity and particle counts and the identification of a suitable surrogate for *Cryptosporidium* removal during treatment processes. The report notes the measurement of *Bacillus* spores as the most promising tool and an approach that has been validated by pilot studies in the UK and North America.

The report notes that an interest in removing protozoan cysts has led to the development of new filtration technologies. Some of these were approved under the Water Supply (Water Quality) Regulations 1989. The report also refers to the use of high intensity UV radiation as a disinfection technology in treating water for *Cryptosporidium*.

The report refers to various research papers that assess treatment processes for *Cryptosporidium*. Key research studies described are listed below:

- A summary of risk assessments and research undertaken in the USA, France and Japan was carried out. A key conclusion (from the French study) was that membrane filtration was needed for completely reliable removal of parasites (Daniel, et al., 1996).
- Research on using a membrane-based filtration for water treatment was undertaken. Using 0.2-µm membranes is suitable for surface waters, groundwater and backwash water. This removes colour and suspended solids as well as bacteria and parasites (Powell, 1996).
- It was recommended to use microscopic particulate analysis (MPA) to assess water treatment plant performance as an alternative to parasite detection (Hancock, et al., 1996).
- Research on the effects of the coagulant dose rate found an optimal dose rate of alum coagulant for 3.6 log removal of *Cryptosporidium*. Halving the coagulant dosage resulted in a significant reduction of removal to about 1.5 log (Ongerth & Pecoraro, 1995).
- A study investigating microfiltration and ultrafiltration for parasite removal found that removal was increased by coating membranes with kaolinite (Jacangelo, et al., 1996).
- A review of coagulation practices on the elimination of particles found that polyaluminium chloride outperformed competitor coagulants (Lind, 1997).
- Dissolved air flotation with iron dosing was shown to remove 3.7 log of *Cryptosporidium* (Plummer, et al., 1995).
- Microfiltration (0.2 µm) was shown to remove >4 log of oocysts over nine trials (Drodz & Schwartzbrod, 1997).
- A study demonstrated a two-stage process in which oocysts were removed using a spirally-wound backwashable depth filter and then destroyed by *in situ* vacuum steam pasteurisation during filtering (Bell & Pearce, 1997).

Research needs identified in the third Report of the Group of Experts

- Development of a standardised approach to conducting disinfection trials.
- Further studies on the application of seroprevalence studies in assessing the impact of water treatment in reducing community exposure to *Cryptosporidium*.

- Investigation of the impact of operating filters under declining rate on the removal of *Cryptosporidium*.
- Evaluation of quality changes in treated waters and development of procedures to allow operators to identify *Cryptosporidium* risk associated with these changes for specific treatment works.
- Development of techniques to specify and assess the performance of filtration systems for oocyst removal from groundwaters.
- Further evaluation and development of the use of bacterial spores to assess treatment performance.

8.2 TECHNOLOGY REVIEW

Since the establishment of the Group of Experts led by Sir John Badenoch, there have been significant advancements in *Cryptosporidium* removal and deactivation technology within the water industry, contributing to improved water treatment and safety standards. A comprehensive review of all relevant treatment technologies has been conducted to evaluate their effectiveness for *Cryptosporidium* treatment. Initially, treatment technologies were categorised as either emerging or established based on their prevalence within the industry. These technologies were subsequently subdivided into either deactivation or solid-liquid separation techniques, and essential information has been summarised in Table 8.1 – Table 8.3.

Table 8.1 – Detailed description of established solid-liquid *Cryptosporidium* removal technologies

Technology	Effective Particle Size Removal	Removal Efficiency *Cryptosporidium (3 – 6 µm)*	CAPEX/OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
Coagulation / Flocculation	0.01 – 10 µm	2.7 log (paired with sedimentation) 3.5 log (paired with dissolved air flotation and filtration (DAFF)	L/M	M	• Negligible waste by-product since the majority of the sludge / overflow waste is often generated in the subsequent solid removal process.	• Coagulation / flocculation are not solid removal technologies on their own, and need to be coupled with a solid-liquid separation process (e.g. sedimentation, filtration, DAF). • The optimum type and quantity of coagulant (often aluminium sulphate, ferric sulphate or ferric chloride) should be identified by jar testing. • The optimum mixing rates for coagulation (> 1500 s-1) and flocculation (5 – 100 s-1) should be identified by jar testing. • Careful control of pH is also crucial for coagulation / flocculation operation. (Metcalf & Eddy, 2014) (Nazih K. Shammas, 2016) (SUEZ, 2021)
Sedimentation	1 – 100 µm	0 – 1.5 log (without coagulation) 2.5 - 2.7 log (with coagulation / flocculation)	M/L	L	• Sludges / residuals generated from the sedimentation process will go through a thickening process. • The sludge cake is sent to landfill, while the concentrate	• High throughput (2,000 – 3,000 $m^3/m^2/d$), suitable for high volume flows of wash water. • Gravity-fed and thus low on energy consumption.

					(from centrifuge) and / or pressate (from filter press) are mixed with the untreated wash water which is usually returned to the head of the works. • A key industry rule is that returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU.	• Sedimentation alone will not remove colloids, viruses, oocysts effectively; further treatment (coagulation / flocculation) is required. • Efficiency dependent on the hydraulic retention time, and the efficiency of the preceding flocculation / coagulation process. • Flow to be maintained in laminar regime, scouring of settled matters to be minimised, and short-circuiting (due to wind) minimised, for best removal efficiency to be achieved. (Nazih K. Shammas, 2016) (van Dijk, 2007)
Dissolved Air Flotation (DAF)	1 – 100 µm	1 – 3.3 log 2 – 2.6 log	M/H	H	• The sludge (underflow) and scums / algae (overflow) will require thickening and disposal through sludge processing. • The sludge cake is sent to landfill, whilst the centrate (from centrifuge) and / or pressate (from filter press) are mixed with the untreated wash water which is usually returned to the head of the works. • Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998).	• More efficient than sedimentation, especially with regards to less settleable contaminants such as algae. • Smaller footprint than sedimentation. Requires coagulation / sedimentation for the effective removal of *Cryptosporidium*. • Not very effective in removing viruses, even with coagulation / flocculation. • Efficiency is dependent on the aeration (bubble size and distribution), hydraulic retention time, and the efficiency of the preceding flocculation / coagulation process. (Nazih K. Shammas, 2016) (SUEZ, 2021)

						(WHO, 2014)
Dissolved Air Flotation – Filtration (DAFF)	0.1 – 100 µm	< 5.4 log	M/H	H	• The sludge (underflow), scums / algae (overflow) and the filter backwash will require thickening and disposal through sludge process. • The sludge cake is sent to landfill, whilst the centrate (from centrifuge) and / or pressate (from filter press) are mixed with the untreated wash water which is usually returned to the head of the works. • Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998).	• Smaller retention time and footprint compared to sedimentation and sand filter. • Higher efficiency of *Cryptosporidium* and virus removal compared to sedimentation and conventional DAF. • Operation and maintenance considerations of both DAF and depth filtration are applied. (WHO, 2014) (Nazih K. Shammas, 2016)

Depth Filtration	>5 µm (more effectively> 15-20 µm)	0 – 1.4 log (without coagulation) Up to 3.3 log (with coagulation)	M/H	L	• 4 – 8 % of filtered water is recycled for backwash / sand cleaning. • The backwash stream can be directly returned to the head of the works without further treatment but must be less than 10 NTU. In most cases treatment, including clarification followed by sludge thickening will be required. • Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998).	• Can be a single layer or multimedia (e.g. sand, anthracite, garnet). • Operate in down-flow or up-flow configuration. Can operate pressurised, but not common for wash water treatment. • Flux: 115 – 475 $m^3/m^2/d$ (up to 2,300 $m^3/m^2/d$ for fuzzy filter) (small footprint). • 12 – 72 hours between cleaning / backwash. Efficiency can be greatly improved if combined with coagulation (often ferric sulphate or ferric chloride as coagulant). • Low levels of iron dosing (0.5 – 1 ppm) – contact filtration. • Suitable influent quality: Total coliform < #500/100 ml, NTU< 7-14, Colour unit (CU) <40. • Turbidity breakthrough (for non-continuous filtration only), mudball formation, build-up of emulsified grease, cracks and contraction of filter bed due to sub-optimal backwash, loss of filter media, and gravel mounding should be prevented for best filtration results. • Scouring using compressed air, or air / water combination, is applied periodically to remove solids from the media surface and the pores.

Slow Sand Filtration	>5 µm (more effectively >15-20 µm)	≤3.0 log	H/L	L	• 0.2 – 0.6 % of filtered water is recycled for cleaning the top layer of sand. • The used water can be directly returned to the head of the works without further treatment but must be less than 10 NTU. In most cases treatment, including clarification followed by sludge thickening will be required. • Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998).	• Can be single or multimedia (e.g. sand, anthracite, garnet). • Operates only in down-flow mode (gravity driven). • Flux: 1 – 10 $m^3/m^2/d$ (large footprint) 20 – 60 days between cleaning. • Pre-treatment: generally none. • Suitable influent quality: Total coliform < #800/100 ml, NTU <10, Colour unit (CU) <5. • Disruption, erosion and scouring of the filter media should be carefully avoided (especially during the cleaning stage). (Metcalf & Eddy, 2014) (van Dijk, 2007) (WHO, 2014) (Nazih K. Shammas, 2016)
Surface Filtration		≤1.0 log	M/M	M	• 1 – 4 % of filtered water used for backwashing. • The backwash stream can be directly returned to the head of the works without further treatment but must be less than 10 NTU. In most cases treatment, including clarification followed by sludge thickening will be required. • Returning wash water should not exceed 10 % of the works	• Includes cloth media filter (CMF), diamond cloth media filter (DCMF), Disk filter (DF), Ultrascreen and Drum filter (DF). • Flux: 115 – 940 $m^3/m^2/d$ (small footprint), Suitable influent quality: Total coliform < #50/100 ml, NTU <2-7, Colour unit (CU) <5. • Pre-treatment: coagulation – flocculation for effective pathogen and virus removal. Would clog much quicker than depth

					inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998).	filtration, and thus require more frequent backwash / cleaning. • Thorough backwash / cleaning, careful control of feed pressure, and regular control of filter health are required for best performance. (Metcalf & Eddy, 2014) (Nazih K. Shammas, 2016) (SUEZ, 2021)
Cartridge Filtration	<0.2 µm	≤1.0 log	L/H	H	• Liquid waste by-product is similar to that of other surface filtration methods (i.e. 1 – 4 % of filtered water used as backwash). • Cartridge filter lifetime is 5 - 20 days. Therefore, used filter is considered as the main solid waste by-product of cartridge filtration.	• Often classified as surface filtration method, with similar operation and maintenance considerations applied to it. • However, the significant sensitivity to feed quality and requirement or regular replacement of the filters would set them aside from more renewable and resilient surface filters. • Require high influent quality (< 2 NTU), thus not suitable for wash water treatment. (WHO, 2014) (Nazih K. Shammas, 2016)
Micro Filtration	0.1-1 µm	2 – 5 log	M/M	M	• 85 – 95 % recovery, therefore 5 – 15 % as retentate which can be recycled by mixing with untreated wash water. This will typically require further treatment before being returned to the head of the works.	• Flux: 1 – 1.5 $m^3/m^2/d$ Energy Requirement: 0.2 – 0.3 kWh/m^3 Operating pressure: 34 – 200 Kpa (Medium OPEX). • Suitable feed turbidity <50 NTU (Max: 300 NTU).

					• Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998). • Chemically enhanced backwashing and Clean in Place (CIP) will generate chemical waste that requires neutralisation and special disposal.	• Pre-treatment: filtration / flotation + chemical dosing to minimise scaling / fouling. • Output quality: 0.1 – 0.4 NTU, 0 – 1 g/l TSS. • Modular, easy to build and operate, fully automated, low labour. (Nazih K. Shammas, 2016) (SUEZ, 2021) (van Dijk, 2007) (DOW, 2011)
Ultra-Filtration	0.01 – 1 µm	3 – 6 log	M/M	M	• 85 - 95% recovery, therefore 5 – 15 % as retentate which can be recycled for mixing with untreated wash water. This will typically require further treatment before being returned to the head of the works. • Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998). • Chemically enhanced backwashing and Clean in Place (CIP) will generate chemical waste that requires neutralisation and special disposal.	• . Flux: 1 – 1.5 $m^3/m^2/d$ Energy Requirement: 0.2 – 0.3 kWh/m^3 Operating pressure: 68-350 kPa (Medium OPEX). • Suitable feed turbidity <50 NTU (Max: 300 NTU). • Pre-treatment (e.g. filtration / flotation w/wo chemical dosing) may be required to minimise scaling, fouling and damage by large contaminants. The type and extent of pre-treatment would be dependent on the feed quality. • Output quality: 0.1 – 0.4 NTU, 0 – 1 g/l TSS. • Modular, easy to build and operate, fully automated, low labour. (Metcalf & Eddy, 2014)

						(DOW, 2011)
Nano Filtration	0.0009 – 0.01 µm	> 6 log	H/H	H	• 85 – 95 % recovery, therefore 5 – 15 % as relatively high TDS retentate which will need to be disposed through environmental discharge or evaporation basins. • Alternatively, additional high-recovery NF or RO units can be operated to reduce the volume of waste brine. • Chemically enhanced backwashing and Clean in Place (CIP) will generate chemical waste that requires neutralisation and special disposal.	• Flux: 0.3 – 0.5 $m^3/m^2/d$ Energy Requirement: 0.4 – 0.5 kWh/m^3 Operating pressure: 700 – 1400 Kpa (High OPEX). • Suitable feed turbidity <1 NTU. • Pre-treatment: filtration / flotation + chemical dosing to minimise scaling / fouling. Fine cartridge filtration may be needed to reduce the Silt Density Index and fouling potential. • Output quality: 0.01 – 0.1 NTU, 1-5 mg/l TOC, 50-100 mg/l TDS. • Modular, easy to build and operate, fully automated, low labour. (Metcalf & Eddy, 2014) (SUEZ, 2021) (Nadir, 2020)

Reverse Osmosis	0.0001 – 0.002 µm	>6 log (loose RO) > 7 log (tubular RO)	H/H	H	• < 80 % recovery, therefore > 20 % as high TDS retentate which will need to be disposed through environmental discharge or evaporation basins. • Alternatively, additional high-recovery RO units can be operated to reduce the volume of waste brine. • Clean in Place (CIP) will generate chemical waste that requires neutralisation and special disposal.	• Flux: 0.3 – 0.5 $m^3/m^2/d$ Energy Requirement: 0.5 – 0.65 kWh/m^3 Suitable feed turbidity <1 NTU [2][3][4] Operating pressure: 800 – 1900 kPa (High OPEX). • Pre-treatment: filtration/flotation + chemical dosing to minimise scaling/fouling. Fine cartridge filtration may be needed to reduce the Silt Density Index and fouling potential. • Output quality: 0.01 – 0.1 NTU, 0.1 – 1 mg/l TOC, 25 – 50 mg/l TDS. • Modular, easy to build and operate, fully automated, low labour. (Nazih K. Shammas, 2016) (SUEZ, 2021) (van Dijk, 2007)
Adsorption Filters (Granular Activated Carbon)	Variable, absorbs down to molecular level	1.3 – 2.7 log	M/M	L	• 4 – 8 % of filtered water back for backwash. • The backwash stream can be directly returned to the head of the works without further treatment but must be less than 10 NTU. In most cases treatment, including clarification followed by sludge thickening will be required. • Returning wash water should not exceed 10 % of the works inlet flow and should be less	• Will be applied as granular (GAC). • Can operate up-flow or down-flow. • Can be applied individually, or as a complementing media in a multimedia depth filtration. • High Flux (12 – 240 $m^3/m^2/d$) best option for handling high volumes of wash water. • Low labour requirement, high degree of automation. • GAC systems are generally duplex to allow for maintenance service / duty

					than 10 NTU (Badendoch & Bouchier, 1998).	arrangement when one bed is regenerating. • Biofilms can form on the carbon, leading to increased clogging and increased backwash requirements. • Can be susceptible to fouling due to certain species if not removed e.g. halogens. • Cleaning in place is conducted using solvents, backwashing and / or high-pressure steam. • Exhausted activated carbon is periodically regenerated through high temperature heating (815 – 927 °C), often in a multiple hearth furnace. (Nazih K. Shammas, 2016) (Hijnen, et al., 2010)

Table 8.2 – Detailed description of established disinfection technologies and their efficacy against *Cryptosporidium*

Technology	Chemicals Used	Log Reduction on Value	Efficacy against *Cryptosporidium*	CAPEX /OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
Chlorination	Chlorine Gas OR Sodium Hypochlorite (liquid) OR Calcium Hypochlorite (solid)	0 log	• Poor. • Theoretically possible to inactivate oocysts through hyperchlorination. • Concentration of disinfectant x contact time (CT) in excess of 15,300 mg/l/min (WHO, 2009) is required. • Not practical for bulk water treatment.	L/L	L	• Not recommended in the context of *Cryptosporidium* removal.	• Not recommended in the context of *Cryptosporidium* disinfection.
Monochlorination	Chlorination chemicals (see above) AND Ammonia	0 log	• Poor. • Less effective than regular chlorination.	L/M	L	• Not recommended in the context of *Cryptosporidium* removal.	• Not recommended in the context of *Cryptosporidium* disinfection.
Chlorine Dioxide	Onsite generation with Sodium	Up to 1 log (Walter Q. Betancourt, 2004)	• Slightly more effective than chlorination. • Some inactivation has been recorded at practical CT values	L/M	M	• Chlorine dioxide in high concentrations can present acute health risks – dosing control and monitoring are critical.	• Chlorine dioxide gas cannot be compressed or stored commercially because it is explosive under pressure. Therefore, chlorine dioxide gas is never shipped, but generated on-site.

Technology	Chemicals Used	Log Reduction on Value	Efficacy against *Cryptosporidium*	CAPEX /OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
	Chlorite solution AND a chemical precursor OR onsite generation with electrochemical process		however available research is limited.			• Disinfection by products (DBP's) – regular monitoring for chlorite concentration required. • Some utilities may have to use activated carbon to reduce to the chlorite residual. (United States Enviromental Protection Agency, 2020)	• When producing chlorine dioxide with sodium chlorite and chlorine gas, safety measures must be taken with regards to the transport and use of chlorine gas. • Stock solutions produced on-site typically have a concentration of 500 mg/L. (United States Enviromental Protection Agency, 2020) Disinfection by-products.

Ozonation	Onsite generation from oxygen
	
	OR dry air
		1 log, when Ct>9.9 mg/l/min
		
		2 log, when Ct>20mg/l/m
		
		3 log, when Ct>30 mg/l/min at water temp of 10°C
			• Moderately effective.
			
			• Relatively high CT values are needed to achieve inactivation resulting in costly consumption of ozone.
				M/H	M	• Disinfection by products (DBP's) – bromate and aldehydes are produced which can be a concern.
						
						• A filtration system required on the back end to prevent precipitated solids from being present in treated water.
						
						• Bromate mitigation steps can include:
						  • pH depression to as low as 6.8
						  • Addition of ammonia
							• Efficacy of ozone is dependent strongly on:
							
							• Temperature – As temperature increases, the disinfection effectiveness increases. 4.5-fold increase in CT for 10 degrees increase in temperature.
							
							• pH – An increase in pH from 6 to 9 pH can reduce ozone dosage required by up to a factor of 40.
							
							• Suspended solids – Radical oxygen compound (ROS) scavengers can reduce capacity of the ozone disinfection.
							Attention to operating conditions is therefore critical in the efficient operation of the technology.

Technology	Chemicals Used	Log Reduction on Value	Efficacy against *Cryptosporidium*	CAPEX /OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
		(Betancourt & Rose, 2004)				• Addition of peroxide; and • Addition of alkalinity.	• Hydraulic retention time is less important as compared to optimisation of mass transfer of ozone which can be low due to poor solubility. • POU/POE systems are widely available, mainly from North American suppliers that can generate and deliver ozone from mains electricity.
Ultraviolet Disinfection	N/A	>4 log, when UV dose >40 MJ/cm^2 (dependant of supplier validation) (Betancourt & Rose, 2004)	• Highly effective against *Cryptosporidium* oocysts. • Water with low turbidity (typically less than 1 NTU) is required. (Betancourt & Rose, 2004)	M/L	M	• Physical process more than a chemical one with no need for toxic or corrosive chemicals to be handled / stored. (United States Enviromental Protection Agency, 1999) • UV irradiation of water with high bromine and / or chlorine concentrations can result in the formation of harmful by-products (van Dijk, 2007)	• UV reactors can be validated for a specific log reduction of *Cryptosporidium*. • Validation procedures have been developed by the USEPA and UVDGM that are recognised globally. • Online monitoring of UV transmittance and UV intensity required to maintain validated dose. • *Cryptosporidium* has genes which can regulate protective metabolic response against radiation. • Parasite concentrations and feasibility assessment maybe required on final effluent before application (Suarez, et al., 2022). • Preventive maintenance maybe required to control fouling (United

Technology	Chemicals Used	Log Reduction on Value	Efficacy against *Cryptosporidium*	CAPEX /OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
							States Enviromental Protection Agency, 1999). Advantages: • No chemicals added; • Cost-effective; • Fast acting; • Effective against a range of organisms broader than chlorine; and • UV water purifier kills bacteria and viruses. Disadvantages: • Incapable of removing dissolved impurities (such as pesticides, rust, arsenic, fluoride, etc.); • Requires electricity – operating costs, back up electric source; • UV light shutoff from operational error or equipment malfunction; and

Technology	Chemicals Used	Log Reduction on Value	Efficacy against *Cryptosporidium*	CAPEX /OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
							• No disinfectant residual in the water.

Table 8.3 – Detailed Description of emerging *Cryptosporidium* removal / deactivation technologies

Technology	Removal Efficiency *Cryptosporidium (3 – 6 µm)*	Readiness (R/L/P/F)[11]	CAPEX/ OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
Ballasted Clarification (i.e. Actiflo®, Rapisand® and Comag®	2.5-2.7 log (with coagulation/flocculation – additional polymer required)	F Large Actiflo® installations in the UK including Severn Trent's	H/H	M	• Sludge is removed from the collection hopper continuously to allow for a consistent recycle of the ballast. This generally will result in wetter sludge that may require further processing.	• Ballasted clarification is a form of high-rate sedimentation that utilises ballasts (i.e. microsand or magnetite) to improve the settling velocity of flocs. This allows for higher loading rates and smaller footprint which makes it ideal for sites with footprint restrictions. • Coagulation and flocculation with a polymer solution is to allow the flocs to adhere to the ballast. Sludge is collected at the base of the clarifier and pumped to a ballast recovery

[11] Readiness: research (R), lab-scale (L), pilot-scale (P), fully commercialised (F)

Technology	Removal Efficiency *Cryptosporidium (3 – 6 µm)*	Readiness (R/L/P/F)[11]	CAPEX/ OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
	Similar to regular sedimentation processes if operated correctly.	Frankley WTW			• The backwash stream can be directly returned to the head of the works without further treatment but must be less than 10 NTU. In most cases treatment, including clarification followed by sludge thickening will be required.	system (a series of hydro cyclones if microsand is used). The ballast is then recycled back into the process whilst the remaining sludge is removed for further processing (i.e. thickener and centrifuge). • Ballasted clarification generally requires intense monitoring and specialist operation for optimal performance.
Ceramic Membranes	Up to 4 log removal	F Numerous ceramic membrane installations in the UK including Severn Trent's Church Wilne WTW	H	H	• Approximately 90 % recovery, therefore 5 - 15 as brine which can be recycled for mixing with untreated wash water. This will typically require further treatment before being returned to the head of the works. • Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998). • Chemically enhanced backwashing and Clean in Place (CIP) will generate chemical waste that requires	• The general operation and maintenance considerations a re similar to conventional (polymeric based) membranes. • The material may demonstrate higher resilient to extreme operating parameters (e.g. high pressure, temperature.) • The lifetime of the ceramic membranes is particularly long (about 20 years).

Technology	Removal Efficiency *Cryptosporidium (3 – 6 µm)*	Readiness (R/L/P/F)[11]	CAPEX/ OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
					neutralisation and special disposal.	
Coagulation/Flocculation using natural substances	N/A	L	CAPEX: L OPEX: M (If can be harvested and supplied in the UK) H (if supply requires export from overseas)	L	• Sludge will require thickening and disposal. Coagulants used are environmentally friendly and impose no damage to the receiving environment.	• Typically, is followed up with a solid-liquid separation process such as DAF or sedimentation. • The experimental work is unconclusive as to the pH / temperature impacts on the process efficiency. • Relatively slower process compared to conventional coagulation due to HRT requirement of 30 - 60 minutes. • Will remove the bulk of large flocs and sediments, however smaller colloids and most *Cryptosporidium* will not be removed. • Certain plant extracts (in this case chicory) show effectiveness for protozoa, anything else will require further removal. • This method utilises natural agents; however, extraction of the agent will be required which involves a harvesting of the agent. • Expected to be resilient to influent quality however research has not progressed enough to support this argument. (Bhuju, 2020) (Woolsey, et al., 2019)

Technology	Removal Efficiency *Cryptosporidium (3 – 6 µm)*	Readiness (R/L/P/F)[11]	CAPEX/ OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
Upflow Direct Filtration	>3.87 log	F	M/H	L	• 4 – 8 % of filtered water is recycled for backwash / sand cleaning • The backwash stream can be directly returned to the head of the works without further treatment but must be less than 10 NTU. In most cases treatment, including clarification followed by sludge thickening will be required. • Returning wash water should not exceed 10 % of the works inlet flow and should be less than 10 NTU (Badendoch & Bouchier, 1998). (Nascimento, et al., 2020)	• General operation and maintenance considerations are similar to Depth Filtration. • With direct up-flow, constant pressure is required to not only pump the water but also to fluidise the filter bed (higher energy cost relative to downflow sand filters) • Coagulant required in order to enhance the filtration. (Nascimento, et al., 2020)
Nature Based solution – Subsurface flow (SSF) and Free surface flow (FSF) wetlands	0.4 – 1.7 log – FWS systems 3 log – HSSF systems	F Numerous installations in wastewater treatment and sludge dewatering application	M/L	L	• Wetlands will typically need to be excavated and refreshed every 5 – 10 years. Waste sludge will go to landfill.	• Promising for water reuse and sludge handling applications. Limited applications for direct source water treatment for reliable *Cryptosporidium* removal. • Appropriate solution for small to medium sized settlements. • Sludge loading rate of 40-80 kg/m^2

Technology	Removal Efficiency *Cryptosporidium (3 – 6 µm)*	Readiness (R/L/P/F)[11]	CAPEX/ OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
		s in Europe.				• Many advantages over traditional systems: • Lower capital cost (depending on land cost); • Lower operating cost; • Infrastructure and design simplicity; and • Ease of operation • However, drawbacks over traditional systems include: • Large area footprint – 2m^2/P.E. (warm climate) and 12m^2/P.E. (cold climate); and • Water evaporation in warmer climates. • Can be found in both aerobic and anaerobic systems. In aerobic systems the oxygen transfer rate is increased by 10x compared to traditional systems. Horizontal subsurface flow (HSF) leading to a reduction in footprint by up to 75 - 80 % but a subsequent energy requirement. (Capodaglio, et al., 2021)
Nanomaterial enhanced filtration	96.4 % to 99.2 % removal	P	L/M	L	• Filter / matrix cleaning wash water requires disposal	• Investigated the effects of silver salt and nanoparticles on *C. parvum*. • Used physical filtration in porous ceramic filter media. • Removal efficiencies ranged from 96.4 % to 99.2 %.

Technology	Removal Efficiency *Cryptosporidium (3 – 6 µm)*	Readiness (R/L/P/F)[11]	CAPEX/ OPEX (H/M/L)	CO_2 Footprint (H/M/L)	Waste By-product and Handling	Key Operation and Maintenance Considerations
						• Physical filtration and silver nanoparticle disinfection contributed to *C. parvum* treatment. • Physical filtration likely had a greater contribution than silver disinfection. • Disinfection of surface water using TiO_2 photocatalysis studied (Sunnotel, et al., 2010). • Inactivation occurred after 180 mins with 73.7 % removal. (Kokkinos, et al., 2021)
Ultrasonication	Approximately 90 % of oocysts deactivated upon exposure to 90 seconds of 20 kHz	R	OPEX: L		Composition of the water not changed or toxic by-products not produced.	• Investigated the effects of silver salt and nanoparticles on *C. parvum*. • More than 90 % of the dispersed *Cryptosporidium* oocysts could be deactivated in about 1.5 min of continuous sonication (Ashokkumar, et al., 2003). • The efficacy of ultrasound disinfection, at three power levels (60, 80 and 100 W), pulsed at 50 % or in continuous mode was investigated. The application of ultrasound irradiation at 80 W power in continuous mode for an exposure time of 10 min drastically reduced the viability of *C. parvum* (Abeledo-Lameiro, et al., 2018).

8.2.1 MANAGING SLUDGE SUPERNATANT AND RECYCLED STREAMS

As shown in Table 8.1, solid liquid separation treatment technologies often produce a sludge stream that can be recycled to the head of the works (following some additional treatment / handling). A key industry rule is that the return stream should not exceed 10 % of the of the overall works inflow and should be less than 10 NTU to manage *Cryptosporidium* risk. This is known as the 10/10 rule in the industry and is a commonly used benchmark across the UK and globally.

Although there has not been any significant literature in recent years to challenge the 10/10 rule, there are some alternative approaches worth noting. The USEPA recommend that the return flow is continuous with a target of 5 % of the inflow and a critical limit of <10 %. It is also recommended that the turbidity of the return stream is 10 NTU with a critical limit of 20 NTU.

As described in Section 3.4.2, the Water Services Association of Australia (WSAA) categorise catchments based on their levels of protection against contamination and microbial indicators. WSAA suggests that sludge produced from clarification processes in high-risk category 4 sites could potentially contain a high concentration of *Cryptosporidium* oocysts. It is therefore recommended that supernatant from this sludge is not returned to the head of the works without additional treatment (i.e., UV irradiation, filtration etc).

8.3 MULTI-BARRIER APPROACH

The World Health Organization (WHO, 2009) stress the need for a wholistic multi-barrier approach for managing *Cryptosporidium* risk in drinking water supplies. This includes implementing risk mitigating strategies through the entire supply chain from catchment to tap. Disinfection with chlorine and subsequent residual maintenance has always been an important barrier for the deactivation of waterborne pathogens. However, since *Cryptosporidium* is resistant to chlorine disinfection, the number of barriers is typically less resulting in the potential risk of breakthrough. For catchments that have a high risk of *Cryptosporidium* contamination, one treatment barrier may not be sufficient especially if the efficacy of the treatment can fluctuate based on feed water quality. Multiple barriers in treatment not only increase the overall removal capacity (i.e. overall log removal), but also reduce the variation in the overall treatment efficiency (WHO, 2009).

8.4 PREVALENT TECHNOLOGIES FOR *CRYPTOSPORIDIUM* DEACTIVATION

The second and third Reports of the Group of Experts discuss ozone and UV disinfection as technically feasible for *Cryptosporidium* treatment but not economically viable on a large-scale. Advancements in these technologies in the past 25 years have seen a significant improvement in relative CAPEX cost and operational efficiency which has resulted in wide-spread application in the UK and across the world – particularly UV disinfection. Both technologies have a relatively small footprint and low CAPEX (compared with solid-liquid separation technologies) and can often be integrated into existing works to provide an additional barrier to *Cryptosporidium*. The *Cryptosporidium* event root cause analysis (Section 3) showed that the installation of UV disinfection was a direct action from at least 15 events between 2005 – 2022.

OZONE

Ozone is an effective clean water disinfection technique used to deactivate bacteria, viruses, and parasites through the process of oxidation. The ozone (O_3) molecule is allotropic, constituting of three oxygen atoms which easily degrades back to oxygen (O_2) while forming a free radical (O•). This makes ozone a powerful oxidising agent, and able to readily accept electrons from organic material. The oxidation process of organic material causes a weakening of cell walls resulting in death of the cell. For this reason, ozone technology has been utilised for clean water disinfection since the 1900s across Europe and Asia predominantly.

Due to the unstable nature of ozone, the molecule must be generated in situ and at the site of implementation. The conversion of oxygen into ozone involves an energy-driven process, typically accomplished through various distinct methods. Commercially, this ozone generation occurs via electric discharge methods, resembling corona discharge systems or by utilising UV radiation, akin to the natural ultraviolet rays from the sun. Besides these established techniques, ozone can also be produced by electrolytic and chemical reactions. In practice, an ozonation system typically entails the passage of dry, clean air through a high-voltage electric discharge, such as corona discharge, resulting in the creation of ozone concentrations at approximately 1 %, equivalent to 10,000 mg/L. For smaller-scale applications involving waste treatment, UV ozonation stands as a prevalent choice, whilst large-scale systems typically opt for corona discharge or alternative bulk ozone production methodologies.

Once ozone is generated, the next stage involves the introduction of raw water and ozone. This can be achieved through a venturi throat, which generates a vacuum effect, facilitating the infusion of ozone gas into the water. Alternatively, the ozonated air can be methodically bubbled up through the water intended for treatment. One significant benefit of ozone disinfection is the absence of the need for chemical agents in the disinfection procedure all while being effective against viruses, bacteria and protozoans as well as inorganic compounds. A disadvantage of ozone-based systems is the requirement for complex equipment, including air treatment (to concentrate oxygen), ozone generator, and off-gas ozone destroyer (Gomes, et al., 2019). A further disadvantage is the health and safety concerns of ozone due to the risk to ozone contamination in the air. Ozone is toxic and can have health impacts if large quantities are inhaled (Campbell, 2022).

Table 8.4 - Influence of water quality parameters on ozone efficacy for *Cryptosporidium* deactivation

Water Quality Parameter	Optimal operating range	Description
Temperature (°C)	20°C (Driedger, et al., 2001)	• An increase in temperature results in improved *Cryptosporidium* deactivation. • A 10°C rise in temperature provides a 4.5-fold increase in CT. (Avery, et al., 2013)
pH	6 (Avery, et al., 2013)	• Changes in water pH impact the availability of O_3 (ozone) and OH (hydroxide ions). • Increasing pH from 6 to 9 decreases the amount of available O_3 by a factor of 40.

		• Inactivation rates among different *Cryptosporidium* species show no substantial differences (Avery, et al., 2013).
Suspended Solids	Low	• Suspended solids can severely reduce the efficiency of ozone deactivation. • Ozone scavengers reduce the disinfection capacity due to the ozone being occupied. • Other contaminants such as bromide and synthetic compounds have a similar impact on ozone efficiency. (Avery, et al., 2013)
Bromide concentration	Low	• Increased bromide concentrations can result in the oxidation and subsequent generation of bromate. • Ozonation by-products including bromate, aldehydes and ketones are potentially carcinogenic. (Avery, et al., 2013)

ULTRAVIOLET DISINFECTION

UV disinfection has been firmly established as a deactivation technology in the field of clean water treatment, spanning across both Europe and North America (Goverment of Western Australia, Department of health, 2023). The effectiveness of this technology in deactivating *Cryptosporidium* is demonstrated in section 2.8 (Major Event Case Studies), wherein all three significant incidents discussed, chose to employ UV technology to mitigate the spread of *Cryptosporidium*. The technology relies on UV light which exists between X-rays and visible light on the electromagnetic spectrum. UV light can be categorised into four distinct sub regions: vacuum UV (100 – 200nm), UV-C (200 – 280nm), UV-B (280 – 315nm), and UV-A (315 – 400 nm). UV-B and UV-C light are significantly more effective as disinfectants when compared to UV-A, and achieving the desired level of disinfection with UV-A requires prolonged exposure (United States Enviromental Protection Agency , 2006). Vacuum UV has demonstrated disinfection capabilities; however, its practical application in a clean water treatment setting renders the technology impractical, making the ideal UV wavelength range for such applications to fall between 200 and 300 nm. UV light-emitting diodes (UV-LEDs) have also been shown to be effective against *Cryptosporidium* (Takahashi, et al., 2020).

The method of pathogen deactivation utilising UV technology stands apart from the processes involving chemical disinfectants like chlorine and ozone. Chemical disinfectants achieve pathogen deactivation through the direct destruction of cellular structures and hampering metabolic functions, therefore preventing the pathogen from replicating. In contrast, UV light achieves microorganism inactivation by causing damage to their nucleic acid, encompassing both DNA and RNA, thereby reducing replication capacity (Drinking Water Inspectorate , 2022). UV rays are able to effectively penetrate the cell walls or membranes of microorganisms, causing damage to the oocyst. This damage results in the inability of the microorganism's DNA to replicate and, consequently, its incapacity to infect a host (United States Enviromental Protection Agency, 2020).

UV light for deactivation of *Cryptosporidium* involves two key steps, firstly, the creation of UV light and secondly, the effective transmission of this light to pathogens. The process of generating UV light employs a lamp which contains an inert gas, such as argon, and a small quantity of liquid

mercury. A voltage is introduced, causing a portion of the liquid mercury to transform into vapor. The collisions between free electrons and gaseous mercury atoms elevate the energy state of the mercury atoms. Subsequently, the excited mercury atoms return to their natural state, releasing energy in the form of UV light (Isha Khedikar, 2016). After UV light is generated, the subsequent critical step involves the efficient transmission of UV light to the pathogens. Managing the turbidity of the wastewater stream is pivotal in enhancing the effectiveness of the UV disinfection process. Elevated turbidity and high solid content within the water can impede the transmission of UV light to the pathogens, as these solids can obstruct the UV light's path. To optimise the UV treatment, it is essential to maintain low levels of solids in the water stream before initiating the UV process. It is advisable to position the UV treatment unit strategically towards the latter stages of the water treatment process, ideally after the filtration and solid separation process units. This arrangement helps ensure that the water is clear and free of solid particulates, allowing the UV light to effectively target and disinfect any remaining pathogens. Another notable differentiation in UV technology for pathogen deactivation pertains to the type of UV lamp used. In general, UV lamps can be classified as either Low Pressure (LP), emitting a single UV wavelength, or High Pressure (HP), emitting multiple wavelengths. A comparison of the two UV lamp types can be seen in Table 8.5.

Table 8.5 – Comparison of Low pressure and Medium-pressure UV lamps

Parameter	Low Pressure (LP)	Medium Pressure (MP)
Energy consumption	Lower energy usage	Higher energy usage
Flow types	More suitable for intermittent flow	More suitable for constant flow
Output	Lower output	Higher output
Footprint	Higher footprint	Lower footprint

A key aspect of UV technology lies in the validation process, which establishes the necessary operating conditions for a UV reactor to consistently deliver an effective dose. This is a critical requirement, as the validated dose must meet or exceed the required dose to attain log inactivation against *Cryptosporidium*. Whilst the precise specifics of UV validation may exhibit minor variations depending on the specific environmental agency and the country in question, the fundamentals remain broadly similar. These minimum requirements, as outlined in Table 8.6, have been sourced from the UV Disinfection Guidance Manual provided by the United States Environmental Protection Agency (EPA) in 2006.

Table 8.6 – UV Validation requirements from the United States Environmental Protection Agency (United States Enviromental Protection Agency , 2006)

Requirement	Conditions
Validated operating conditions must include	• Flow rate. • UV intensity as measured by a UV sensor. • UV lamp status.

Validation testing must include	• Full-scale testing of a reactor that conforms uniformly to the UV reactors used by the water system. • Inactivation of a test microorganism whose dose-response characteristics have been quantified with a low-pressure mercury vapor lamp
Validation testing must account for	• UV absorbance of the water. • Lamp fouling and aging. • Measurement uncertainty of online sensors. • UV dose distributions arising from the velocity profiles through the reactor. • Failure of UV lamps or other critical components. • Inlet and outlet piping or channel configurations of the UV reactor.

8.5 OVERVIEW TABLE FOR TREATMENT TECHNOLOGIES SECTION

Table 8.7 – Overview table for treatment technologies

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of experts (1998)	Literature
Solid-liquid separation technologies	Two key principles of treatment for lowland water: 1) rapid filtration and 2) slow sand filtration. Aluminium and ferric salts equally effective for coagulation. Polymer for potential to improve rapid filtration of oocysts.	Further recommendations on operational best practices for media filters. Activated carbon filters and membrane filters have been shown to be effective. Variable performance has been shown with textile filters.	Discussion on chemical coagulation-based treatment for oocyst removal. Reliant on the ability to maintain a suitable coagulant dose, which is governed by the raw water quality, in particular colour and turbidity. Further recommendations on best practice filter operation to avoid oocyst breakthrough. Efficacy of DAF and membrane technologies discussed.	13 types of solid-liquid separation technologies reviewed and compared. The comparison included efficacy against *Cryptosporidium* waste handling, CAPEX/OPEX and other operation challenges. Membrane technologies are highly effective at removing oocysts, with increased log removal as pore size decreases. However, these technologies are expensive to build and operate, and produce chemical waste. Suitable for high-risk sites Traditional slow sand filters and depth filters can have varying performance depending on design and operation. Generally, less reliable than membrane technologies. DAF is a viable alternative to traditional sedimentation. When coupled with depth filtration (DAFF), strong oocyst removal has been witnessed. Cartridge filtration and surface filtration (i.e., disk filters) generally have a relatively low log removal of oocysts, however these technologies are cheaper to build and operate.
Traditional disinfection methods	Concentrations between 8,000 and 16,000 mg/l of chlorine required to deactivate oocysts.	Chlorine dioxide is more effective than chlorine, but there may be safety issues associated with the dose levels that are required.	N/A	Chlorine and monochloramine are ineffective to oocysts. Not recommended for the application of oocyst deactivation. Ozone or UV disinfection are required to provide an additional barrier against oocysts at conventional water treatment works.

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of experts (1998)	Literature
Ozone	Further research for ozone disinfection required.	Ozone has been shown to be more effective than other disinfection options, but the required dose and contact times are likely to be outside of the normal design range.	N/A	Ozone dosing technology has become cheaper and more efficient in recent years. Water quality parameters such as pH, suspended solids and bromide must be monitored for effective operation. Slightly less effective compared to UV disinfection.
Ultraviolet Disinfection	Other disinfectants such as chlorine dioxide, hydrogen peroxide and the use of ultraviolet radiation with may be technically feasible, but expensive for large-scale supplies.	The energy levels required for UV are likely higher than what is achievable under normal operating conditions.	Due to the exposure characteristics and design of UV systems, they are only applicable in small water supply systems.	UV disinfection has been a popular solution to increase *Cryptosporidium* removal capacity and reliability in recent years. Advancements in the technology have allowed it to be utilised in large scale applications e.g Franklaw. UV units can now obtain globally recognised validation for *Cryptosporidium* log removal. UV dose and feed water UVT typically determine the log removal credits. Low pressure and medium pressure lamps can be used depending on the site-specific requirements and constraints.
Operational measures and controls	Highlights best practice operational techniques to avoid oocysts breakthrough	Water utility companies reviewed their operation practices, and these were inspected by the DWI. Studies at treatment plants further demonstrated the tendency for particles to be released from filters during flow	Water treatment plant s should be operated at all times to minimise the turbidity of the final water. Continuous turbidity measurement on the outlet of each filter and on the final water using instruments capable of detecting changes of less than 0.1 NTU.	N/A

Topic	First Report of the Group of Experts (1990)	Second Report of the Group of Experts (1995)	Third Report of the Group of experts (1998)	Literature
		changes and filter start up.		
Emerging opportunities and research	Polymers used as filter aids may improve rapid filtration of oocysts, but this requires further research.	Further work in progress to evaluate if washing filters following shut-down before returning them to service significantly reduces the passage of particles.	Extensive research on membrane-based filtration. Membrane filtration needed for completely reliable removal of parasites.	Six emerging and non-traditional treatment technologies were reviewed and compared in the context of *Cryptosporidium*. Ballasted clarification and ceramic membranes have had recent large-scale installations in the UK and show promising results. Coagulation with natural substances and nature-based solutions are potential areas for further research as the industry looks towards a sustainable future.

9 CONCLUSIONS AND NEXT STEPS

Following outbreaks of the disease caused by *Cryptosporidium* in the late 80s, the UK government set up a Group of Experts for *Cryptosporidium* in Water Supplies. Three reports were published by the Group of Experts providing recommendations on how to safeguard against *Cryptosporidium*. An overview of the information provided in the three reports by the Group of Experts, relating to the key thematic areas is presented in this report. This serves as a baseline of the approaches for *Cryptosporidium* management at the time of the last report of the Group of Experts. A gap analysis of the content of the three reports by the Group of Experts and against more recent literature will next be undertaken.

A review was undertaken of *Cryptosporidium* events in England and Wales between 2005 and 2022. This showed that there was no single cause that was the most prevalent for causing a *Cryptosporidium* event. Insufficient treatment for corresponding catchment risk, faulty assets and poor procedures or staff training were the causes of most *Cryptosporidium* events from 2005 – 2022. For major and serious events, insufficient treatment for corresponding catchment risk, faulty assets and contamination or vermin breach were the most frequent causes.

Recent literature was consolidated for key topics including *Cryptosporidium* species, detection and monitoring, treatment technologies and processes and other key areas of interest. The species *C. parvum* and *C. hominis* cause the most infections in humans. Within these species, there are particular subtypes that are responsible for more infections but these emerge and predominance changes. There are various options for monitoring and detecting of *Cryptosporidium* in water supplies, these include monitoring for surrogates for *Cryptosporidium*, such as turbidity monitoring and particle counters or using methods to directly detect the organism. It is highly desirable for *Cryptosporidium* detection to be rapid and automated. Molecular techniques and miniaturised detection devices are useful methods for *Cryptosporidium* detection but do require effective sample processing. They can be automated which can mean a reduction in the staff time required and a reduction in human error in some aspects of the process. They can also provide more detailed information related to the detection, such as genotyping within *Cryptosporidium* species.

Cryptosporidium can pose a particular challenge in the context of water treatment due the chemical and temperature resistance of oocysts. This report presents a review of the various treatment technologies and their efficacy against *Cryptosporidium*. Since the last Report of the Group of Experts, ozone and UV disinfection have become more efficient, more compact, and more reliable. As a result, these are now considered to be cost effective and less carbon intensive options to increase *Cryptosporidium* removal / deactivation capacity. Other emerging technologies such as ballasted clarification, ceramic membranes and nature-based solutions were reviewed and show *Cryptosporidium* log removal of between 0.4 – 4.0 depending on the method.

A subsequent stage of this project will be to further develop the evidence base collected within this report by undertaking stakeholder engagement with water utility companies and the *Cryptosporidium* Reference Unit. This will allow expert recommendations to be collated to support the ultimate development of a guidance document for *Cryptosporidium* management. Some key questions and topics to discuss with the stakeholders have been identified and are listed below:

- Are the reports of the Group of Experts the current benchmark for best practice *Cryptosporidium* catchment management? Are there other guidance or materials that are used?
- What risk assessment procedures are used to identify high risk catchments?
- The process in establishing a *Cryptosporidium* log-removal requirement for a particular catchment.
- Techniques for agricultural engagement and it benefits.
- What monitoring and detection systems are most commonly used amongst UK water treatment works?
- Are molecular techniques such as PCR or similar methods being implemented? If so, what is being used?
- Have any novel detection and monitoring methods been trialled at water treatment works?
- What are the most common treatment technologies amongst UK water treatment works?
- The difference between slow sand filters, rapid gravity filters and membranes for high-risk *Cryptosporidium* catchments?
- A discussion of the challenges associated with retrofitting ozone and / or UV into existing works.
- Have any novel treatment methods been trialled at water treatment works?
- A discussion on the treatment and detection and monitoring methods outlined in the literature review to understand the interest amongst experts on which are the most promising.
- Are water companies reliant on the experience of employees to drive operational best practices?
- What are some common responses to treatment works alarms and failures?
- How can specific *Cryptosporidium* risk mitigation be implemented in operational strategies?
- Do the three Reports of the Group of Experts provide sufficient guidance on how networks should be managed to prevent *Cryptosporidium* contamination? Are there any other guidance or materials that water companies use?
- What types of network configurations or arrangements have been shown to be higher risk than others?

10 REFERENCES

Abeledo-Lameiro, M. J., Ares-Mazás, E. & Goméz-Couso, H., 2018. Use of ultrasound irradiation to inactivate Cryptosporidium parvum oocysts in effluents from municipal wastewater treatment plants.. *Ultrasonics Sonochemistry,* Volume 48, pp. 118-126.

Ainsworth, R. et al., 2004. *Safe Piped Water: Managing Microbial Water Quality in Piped Distribution Systems,* s.l.: IWA.

Ashokkumar, M. et al., 2003. Ultrasonic treatment of Cryptosporidium oocysts.. *Water Science and Technology,* 47(3), pp. 173-177.

Avery, L., Jarvis, P. & Macadam, J., 2013. *Review of literature to determine the uses for ozone in the treatment of water and wastewater: Executive Summary,* Scotland: Centre of Expertise for Waters.

Bakheit, M. A. et al., 2008. Sensitive and specific detection of Cryptosporidium species in PCR-negative samples by loop-mediated isothermal DNA amplification and confirmation of generated LAMP products by sequencing. *Veterinary Parasitology,* pp. 11 - 22.

Batt, C. A. & Tortorello, M., 2014. *Encyclopedia of Food Microbiology.* 2nd ed. s.l.:Academic Press.

Bell, J. A. & Pearce, G. K., 1997. Filter process removes cryptosporidial oocysts from water supplies.. *Water Engineering & Management,* pp. 18 - 19.

Bernhardt, H. & Clasen, J., 1996. Elimination of micro-organisms illustrated with reference to the treatment. *GWF-Wasser/Abwasser,* pp. 109 - 116..

Bhuju, R., 2020. *Removal of Microplastics from Fresh Water Using Plant Derived Polysaccharides,* Stephenville, Texas, USA : Tarleton State University ProQuest Dissertations Publishing.

Boks, M. et al., 2023. Persisting symptoms after Cryptosporidium hominis outbreak: a 10-year follow-up from Östersund, Sweden.. *Parasitol Res.,* 122(7), pp. 1631-1639.

Bridle, H., 2021. *Waterborne Pathogens: Detection Methods and Applications.* s.l.:Elsevier.

Bridle, H. et al., 2021. *Maximising the safe return of recovered process water,* Newcastle Upon Tyne: Wood PLC.

Bridle, H. et al., 2012. Detection of Cryptosporidium in miniaturised fluidic device. *Water Research,* Volume 46, pp. 1641 - 1661.

Cacciò, S. M. & Chalmers, R. M., 2016. Human cryptosporidiosis in Europe. In Clinical Microbiology and Infection. *Clinical Microbiology and Infection,* pp. 471 - 480.

Campbell, B., 2022. *Ozone in Water Treatment.* [Online]
Available at: https://www.wqpmag.com/home/article/21175003/ozone-in-water-treatment
[Accessed 03 January 2024].

Capodaglio, A. G., Bolognesi, S. & Cecconet, D., 2021. Sustainable, Decentralized Sanitation and Reuse with Hybrid Nature-Based Systems. *Water,* p. 1583.

Carter, B., Chalmers, R. & Davies, A. H., 2020. Health sequelae of human cryptosporidiosis in industrialised countries: a systematic review. *Parasites & Vectors,* 13(443).

Centers for Disease Control and Prevention, 2011. *Comparison of Ultrafiltration Techniques for Recovering Biothreat Agents in Water,* s.l.: United States Environmental Protection Agency.

Centers for Disease Control and Prevention, 2024. *Cryptosporidiosis.* [Online]
Available at: https://www.cdc.gov/dpdx/cryptosporidiosis/index.html

Chalmers, R. M., Robinson, G., Elwin, K. & Elson, R., 2019. Analysis of the Cryptosporidium spp. and gp60 subtypes linked to human outbreaks of cryptosporidiosis in England and Wales, 2009 to 2017. I. *Parasites and Vectors.*

Chalmers, R. et al., 2018. Cryptosporidium genotyping in Europe: The current status and processes for a harmonised multi-locus genotyping scheme. *Experimental Parasitology,* Volume 191, pp. 25-30.

Chappell, C. L. et al., 2006. Cryptosporidium hominis: experimental challenge of healthy adults.. *American Journal of Tropical Medicine and Hygiene,* pp. 851 - 857.

Daniel, P. A. et al., 1996. Pathogenic protozoa in raw and drinking water: occurrence and removal.. *Water Supply,* pp. 387 - 401.

Dixon, B. R., 2014. Encyclopedia of Food Safety. In: *Protozoa: Cryptosporidium spp..* s.l.:Academic Press, pp. 18-22.

Dong, S. et al., 2020. Prevalence of Cryptosporidium Infection in the Global Population: A Systematic Review and Meta-analysis. *Acta Parasitologica,* 65(4), pp. 882-889.

DOW, 2011. *Ultrafiltration Product Manual.* [Online]
Available at: https://www.lenntech.com/Data-sheets/Dow-Ultrafiltration-Product-Manual-L.pdf

Driedger, A., Rennecker, J. L. & Marinas, B. J., 2001. Inactivation of Cryptosporidium Paravum oocysts with ozone and monochloramine at low temperature. *Wat. Res,* pp. 41-48.

Drinking Water Inspectorate , 2022. *UV Disinfection.* [Online]
Available at: https://www.dwi.gov.uk/uv-disinfection/#:~:text=Unlike%20chlorination%2C%20UV%20is%20effective,required%20prior%20to%20UV%20disinfection.

Drodz, C. & Schwartzbrod, J., 1997. Removal of Cryptosporidium from river water by crossflow microfiltration.. *Water Science and Technology,* pp. 391 - 396.

Dupont, H. L. et al., 1995. The infectivity of Cryptosporidium parvum in healthy volunteers. *The New England Journal of Medicine,* Volume 322, pp. 855-859.

DWI, 2005. *A brief guidance to drinking water safety plans,* s.l.: s.n.

Fradette, M., Culley, A. I. & Charette, S. J., 2022. Detection of Cryptosporidium spp. and Giardia spp. in Environmental Water Samples: A Journey into the Past and New Perspectives. *Microorganisms ,* 10(6), p. 1175.

Fradette, M. S., Culley, A. I. & & Charette, S. J., 2022. Detection of Cryptosporidium spp. and Giardia spp. in Environmental Water Samples: A Journey into the Past and New Perspectives. *Microorganisms,* p. 1175.

Gabriella Rundblad, P. R. H. O. K. J. V. H., 2011. *Improving communication on Cryptosporidium and 'Boil Water' notices: Lessons from Pitsford,* London: Drinking Water Inspectorate.

Goh, S. et al., 2004. Sporadic Cryptosporidiosis, North Cumbria, England, 1996–2000. In: *Emerging Infectious Diseases.* s.l.:s.n., pp. 1007-1015.

Gomes, J. et al., 2019. Ozone and Photocatalytic Processes for Pathogens Removal from Water: A Review. *Catalysts,* 9(46).

Goverment of Western Australia, Department of health, 2023. *Ultraviolet disinfection of drinking water.* [Online]
Available at: https://www.health.wa.gov.au/Articles/U_Z/Ultraviolet-disinfection-of-drinking-water

Hagedorn, C., Blanch, A. R. & Harwood, V. J., 2011. *Microbial Source Tracking: Methods, Applications, and Case Studies..* s.l.:s.n.

Hancock, C. M. et al., 1996. Assessing plant performance using MPA.. *Journal of American Water Works Association,* pp. 24 - 34.

Hannouche, A. et al., 2011. Relationship between turbidity and total suspended solids concentration within a combined sewer system.. *Water Science Technology,* pp. 2445 - 2452.

Hargesheimer, E. E. & Lewis, C. M., 1995. A Practical Guide to On-line Particle Counting. AWWA. *AWWA Research Foundation.*

Hassan, E. M. et al., 2020. A review of Cryptosporidium spp. and their detection in water. *Water Science and Technology,* pp. 1 - 25.

Hemati, S. et al., 2022. Occurrence of Giardia and Cryptosporidium in effluents of urban wastewater treatment plants: A global systematic review and meta-analysis. *Journal of Cleaner Production,* Volume Volume 378.

Hernández-Castro, C. et al., 2022. First report of rodent-adapted Cryptosporidium wrairi in an immunocompetent child, Spain. *Parasitology Research,* 121(10).

Hijnen, W. et al., 2010. GAC adsorption filters as barriers for viruses, bacteria and protozoan (oo)cysts in water treatment.. In: s.l.:Water Research, pp. 1224-34.

Horne, S., Sibal, B., Sibal, N. & Green, H. K., 2017. Cryptosporidium outbreaks: identification, diagnosis, and management.. *British Journal of General Practice,* pp. 425 - 426.

Huang, J. et al., 2023. Cryptosporidium equi n. sp. (Apicomplexa: Cryptosporidiidae): Biological and genetic characterisations. *Int J Parasitol.,* 53(10), pp. 545-554.

Hunter, P., Hughes, S., Syed, Q. & Woodhouse, S., 2004. *A Case-Control Study of Sporadic Cryptosporidiosis,* Norwich, Norfolk: s.n.

Hunter, P. R. et al., 2007. Correlation between Subtypes of Cryptosporidium parvum in Humans and Risk. *Emerging Infectious Diseases,* pp. 82 - 88.

Hunter, P. R. & Nichols, G., 2014. Epidemiology and clinical features of Cryptosporidium infection in immunocompromised patients. *Clinical Microbiology Reviews,* pp. 581 - 589.

Hunter, P. & Thompson, A., 2005. The zoonotic transmission of Giardia and Cryptosporidium. *Internation Journal of Parasitology.*

Innes, E. A., Chalmers, R. M., Wells, B. & Pawlowic, M. C., 2020. A One Health Approach to Tackle Cryptosporidiosis. *Trends in Parasitology,* pp. 290 - 303.

Innes, E. & Wells, B., 2021. *Protecting water catchments from zoonotic Cryptosporidium parasites.* [Online]
Available at: https://sefari.scot/blog/2021/03/22/protecting-water-catchments-from-zoonotic-cryptosporidium-parasites#:~:text=Fencing%20of%20livestock%20away%20from,faecal%20matter%20into%20water%20courses.
[Accessed 14 November 2023].

Isha Khedikar, A. A. P., 2016. Overview of Water Disinfection by UV Technology -A Review. *IJSTE - International Journal of Science Technology & Engineering.*

Jacangelo, J. G., Adham, S. S. & Laine, J. M., 1996. Mechanism of Cryptosporidium, Giardia and MS2 removal by MF and UF.. *Journal of American Water Works Association ,* p. 121.

Jain, S., Costa Melo, T. G., Dolabella, S. S. & & Liu, J., 2019. Current and emerging tools for detecting protozoan cysts and oocysts in water.. *TrAC Trends in Analytical Chemistry,* Volume 121, p. 115695.

Khan Academy, 2023. *Khan Academy.* [Online]
Available at: https://www.khanacademy.org/science/ap-biology/gene-expression-and-regulation/biotechnology/a/polymerase-chain-reaction-pcr
[Accessed November 2023].

Khorana, S., 2018. Recognition of cryptosporidiosis in immunocompromised patients.. *British Journal of General Practice.*

Kokkinos, P., Venieri, D. & Mantzavinos, D., 2021. Advanced Oxidation Processes for Water and Wastewater Viral Disinfection. A Systematic Review. *Food and Environmental Virology,* pp. 283-302.

Kotloff, K. L. et al., 2013. Burden and aetiology of diarrhoeal disease in infants and young children in developing countries (the Global Enteric Multicenter Study, GEMS): a prospective, case-control study. *The Lancet,* pp. 209 - 222.

Kváč, M. et al., 2025. The first appearance of the zoonotic parasite Cryptosporidium mortiferum in human and tree and ground squirrels in Central Europe. *Emerging Microbes & Infections,* 14(1).

Lamb, N. S. T., 2015. Controlling Cryptosporidium in Vulnerable Catchments used for Drinking Water Supply. *Cranfield Water Science Institute.*

Leoni, F. et al., 2006. enetic analysis of Cryptosporidium from 2414 humans with diarrhoea in England between 1985 and 2000.. *Journal of Medical Microbiology,* pp. 703 - 707.

Lind, C. B., 1997. Particle counts can benefit from changes in coagulant programs.. *Water Engineering and Management,* pp. 26 - 28.

Lines, C., 2005. *Outbreak of cryptosporidiosis in North West Wales,* North West Wales: Anglesey County Council, Anglesey Local Health Board, Centre for Research into Environment and Health Dwr Cymru, Gwynedd County Council, Gwynedd Local Health Board, National Public Health Service for Wales.

Liu, Y. et al., 2023. Rapid detection of Cryptosporidium spp. in diarrheic cattle feces by isothermal recombinase polymerase amplification assays.. *Heliyon,* 9(10), p. e20794.

Li, Y. et al., 2021. CRISPR/Cas12a-powered immunosensor suitable for ultra-sensitive whole Cryptosporidium oocyst detection from water samples using a plate reader. *Water research,* Volume 203.

Luka, G. et al., 2022. Comprehensive review of conventional and state-of-the-art detection methods of Cryptosporidium.. *Journal of Hazardous Materials,* p. 126714.

Malpas, C. et al., 2008. Contaminated Water - Task and Finish Group. *Overview & Scrutiny Committee 2: Housing and Enviroment,* pp. 3-12.

Martzy, R. et al., 2019. Challenges and perspectives in the application of isothermal DNA amplification methods for food and water analysis.. *Analytical and Bioanalytical Chemistry,* pp. 1695 - 1702.

Metcalf & Eddy, I., 2014. *Wastewater Engineering: Treatment and Resource Recovery..* Boston, USA: McGraw-Hill.

Morris, B. & Cunningham, J., 2005. The 1999 Cryptosporidium risk assessment exercise in england and wales- a groundwater overview.. *Water and Environment,* pp. 238 - 247.

Morris, B. L. & Foster, S. D., 2000. Cryptosporidium contamination hazard assessment and risk management for British groundwater sources.. *Water Science and Technology,* pp. 67 - 77.

Mthethwa, N. P. et al., 2022. luorescence and colorimetric LAMP-based real-time detection of human pathogenic Cryptosporidium spp. from environmental samples. *Acta Tropica,* Volume 235.

Mudanyali, O., Oztoprak, C., Tseng, D. E. A. & Ozcan, A., 2010. Detection of waterborne parasites using field-portable and cost-effective lensfree microscopy. *Lab on a Chip,* 10(18), pp. 2419 - 2423.

Mudanyali, O. et al., 2010. Detection of waterborne parasites using field-portable and cost-effective lensfree microscopy.. *Lab on a Chip 10,* Volume 18, pp. 2419 - 2423.

Nadir, M., 2020. *Feedwater Parameters: Assessing RO & NF Feed Water Quality. Technical Service Guide.* [Online]
Available at: https://www.microdyn-nadir.com/wp-content/uploads/TSG-C-010-Feed-Water-Parameters-Assessing-RO-NF-Feed-Water-Qualit

Nascimento, M., Ginoris, Y. P. & Brandão, C. C. S., 2020. Cryptosporidium Oocysts Removal by Upflow Direct Filtration: Pilot Scale Assessment. In: s.l.:Department of Civil and Environmental Engineering, University of Brasilia, p. 1328.

Nazih K. Shammas, L. K. W., 2016. *Water Engineering: Hydraulics, Distribution and Treatment.* New Yersey, USA: Wiley & Sons Inc..

Notomi, T. et al., 2000. Loop-mediated isothermal amplification of DNA.. *Nucleic Acids Research ,* p. e63.

Okhuysen, P. C., Chappell, C. L. C. J. H., Sterling, C. R. & DuPont, H. L., 1999. Virulence of three distinct Cryptosporidium parvum isolates for healthy adults. *Journal of Infetious Disease,* pp. 1275 - 1281.

Ongerth, J. E. & Pecoraro, J. P., 1995. Removing Cryptosporidium using multimedia filters.. *Journal of American Water Works Association,* pp. 83 - 89.

Ongerth, J. E. & Saaed, F. M. A., 2020. Multiplex LAMP for Simplified Monitoring Cryptosporidium and Giardia in Surface Water. *Cold Spring Harbor Laboratory..*

Phillips, A. D., Thomas, A. G. & Walker-Smith, J. A., 1992. Cryptosporidium, chronic diarrhoea and the proximal small intestinal mucosa. *Gut,* pp. 1057 - 1061.

Plummer, J. D., Edzwald, J. K. & Kelley, M. B., 1995. Removing Cryptosporidium by dissolved air floatation. *Journal of American Water Works Association,* pp. 85-95.

Powell, N., 1996. Membrane microfiltration for municipal water treatment. *Membrane Technology,* pp. 7 - 9.

Prasad, M. N. V. & Grobelak, A., 2020. *Waterbourne Pathogens: Detection and Treatment.* 1st ed. s.l.:Butterworth-Heinemann.

Puleston, R. L. et al., 2013. The first recorded outbreak of cryptosporidiosis due to Cryptosporidium cuniculus (formerly rabbit genotype), following a water quality incident. *Journal of Water and Health,* pp. 41 - 50.

Puleston, R. et al., 2014. The first recorded outbreak of cryptosporidiosis due to Cryptosporidium cuniculus (formerly rabbit genotype) following a water quality incident. *Journal of Water and Health,* 12(1).

Richardson, A. J. et al., 1991. An outbreak of waterborne cryptosporidiosis in Swindon and Oxfordshire. In: *Epidemiology and Infection.* s.l.:Cambridge University Press, pp. 485-495.

Rink, M., 2017. *Report of the Drinking Water Inspectorate's Investigation into the Cryptosporidium Contamination of Franklaw Treatment Works in August 2015 ,* s.l.: Drinking Water Inspectorate.

Risby, H. et al., 2023. Application of a new multi-locus variable number tandem repeat analysis (MLVA) scheme for the seasonal investigation of Cryptosporidium parvum cases in Wales and the northwest of England. *Current Research in Parasitology & Vector-Borne Diseases,* 4(100151).

Robinson, G., Elwin, K., Jones, M. & Chalmers, R. M., 2023. A comparison of qPCR and microscopy for the detection and enumeration of Cryptosporidium oocysts from drinking water. *Journal of Medical Microbiology,* 72(6).

Robinson, G. et al., 2022. Validation of a multilocus genotyping scheme for subtyping Cryptosporidium parvum for epidemiological purposes.. *Waterborne Parasitology,* Volume 27, p. e00151.

Robinson, G. et al., 2022. Validation of a multilocus genotyping scheme for subtyping Cryptosporidium parvum for epidemiological purposes.. *Food and Waterborne Parasitology,* Volume 27, p. e00151.

Rügner, H. et al., 2013. Turbidity as a proxy for total suspended solids (TSS) and particle facilitated pollutant transport in catchments.. *Environmental Earth Sciences,* 69(2), pp. 373-380.

Ryan, U., Fayer, R. & Xiao, L., 2014. Cryptosporidium species in humans and animals: current understanding and research needs.. *Parasitology,* pp. 1667 - 1685.

Ryan, U., Feng, A. & Xiao, L., 2021. An Update on Zoonotic Cryptosporidium Species and Genotypes in Humans. In Animals. *Animals,* p. 3307.

Ryan, U. M., Fayer, R. & Xiao, L., 2021. Taxonomy and molecular epidemiology of Cryptosporidium and Giardia – a 50 year perspective.. *International Journal for Parasitology,* pp. 1099 - 1119.

Sharma, K., Srivastava, S. & Tak, V., 2023. Cryptosporidiosis in India and the World: A Review. In Infectious Disorders - Drug Targets. *Infectious Disorders - Drug Targets.*

Silverlås, C., Mattsson, J. G., Insulander, M. & Lebbad, M., 2012. Zoonotic transmission of Cryptosporidium meleagridis on an organic Swedish farm. *International Journal of Parasitology,* pp. 963 - 967.

Stadterman, K. L., Sninsky, A. M., Sykora, J. L. & Jakubowski, W., 1995. Removal and inactivation of Cryptosporidium oocyst by activated sludge treatment and anaerobic digestion. *Water, Science and Technology,* Volume 31.

Sturdee, A. P., Bodley-Tickell, A. T. & Kitchen, S. E., 1998. Cryptosporidium in farmed and wild animals and in the implicatons for water contamination.. *Ministry of Agriculture, Fisheries and Food Project CSA2783 Final Report..*

Suarez, P., Alonso, J., Gómez, G. & Vidal, G., 2022. *Performance of sewage treatment technologies for the removal of Cryptosporidium sp. and Giardia sp.: Toward water circularity.,* s.l.: J Environ Manage.

SUEZ, 2021. [Online]
Available at: https://www.suezwaterhandbook.com/

Sunnotel, O. et al., 2010. Photocatalytic inactivation of Cryptosporidium parvum on nanostructured titanium dioxide films. *Journal of Water and Health,* 8(1), pp. 83 - 91.

Takahashi, K. et al., 2020. Efficacy of ultraviolet light-emitting diodes (UV-LED) at four different peak wavelengths against Cryptosporidium parvum oocysts by inactivation assay using immunodeficient mice.. *Parasitology International,* Volume 102108, p. 77.

The Envionment Agency, 2010. The Microbiology of Drinking Water - Part 14 - Methods for the isolation, identification and enumeration of Cryptosporidium oocysts and Giardia cysts.

U. S. Environmental Protection Agency (EPA), 2005. Method 1623: Cryptosporidium and Giardia in Water by Filtration/IMS/FA..

U. S. Environmental Protection Agency (EPA), 2012. Method 1623: Cryptosporidium and Giardia in Water by Filtration/IMS/FA.

UKWIR, 1998. *Guidance Manual Supporting Water Treatment Recommendations from the Badenoch Group of Experts on Cryptosporidium (98/DW/06/5)..* s.l.:UK Water Industry Research Limited. London, UK.

United States Enviromental Protection Agency , 2006. *Ultraviolet Disinfection Guidance Manual for the Final long term 2 Enhanced Surface Water Treatment Rule ,* Pennsylvania: Office of Water .

United States Enviromental Protection Agency , 2020. *Disinfection Profiling and Benchmarking - Technical Guidance Manual,* USA: Office of Water, United States Enviromental Protection Agency.

United States Enviromental Protection Agency, 1999. *Wastewater Technology Fact Sheet - Ultraviolet Disinfection,* Washington, D.C, USA: Office of Water, United States Enviromental Protection Agency.

United States Enviromental Protection Agency, 2020. *Disinfection Profiling and Benchmarking - Technical Guidance Manual,* s.l.: Office of Water.

USEPA, 2006. *National Primary Drinking Water Regulations: Long Term 2 Enhanced Surface Water Treatment Rule,* s.l.: s.n.

van Dijk, 2007. *Drinking Water Treatment Technology.* The Netherlands.: Sanitary Engineering Department, Faculty of Civil Engineering, Delft University of Technology,.

Villacorta-Martinez de Maturana, I., Ares-Mazás, M. E., Duran-Oreiro, D. & Lorenzo-Lorenzo, M. J., 1992. fficacy of Activated Sludge in Removing Cryptosporidium parvum Oocysts from Sewage.. *Applied and Environmental Microbiology,* 58(28), pp. 3514-3516.

Betancourt, W.Q. & Rose B. Q., 2004. Veterinary Parasitology. In: *Drinking water treatment processes for removal of Cryptosporidium and Giardia.* Michigan, USA: Department of Fisheries and Wildlife, Michigan State University, pp. 219-234.

Wang, Z., Vora, G. J. & Stenger, D. A., 2004. Detection and Genotyping of Entamoeba histolytica, Entamoeba dispar, Giardia lamblia, and Cryptosporidium parvum by Oligonucleotide Microarray. *Journal of Clinical Microbiology,* p. 3262 –v3271.

West, A. O. & Scott, J. T., 2016. Black disk visibility, turbidity, and total suspended solids in rivers: A comparative evaluation.. *Limnology and Oceanography,* pp. 658 - 667.

WHO, 2009. *Risk Assessment of Cryptosporidium in Drinking Water,* s.l.: s.n.

WHO, 2014. *Guidelines for drinking-water quality: fourth edition incorporating the first addendum.* Geneva: World Health Organisation .

WHO, 2023. *Water safety plan manual: step-by-step risk management for drinking-water suppliers, 2nd ed,* s.l.: s.n.

Widerström, M. et al., 2014. Large Outbreak of Cryptosporidium hominis Infection Transmitted through the Public Water Supply, Sweden. *Emerging Infectious Diseases,* pp. 581 - 589.

Woolsey, I. et al., 2019. *Anti-protozoal activity of extracts from chicory (Cichorium intybus) against Cryptosporidium parvum in cell culture,* s.l.: Scientific Reports.

WSAA, 2015. *Manual for the application of health-based targets for drinking water safety,* s.l.: Water Services Association of Australia.

Xiao, L., 2010. Molecular epidemiology of cryptosporidiosis: An update. In Experimental Parasitology. *Experimental Parasitology,* pp. 80 - 89.

Xiao, L. & Feng, Y., 2017. Molecular epidemiologic tools for waterborne pathogens Cryptosporidium spp. and Giardia duodenalis.. *Food and Waterborne Parasitology,* pp. 14 - 32.

Yu, F. et al., 2021. CRISPR/Cas12a-based on-site diagnostics of Cryptosporidium parvum IId-subtype-family from human and cattle fecal samples. *Parasites and Vectors,* 208(1).

Zahedi, A. et al., 2016. Public health significance of zoonotic Cryptosporidium species in wildlife: Critical insights into better drinking water management.. *International Journal for Parasitology,* pp. 88 - 109.

3rd Floor
11 Westferry Circus, Canary Wharf
London
E14 4HD

wsp.com