The Environmental Protection Agency

EPA DRINKING WATER ADVICE NOTE
Advice Note No. 9:
Cryptosporidium Sampling & Monitoring

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1 INTRODUCTION

The EPA commissioned a study of best international practice for monitoring of *Cryptosporidium* in drinking water. The report from the study contained in Appendix 1 summarises international case studies and proposes a number of recommendations aimed at water service authorities (WSA) in Ireland.

In particular the report reviews:

- The factors to consider when developing a programme for monitoring *Cryptosporidium* for raw and treated waters being used for human consumption;
- The sampling and analysis methods that are appropriate for both raw and treated waters;
- The monitoring frequencies of raw and treated waters used internationally for *Cryptosporidium*.

The appropriate monitoring frequency for *Cryptosporidium* is dependent on the quality and the risk category of the source water in addition to the effectiveness of the treatment barrier. The report makes recommendations in relation to the development of appropriate monitoring programmes, including monitoring frequency, for raw and treated water used for human consumption for *Cryptosporidium* for different scenarios including the source, treatment type, population and overall risk.

While there is no standard for *Cryptosporidium* in Ireland, the *European Communities (Drinking Water) (No. 2) Regulations 2007* requires water suppliers to ensure that *"water is wholesome and clean and meets the requirements of the Regulations"*. Furthermore, the Regulations state that water must be free from any micro-organisms or parasites which *"constitute a particular danger to human health"*. To achieve this, WSA should use a risk based method to develop appropriate monitoring programmes for *Cryptosporidium* in their water supplies.

2 DRINKING WATER SAFETY PLAN APPROACH

The attached report considers case studies of international and Irish outbreaks of Cryptosporidiosis. Common to many of these outbreaks were factors such as unidentified source contamination, inadequate treatment including lack of barriers; and lack of knowledge of relevant factors (e.g. changes in water quality or characteristics).

The EPA has published an advice note on the development of a drinking water safety plan. This provides a framework within which the risk of *Cryptosporidium* can be assessed and therefore should enable decisions to be taken on a suitable monitoring programme.

The Water Safety Plan approach enables a WSA to:

a. Assess the risk of the water source to contamination by *Cryptosporidium* using the EPA publication "Drinking Water Regulations Guidance Booklet No. 4- Risk Screening Methodology for *Cryptosporidium*" as a starting point.

b. Describe the potential vulnerabilities of the water treatment and supply systems, for example validation of UV systems for inactivation of *Cryptosporidium* oocysts.

c. Control and operate the treatment processes using the following.

- **i.** Appropriate monitoring for each stage of treatment, e.g. continuous turbidity monitoring or particle counters on each filter to determine the effectiveness of the filtration process.
- **ii.** Appropriate alarm levels established for each stage of treatment.
- **iii.** Robust procedures to ensure effective response to alarms and monitoring results.

d. Validate and monitor control measures which are introduced, with appropriate responses planned to address developing problems.

These measures may be assessed during future audits carried out by the EPA.

3 SAMPLING AND MONITORING

The EPA's *"Advice Note No. 5 Turbidity in Drinking Water"* provides advice to a WSA in relation to the monitoring of turbidity. The report in Appendix I recommends that continuous turbidity monitors or particle counters should be used to monitor the effectiveness of each filter.

The interpretation of results of routine monitoring of *Cryptosporidium* poses difficulties such as the assessment of public health significance, as not all species are pathogenic or as virulent as *C. hominis* or *C. parvum*. Demonstration of viability is slow and expensive. Therefore protection of the source catchment and the optimization of the treatment system should be a priority.

Sampling of raw waters for *Cryptosporidium* oocysts should be designed on a site specific basis, having regard to such factors as activities in the catchment, level of treatment provided by the plant, turbidity levels, or detections of other parameters indicative of faecal contamination. Representative sampling of treated water for Cryptosporidium requires a continuous sample over 24 hours of 1,000 litres.

While it may be possible to design a template sampling programme for all water supplies county wide, this should be used with care and site specific plans will be more representative, having regard to the guidance in Appendix A of the attached report. To clarify the sampling protocol listed in Appendix A, the EPA considers that where a system supplies 5,000 to 10,000 people with a high or extremely high Cryptosporidium risk score, the cost of monitoring versus the cost of providing suitable remedial measures should be evaluated. Such remedial measures should be provided within one year (i.e. the same timeframe as the sampling programme).

Where oocysts are detected, the WSA must consult with the HSE to assess whether there is a danger to public health and agree appropriate actions. In the case of UV treatment where oocysts may still be detected it is important that the WSA can demonstrate whether the oocysts are active or inactive. The UV system should be verified having regard to *Advice Note No.3 - E. coli in Drinking Water* and the shortly to be published *Water Treatment Manual on Disinfection*.

The EPA, through STRIVE, is currently funding a research project on Developing a *Cryptosporidium* Monitoring Protocol. The first phase of the project involved a survey of 31 WSAs to assess current *Cryptosporidium* monitoring practice in a selection of drinking water supplies within their functional area. The report summarising this survey will be made available on the EPA website upon completion. Further work within the project scope includes the establishment of a Cryptosporidium test laboratory at the Backweston Veterinary Laboratory at Abbotstown Dublin 15,. The project team will also develop a standard operating procedures manual for the monitoring of *Cryptosporidium* oocysts in drinking water.

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APPENDIX A

Cryptosporidium Monitoring in Drinking Water - Best International Practice

by John Gray

EXECUTIVE SUMMARY

There are numerous animal vectors whereby *Cryptosporidium* may gain access to water sources, and in some instances, to treated water. Key features of some 51 incidents involving cryptosporidiosis in the community between 1984 and 2009 are summarised and common issues identified. Outbreaks of other microbiological waterborne disease may offer learning opportunities. Most incidents arose through contamination of source waters, deficiencies in treatment or ignorance of relevant factors.

Multiple barriers are important in preventing the occurrence of *Cryptosporidium* in treated water supplies. A source of good quality water should be protected by active efforts to establish and maintain a catchment protection policy. Although initially of good quality, a source may not necessarily remain so and routine operational monitoring is required to inform of any deterioration. Appropriate treatment must be in place and operated according to design criteria.

Significant changes in water quality either at source or during or after treatment must be detected by appropriate monitoring and acted upon. Factors that might impinge adversely on water quality, include environmental, hydrological and climatic conditions.

An overview is presented of treatment processes, including clarification and filtration, and critical points are identified. Efficient removal of particulate matter is important since *Cryptosporidium* oocysts are small particles and are not susceptible to many of the disinfection systems currently installed. Alternative disinfection systems include ozonation, UV light, membrane filtration and chlorine dioxide.

Continuous monitoring for bacteriological and other microbiological parameters, including *Cryptosporidium*, is not possible. The determination of surrogate other parameters such as turbidity or particle counts, may give information on the effectiveness of particle separation processes.

The application of risk management plans is vital in the identification of potential sources of contamination. The risk assessment method developed by the Ministry of Health in New Zealand is recognised as a benchmark of well-recognised global approaches.

The water safety plan approach as proposed by the World Health Organisation has been adopted by many countries and the Australian framework for management of drinking water quality is one useful approach. Application of the method approach to water catchments, treatment works, distribution systems and consumer installations could be considered part of the multiple-barrier approach.

Generally, European countries follow the WHO guidance. The US, Canada, New Zealand and Australia have their own standards. Most countries do not require regulatory monitoring for *Cryptosporidium* and treatment criteria have been adopted with monitoring of surrogate parameters.

The USEPA has introduced a robust analytical system for *Cryptosporidium* based on filtration, magnetic bead separation and antibody recognition.

Recommendations are made to incorporate key findings in future operations and water supply.

1 BACKGROUND

This report has been prepared to meet the requirements of the Office of Environmental Enforcement (OEE) for the provision of assistance to review and report on best international practice in relation to monitoring for *Cryptosporidium* in waters used for human consumption.

The European Communities (Drinking Water) Regulations (No.2) 2007 came into force in March 2007. The Environmental Protection Agency (EPA) then became the supervisory authority of public water supplies with new enforcement powers to ensure, by means of a legally binding direction on the relevant local authority, that in the event of a deficiency in drinking water quality, the local authority takes remedial action. Under the Regulations, the EPA has a responsibility to audit local authority water treatment plants. Priorities and targets for the EPA in 2008 are set out in the Authority's annual enforcement plan.

The EPA issued on 22 January 2008 Booklet No.4 entitled Risk Screening Methodology for *Cryptosporidium* and considers this methodology as a pre-cursor to the application of a Drinking Water Safety Plan approach to the management of drinking water. The World Health Organisation (WHO) has set out three essential components to a water safety plan: a risk assessment of the water supply; effective operational monitoring; and effective management. Consideration of best international practice will allow the development of a robust monitoring strategy.

This report makes recommendations in relation to the development of appropriate monitoring programmes for raw and treated water used for human consumption for *Cryptosporidium* for different water supply scenarios in Ireland. It:

- reviews the factors to consider when developing a programme for monitoring *Cryptosporidium* for raw and treated waters being used for human consumption;
- reviews the sampling and analysis methods that are appropriate for both raw and treated waters;
- reviews the monitoring frequencies of raw and treated waters being used internationally for *Cryptosporidium*; and
- makes recommendations in relation to the development of appropriate monitoring programmes, including monitoring frequency, for raw and treated water used for human consumption for *Cryptosporidium* for different scenarios including but not limited to the source, treatment type, population and overall risk.

2 INTRODUCTION

Cryptosporidium parvum and _Cryptosporidium_ hominis are among the medically important _Cryptosporidium_ species. _C. parvum_ was first implicated as a cause of human disease in 1976 but it was not until an outbreak in 1984 in Braun Station in Texas that cryptosporidiosis was recognised as a waterborne disease. _C. parvum_ occurs in the intestines of warm-blooded animals and the normal hosts and reservoirs of the obligate parasite include humans, domestic animals including cattle and pigs, birds and reptiles. Two genotypes were identified: _C. parvum_ genotype 1 which apparently only causes infection in humans and _C. parvum_ genotype 2 which may cause infections in both humans and animals (1).

C. hominis (previously *C. parvum* genotype 1) is an obligate parasite of humans that can colonize the gastrointestinal tract causing gastroenteritis and diarrhoea. *C. hominis* is almost exclusively a parasite of humans and thus has a low zoonotic potential compared to *C. parvum*. It may be transmitted through the faecal-oral route via contaminated drinking water. *C. hominis* and *C. parvum* have identical oocyst morphology and life-cycle and are usually differentiated by genetic analysis.

An outbreak in 2007 of cryptosporidiosis in the Northampton and Daventry area was associated with the ingress of a rabbit into the treated water contact tank. Genotyping of a number of water samples taken from the distribution system and stool samples from consumers affected during the incident, confirmed that they all belonged to the same rabbit genotype. Accordingly, this genotype should now be regarded as a human pathogen (2). There are a number of animal host-specific strains that have been detected in water but their significance to human health has not been established (3) (4) (5). Some 15 species of *Cryptosporidium* have been recognised (6)

Cryptosporidium survives in the environment as an oocyst, approximate size between 4 and 6 µm. The thick double wall of the oocysts allows them to survive in cold, moist conditions for several months. They are however, susceptible to heat and desiccation. Oocysts may be found in both surface and ground waters. Typical concentrations of *Cryptosporidium* oocysts in raw sewage are between 103 and 104 per litre and in secondary treated effluent between 10 and 103 per litre (7). Reported concentrations of oocysts in surface water range between 0.01 and 100 per litre (8).

The incubation time for cryptosporidiosis is generally estimated to be seven days but has been reported to be as low as one day and as long as 28 days. In two volunteer studies, the median infective dose was reported as 30 and 132 oocysts. Subsequent studies have indicated infective doses of as low as 10 or as high as 1000, depending on the strain. Haas and Eisenberg (9) consider the technique of microbial risk assessment and tabulated best-fit dose response parameters for a number of pathogens including *Cryptosporidium*. MacGill et al (in (9)) used the example of *Cryptosporidium* in drinking water and reported a variety of risk assessment results. It has been calculated that to account for the level of illness seen during the Milwaukee outbreak, consumers would have been exposed to between 0.42 to 4.5 oocysts per litre (10)

Major instances of cryptosporidiosis often occur in spring with a smaller autumn peak. The spring peak has been attributed to lambing, calving and runoff of spring rain and the autumn peak to the return of travellers from overseas during summer. It is interesting to note that the spring peak in 2001 was markedly attenuated compared with previous years which fact is considered consistent with a zoonotic contribution to the spring peak. Foot and Mouth Disease controls were in place at the time reducing exposure to animals and the rural environment (11) .

3 OVERVIEW OF SIGNIFICANT DRINKING WATER INCIDENTS INVOLVING CRYPTOSPORIDIUM

3.1 INTRODUCTION

Waterborne disease can be associated with a number of organisms in addition to *Cryptosporidium*. Waterborne pathogens known to have caused gastrointestinal illness in humans include E.coli 0157:H7, Salmonella, Shigella, Campylobacter jejuni, enteric viruses such as Hepatitis A, and protozoa such as *Cryptosporidium*, Giardia and Toxoplasmosis gondii. Emerging pathogens include Norovirus, Legionella, Mycobacterium avium complex, Aeromonas hydrophila and Helicobacter pylori. Cyanobacteria produce toxins which, during periods of algal blooms, may have an adverse effect on human health.

Only significant incidents involving an increase in the number of cases of cryptosporidiosis in the community that are associated with drinking water supplies will be considered here although incidents involving other microbiological species may also provide opportunities for learning from deficiencies that impact adversely on public health. Other sources of outbreaks of cryptosporidiosis such as food and recreational waters are not considered here. Information has been taken from a number of published sources including Bouchier (12), Hrudey and Hrudey (13), Fayer (14), as well as web-based sources such as Water Quality Research Australia, CRC Reports, USEPA and UK Water Industry Research. Annual reports on drinking water quality in England and Wales published by the Drinking Water Inspectorate identify for each year the number of incidents involving *Cryptosporidium* (15). Data for the period 1997-2009 is given in Table 1. Because of a different reporting regime, detailed information on each incident in early years is not readily available. The increase in incidents toward the end of the period may similarly be attributed to changes in reporting requirements not necessarily involving the presence of *Cryptosporidium* in water in supply.

Table 1 Number of incidents involving *Cryptosporidium* in England and Wales 1997-2009

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008
No. of incidents	9	1	6	6	2	0	2	1	4	2	3	11

Following a survey in 1997 of 52 European countries, 19 provided information specifically on outbreaks of waterborne disease (16). Outbreaks of cryptosporidiosis were reported by only four countries, Croatia (1), England and Wales (13), Spain (1) and Sweden (1). Some 16 European countries started in 2000 to collect and report data on cryptosporidiosis cases with confirmed cases reported to the European Basic Surveillance Network (BSN) (17). Data for 2005 are presented in Table 2 below.

Table 2 Reported cases of cryptosporidiosis by country for 2005

Belgium	357	Lithuania	0
Cyprus	0	Malta	6
Czech Republic	1	Poland	0
Estonia	0	Slovakia	0
Germany	1284	Slovenia	9
Hungary	0	Spain	108
Ireland	565	Sweden	69
Latvia	0	UK	5561

A brief synopsis of the more significant recent occurrences in the UK is included.

3.2 INCIDENTS[1]

Braun Station, Texas, May to July 1984. An estimated 117 cases of cryptosporidiosis occurred following an outbreak of Norwalk virus. Treatment for the artesian well ground water comprised chlorination without filtration. Sewage contamination of the source well occurred intermittently.

Carrollton, Georgia, January to February 1987. An estimated 13,000 cases associated with a river derived surface water source which flowed through rural agricultural land. Treatment comprised coagulation with alum, sedimentation, rapid sand filtration and chlorination. Removal of fine particles was poor and the source was challenged with *Cryptosporidium* following heavy rains and potential sewage overflow. The hydraulic loading on the filters was poorly controlled and there were no proper protocols for the return of filters to service after backwashing

Saltcoats and Steventson, Scotland, March to April 1988. 27 confirmed cases. Water was derived from an impounding reservoir and treatment comprised coagulation, filtration and chlorination. Treated water was stored in a tank into which entered an old pipe which collected contaminated surface water and which was shown on plans to be sealed off. Liquid cattle manure had been spread on ground near to the tank and following heavy rains, run-off entered the pipe.

Swindon and Oxfordshire (Farmoor), UK, December 1988 to April 1989. 516 confirmed cases associated with a river derived surface water source. Treatment comprised coagulation and filtration. Fine particle removal was inconsistent and backwash water was recycled. Heavy rain preceded an increase in raw water of the number of oocysts which filtration could not remove.

Isle of Thanet, Kent, UK, December 1990 to January 1991. 47 confirmed cases. The normal ground water source was supplemented during dry weather conditions by river water and treated by alum coagulation, flotation, filtration, activated carbon and super- and de-chlorination. One of the two flotation units was not operating prior to the outbreak. No specific cause was found for the outbreak but an increased turbidity from 1 NTU to 2 NTU was noted on the filtered water from the single flotation stream over a three day period. The dosing pump was being repaired. An increase in raw water turbidity was associated with increased river flow following heavy rain.

Sweden, 1991. 600 cases of gastrointestinal illness, some with *Cryptosporidium*. A cross connection to a contaminated stream was identified.

Jackson County, Oregon, January to June 1992. An estimated 15,000 cases occurred during drought conditions in a river source. Two filtration works drew water from two sources, Bear Creek and Medford Water Commission (MWC). Bear Creek supplied surface water treated by a package plant comprising coagulation, flocculation, filtration and sedimentation followed by granular dual-media filtration, GAC filtration and chlorination. MWC water was drawn from a mountain stream which was not filtered but was chlorinated. The origin of the outbreak was initially unclear but later was attributed to Bear Creek. A discharge of treated waste water was located 7.5km upstream of the drinking water intake which in May was estimated to contribute some 30% of the total flow. There were fluctuations in turbidity.

1 An incident is a set of circumstances that, in the context of this report, lead to the presence of Cryptosporidium oocysts in drinking water and an increase in the number of cases of cryptosporidiosis in the community supplied. Most incidents occur as a result of failures or deficiencies – See Section 4. An outbreak refers to the increase in the number of cases of cryptosporidiosis and is usually associated with a particular incident.

The rapid mix unit was inoperable, the filter-rate control valves were inoperable and polymer coagulant addition was used without alum which resulted in poor turbidity removal.

Bradford, West Yorkshire, November to December 1992. 125 confirmed cases. Surface water derived from an impounding reservoir was treated by slow sand filtration and chlorination. No specific cause was identified although a slow sand filter was recommissioned prior to the outbreak and returned to service prematurely. Heavy rain led to increased turbidity in the incoming water.

Warrington, Cheshire, November 1992 to February 1993. 47 confirmed cases. Ground water sources were chlorinated before entering a service reservoir. Heavy rainfall washed drainage water from pasture ground used by livestock into the groundwater collection system. There was also a cross connection between one well shaft and a sewage leak. High turbidity had been noted on a previous occasion in the service reservoir. There was no raw water monitoring.

Kitchener/Waterloo, Ontario, February to May 1993. Over 1,000 estimated cases. Ground water sources were supplemented to the extent of 20% with surface water from a river. Treatment comprised ozonation, coagulation, flocculation, plate-settlers, sedimentation, dual media and GAC filtration and chlorination. Turbidity spikes were observed in filtered water during times of spring run-off. Recycling of supernatant water from filter backwash water was identified as a potential risk. Epidemiology did not confirm the waterborne nature of the outbreak. Ingress of wells from river bank was suspected.

Milwaukee, Wisconsin, November to December 1993. An estimated 400,000 cases. Surface water was derived from a lake and treatment at two works comprised coagulation, rapid sand filtration and chloramination. The outbreak was associated with contamination by sewage effluent of the water abstraction point in the lake. Raw water turbidity was significantly higher than normal as was treated water turbidity. A change in coagulant was made at one works from alum to polyaluminium chloride. The filtration process was not optimised.

Washington State, 1994. 86 cases. Rural water supply from a deep well with no chlorination. The well was contaminated by leakage from a rusted pipe containing treated wastewater from a piped irrigation system (18).

Torbay, South Devon, August to September 1995. 575 confirmed cases. Five sources were in use: a surface water source derived from a river; two Ranney wells in alluvial gravel; an impounding reservoir; and a second river. Treatment comprised a patented clarification process (polyelectrolyte and fine magnetite particles), rapid granular media filtration, two stand-alone flotation filtration units and chlorination. A power failure isolated one source of water at the time when there was a need for an increase in output to meet summer demand. Flood conditions on one river source resulted in increased raw water turbidity. One Ranney well source was diverted prior to the incident and was not subject to clarification. Removal of fine particles was less than optimal and sewage contamination was likely of the river or riverbank infiltration sources. There were changes in treatment prior to the incident including washing of magnetite separation media with backwash water.

Ogose Town, Saitama Prefect, Japan, June 1996. Over 9,100 estimated cases. Surface water derived from two rivers with treatment comprising polyaluminium chloride coagulation, sedimentation, rapid sand filtration and chlorination. Drought was followed by heavy rains

resulting in an increase in turbidity in the raw water. Polyaluminium chloride coagulant was added only when raw water was turbid although the value which would trigger such dosing was not defined. PAC was not added at the critical time. Two small sewage treatment works were located 400m and 1200m upstream of the river intake.

Cranbrook, BC, Canada, May to July 1996. An estimated 2000 cases. Surface water sources from creeks and a reservoir. Treatment comprised chlorination. Cattle grazed near the reservoir and increased turbidity in the raw water occurred during spring run-off.

North West London and West Hertfordshire, UK, February to March 1997. 345 confirmed cases. Ground water source from deep wells and adits in a chalk aquifer. Treatment comprised ozonation, granular activated carbon filtration and chlorination. Drought was followed by heavy rain. Oocysts were found in the raw water entering the treatment works and potential sources of contamination included livestock grazing on land overlying the aquifer and a sewage works discharge some 8km upstream of one well which was 17m from the river. Backwash water was recycled. After the two driest years for 200 years followed by rainfall at 162% above average, geological conditions may have allowed contamination of ground water.

Bushy Creek, Texas, July 1988. Up to an estimated 1500 cases. Two sources – chlorinated ground water from five wells in a limestone aquifer and a surface supply with conventional treatment comprising coagulation, flocculation, sedimentation, filtration and chloramination. Deep wells became contaminated through underground fissures by a spill of raw sewage into a stream 0.4 km upstream following drought and extreme heat. The vulnerability of the aquifer had been recognised although there was no bacteriological testing of the wells.

Sydney, Australia, July to September 1998. No cases reported in the community. *Cryptosporidium* oocysts were reported in high numbers in treated water in a succession of events. Advice to boil water was issued to three million consumers. Some eleven treatment works were involved all including filtration, disinfection and fluoridation. The largest used contact filtration with no sedimentation between coagulation and single media high-rate filters. Although issuing advice to boil water was deemed appropriate, deficiencies identified at treatment works included surges in flow in inlet channels which scoured sediment deposits, loss of dilution water affecting coagulant dosing, recycling of backwash water, off-line treatment of backwash water was inadequate, long filter runs and minimised dosage of coagulant. It is possible that the oocysts in the system were not viable or that their numbers were overestimated (8).

Guadarrama, Madrid, Spain, 1998. 21 cases. No *Cryptosporidium* detected in water supply although deficiencies in treatment were noted (but not reported).

Clitheroe, Lancashire, March 2000. 58 confirmed cases. Ground water derived from springs supplying a collection reservoir. Treatment comprised chlorination and microstraining but no filtration. Supply was supplemented on occasion with water from another system. The spring supply was considered to be dependent on rainfall and hence under the influence of surface inflow and any potential contamination. Spring chambers were damaged allowing ingress by runoff contaminated by manure following heavy rain and flooding. Cattle faeces was present around and in contact with spring collection chambers and manure had been spread within 5m of a wellhead. The mandatory risk assessment required by UK regulations did not identify deficiencies in system security.

Glasgow, November 2001. Approximately 90 cases. It was suggested that sheep grazing adjacent to Loch Katrine, from which water was abstracted, was the source of the oocysts. Treatment at Milngavie works was to be upgraded to full microfiltration.

Dracy Le Fort, Burgundy, France, 2001. 563 cases. *Cryptosporidium* found in water supply. No details published.

Belfast, NI, April and August 2000 and April 2001. 129, 117 and 191 confirmed cases respectively for each of three outbreaks. A surface water source was treated by filtration. The bovine strain of *Cryptosporidium* was involved in the first incident and the human strain in the other two. The August 2000 outbreak involved a works where treatment comprised slow sand and rapid gravity filtration followed by chlorination. Contamination occurred of a water main between the works and a service reservoir running under farmland and was attributed to septic tank seepage. The April 2001 outbreak involved a works where treatment comprised rapid gravity filtration followed by slow sand filtration. Potential sources of oocysts included leaking sewage associated with a blocked sewer near to a leaking supply pipe. The most likely cause was considered to be cable ducts running from sewer manholes to the slow sand filters which were not draining freely and could permit contaminated water to enter the filters. Holes were noted in the filter bed where the underdrain system was damaged.

Mullingar, 2001. 26 cases in the community. Surface water sources derived from Lough Owel, a spring water fed lake considered to be of pristine quality. Treatment comprised removal of gross solids, disinfection and fluoridation (19) (20) (21). The vulnerability of the catchment was assessed as mostly 'extreme' and 'high' and the groundwater was considered to be a potentially significant pathway for contamination. Risk assessments carried out at the time identified potential sources of pollution from agriculture and there was heavy rain in April which may have increased surface water runoff. The true incidence of cryptosporidiosis was unknown at the time (22). Despite the installation in December 2003 of a filtration system, further cases in the same region were noted in June 2004 during a period of high demand. The system could not cope with increased turbidity and unfiltered water was mixed with filtered water at a ratio of 1:4. Daily testing for *Cryptosporidium* had been initiated at the start of the blending period.

North Battleford, Saskatchewan, Canada, March to April 2001. Surface water was derived from a river. Treatment comprised potassium permanganate dosing to control taste and odour, alum coagulation with polyaluminium chloride in spring and summer, lime for pH adjustment, polymer coagulant as filtration aid, anthracite-sand filtration and chlorination. Up to an estimated 7,100 cases. Fine particle removal was poor and there was a sewage works discharge some 3.5km upstream of the river intake. Maintenance of an upflow clarifier in March 2001 was followed by poor turbidity removal. Raw water quality issues had been previously recognised.

Glasgow, August 2002. *Cryptosporidium* found in water in supply from Mugdock reservoir, Milngavie following heavy rain and flooding.

Edinburgh, August 2002. *Cryptosporidium* found in water in supply following failure of filtration.

Ennis, Ireland, 2003, 2005 and 2008. Assessed as high risk for *Cryptosporidium*. A spring source was influenced by surface water and was not fully filtered although it was disinfected using chlorine. A multi-barrier treatment has been proposed, due for completion in 2009.

Portsmouth, October 2005. Some 44 cases during September 2005 mainly in the Fareham and Gosport areas. Treatment at the River Itchen works comprised full conventional treatment including coagulation, clarification, rapid gravity filtration and disinfection. Although no exceedences of the treatment standard of 1 oocyst per 10 litres were detected, the treatment works was shut down for a period of time.

Llyn Cwellyn, Wales, November 2005. 231 confirmed cases. Surface water source with inadequate treatment. Treatment comprised microstraining, pressurised sand filtration and chlorination. The works was vulnerable to turbidity and *Cryptosporidium* breakthrough under certain raw water conditions occurred due to the positioning of the raw water inlet and the lack of a coagulation stage. The catchment for the impounding reservoir had a mixture of land uses including grazing of sheep and cattle. The catchment also contained a village which discharged treated sewage to the reservoir, together with a number of houses with septic tank systems. Turbidity spikes occurred following filter washing because there was no ability to run to waste. The Report of the Outbreak Control Team (23) recommended that water suppliers should, if they have not already done so, review their risk assessments in line with advice issued by the Environment Agency. A UV disinfection system was subsequently installed.

Carlow, Ireland, December 2005 (24). 31 cases. Two surface water sources, the Slaney and Burren rivers were treated at Rathvilly and Sion Cross respectively. Treatment at Rathvilly comprised chemical coagulation, sludge blanket clarifiers, rapid gravity sand filtration, chlorination, fluoridation and pH correction. Sand filters are backwashed daily. The Sion Cross water treatment plant abstracted water from the river Burren which drained a highly agricultural basin with traditional stock watering points along the river valley and a number of sewage treatment plants upstream of the extraction point. There were two treatment streams both including chemical coagulation, rapid gravity filters, chlorination and fluoridation. In addition, one stream includes a circular flocculation tank and horizontal flow sedimentation tank while stream 2 included hopper bottom sedimentation tanks and chemical coagulation with a flash mixer. Filters were backwashed daily. Replacement of sand filters in 2004 at Sion Cross reduced the turbidity of the treated water. Treated water from both Rathvilly and Sion Cross was mixed at Brownshill reservoir before supplying Carlow town. *C. parvum*, C.andersoni and C. muris were identified in the water and *C. hominis* identified in human faecal samples. Low levels of *Cryptosporidium* (0.04 oocysts/10L) were found in treated water although there was no evidence of a breach in the water treatment process.

Otterbourne, March 2006. Surface water source where the coagulation process failed.

Portlaw, Ireland, November 2006. 8 cases (25). A spring source at Laherden supplying a storage reservoir was supplemented by a borehole. The spring was collected in a concrete tank buried in boggy ground. Treatment comprised chlorination, fluoridation and pH control.

Fairford, Gloucestershire, January 2007. Sudden rise in turbidity caused by heavy rain and a landslide. *Cryptosporidium* risk assessment reviewed.

Galway, Western Ireland, March 2007. Over 240 cases linked to water supplied form Lough Corrib. The older treatment plant did not have filtration processes adequate for removing *Cryptosporidium* oocysts. Treatment at the newer plant comprised coagulation, rapid gravity filtration and disinfection. Treated water from both plants was blended before entering supply.

Heavy rain prior to the outbreak may have washed manure from surrounding farmland into the lake following spreading of slurry (26) (27). Additionally, an upstream sewage treatment plant, originally designed to service 250 households, was receiving sewage from 800 properties.

Hull, May 2007. Deterioration in raw water quality. *Cryptosporidium* risk assessment reviewed in light of potentially reduced filter availability. A detailed water safety plan was subsequently prepared clearly setting down all the identifiable risks that could occur.

North Walsham, June 2007. Raw water contamination. Investigatory boreholes required permanent sealing to prevent any recurrence of aquifer contamination

Clonmel, Ireland, August 2007 (20). Glengarry treatment works derived water from a surface source influenced by rain. The source is to be replaced by groundwater source and treatment is to be upgraded.

Oslo, Norway, 2007. Contamination occurred in water in distribution (28). Initial reports of coliform bacteria detected in tap water samples led to an investigation which confirmed by PCR analysis the presence of *C. hominis*. Together with bacteriological findings this indicated that this was probably a post-treatment contamination event with faecal matter of human origin, possibly at a single location and probably a single incident associated with maintenance work. PCR of oocysts in a subsequent sample identified *C. parvum* which may indicate contamination from either human sources or from animals and may have been a separate incident. There was no evidence of failure in the distribution system although there was construction work in the area, work on the distribution network itself and a loss of water pressure due to fire department activity.

Berkshire, UK, January to February 2008. *Cryptosporidium* oocysts found in treated water from an underground source. Action was not taken on an uncharacteristic raw water turbidity alarm and the site should have been risk assessed as being vulnerable to flooding and *Cryptosporidium* at a time of heavy rainfall and high river levels. Further staff training was required and the event response procedure revised including the guidance for responding to alarms. All boreholes at risk of flooding were reviewed and mitigation/protection measures implemented. Turbidity alarms were reviewed.

Hertfordshire, UK, 3 February 2008. *Cryptosporidium* oocysts found in treated water. Training of operators was reviewed.

Eastbourne area, UK, 17 June 2008. *Cryptosporidium* in treated water in supply. Operational deficiencies including inadequate filtration leading to reclassification of site as very high risk for *Cryptosporidium*

Pitsford, Northampton, 25 June to July 2008. Water was drawn from a large surface reservoir, open to the public for recreational uses including fishing, sailing and windsurfing. Treatment comprised clarification, filtration, ozonation, granular activated carbon filtration and disinfection. Lack of maintenance of tank hatches/vents allowed a rabbit to gain access to treated water. All treatment and storage units were reviewed to prevent future ingress. Risk assessment methodology was reviewed to ensure the hazard was both recognised and assessed and appropriate control measures and action plans were incorporated. Access hatches and ventilators on the GAC backwash water tank were replaced to improve security and UV treatment was installed. This was the first occasion when a *Cryptosporidium* of a rabbit genotype infected humans.

Bangor, Wales, August 2008. *Cryptosporidium* detected in water supplied from Mynydd Llandygai water treatment works.

France 2009. 150 cases. Limited information on the presence of *Cryptosporidium* found in a river (29). Flood water contaminated drinking water.

4 COMMON THEMES OF WATERBORNE OUTBREAKS AND KEY ISSUES

Bouchier reviewed some 25 incidents involving outbreaks of cryptosporidiosis between April 1988 and April 1998 in the UK (12). Of these, 22 involved surface water sources including rivers, springs and impounding reservoirs. In none of the three incidents involving groundwater sources was filtration part of the treatment. The majority of incidents were associated with deficiencies in treatment or when the integrity of the treatment had been compromised. Typical contributing factors included source contamination with agricultural slurry, animal wastes or sewage effluents and high rainfall with increased turbidity in the source water. Operational factors included running filters at an excessive head or at a rate exceeding the design capacity and filter break-though. Many involved rapid fluctuations in source water quality with ground waters showing increased turbidity. Oocysts were not always detected in treated water.

Deere et al (30) identified well established sources of microbial risk at various stages of the water supply chain. The catchment could be affected by urban runoff, septic tanks, native animals, human pollution, upstream sewage treatment and grazing or domestic animals. Reservoirs and rivers are potentially affected by algal blooms, sediments and short circuiting. Treatment may be compromised by a loss of effectiveness or an event that adversely impacts on the treatment process. Water quality in the distribution system may be affected by open storage systems, pipeline growth, cross contamination and contamination arising during maintenance and consumers' taps may be subject to gross contamination

Davison et al (31) identified deficiencies in outbreaks of cryptosporidiosis in the US. These are tabulated below (adapted from Deere et al). Similar observations were made regarding outbreaks in the UK (32).

Table 3 Deficiencies occurring in cryptosporidiosis outbreaks in the US

Deficiency	Comment
Monitoring equipment for optimising filtration during periods of rapid changes in raw water	Improperly installed equipment; poor maintenance; equipment turned off, ignored or temporarily inoperative
Personnel did not respond to faulty or inoperable monitoring equipment	Deficiencies not addressed by increasing monitoring frequency or number of parameters
Filter backwash water recycled to head of works	Possibility of concentrating oocysts which may be returned to head of treatment if filtration breached
Sources of high contamination near treatment works	No mitigating barriers in place to provide protection during high runoff
Sources of *Cryptosporidium* unknown in catchment before outbreak	Knowledge of sources could have mitigated risk
Natural events may flush high numbers of oocysts into receiving waters	Heavy rain can flush oocysts into water upstream of treatment works
Filtration processes inadequate or altered	During period of high turbidity, altered or suboptimal filtration resulted in turbidity spikes and high turbidities in filtered water

A number of other reviews of the causes of outbreaks have been published (33) (34) (35) (36) with similar findings.

Detailed guidance on protecting water from source to tap using the multi-barrier approach has been published by a number of organisations (37).

As a response to learning from the failures of the past, the Australian Drinking Water Guidelines (38) were restructured to provide a comprehensive framework for the management of drinking water quality. Six guiding principles were identified for the provision of safe drinking water (13) and may be summarised as:

- Pathogens pose the greatest risk to drinking water safety;
- Robust multiple barriers are essential;
- Trouble is preceded by change;
- Operators must be capable and responsive;
- Drinking water professionals must be accountable to consumers; and
- Risk management – making sensible decisions under uncertainty.

With the exception of Accountability, these aspects are now briefly considered.

4.1 PATHOGENS

Pathogens, including *Cryptosporidium* spp. generally derive from human or animal faeces and it has been suggested that a reduction in the presence of enteric disease in the general population will reduce the risks of subsequent infection although some background pathogen presence will always persist. Health effects arising from chemical contamination of drinking water are much rarer than those associated with pathogens.

Many of the 98 incidents reviewed by Hrudey and Hrudey (13), where pathogens were present in drinking water, occurred because of the lack of treatment or an appropriate disinfection barrier. Similar issues have arisen in incidents reported elsewhere.

Contamination of the source may occur where it might be expected that routine checks on raw water quality would identify the need for appropriate treatment. Even when a good quality water source requires minimal treatment, and even when comprehensive treatment is available, contamination may also occur in storage or in distribution, for example the incident in 2007 in Oslo (28).

4.2 MULTIPLE BARRIERS

The need for multiple barriers is paramount whenever there is a risk to the quality of water sources. Reliance should not be placed on a single process, even for good quality source waters. Where, according to the historical quality of the water, there is apparently only the need for simple disinfection, protection of the source becomes another and even more vital barrier. An understanding of the catchment of the source water and the factors affecting

it are essential. Catchment studies and protection regimes are part of an overall strategy whether the source is a good quality underground source or a more suspect surface water derived from a river or an impounding reservoir. A significant number of historical outbreaks occurred because of an over-reliance on the (historically good) quality of the source water and where there is no subsequent treatment or only marginal disinfection. Too much confidence has sometimes been placed on the continuation of the historically good quality of underground waters with little knowledge of hydrological conditions in the aquifer (39).

Australia has developed a Framework for the Management of Drinking Water Quality which demonstrates commitment to the multiple barrier approach. Some twelve components are identified and discussed in detail (38):

- Commitment to drinking water quality management;
- Water supply system analysis;
- Preventative measures for drinking water quality management;
- Operational procedures and process control;
- Verification of drinking water quality;
- Management of incidents and emergencies;
- Employee awareness and training;
- Community involvement and awareness;
- Research and development;
- Documentation and reporting;
- Evaluation and audit; and
- Review and continual improvement.

Removal of microbial contaminants often requires a number of different processes, each in themselves appropriate to raise the quality of the water to meet the standards required of a drinking water supply. Removal of particulate material, which itself may be a source of contamination or which may act as a reservoir for pathogenic and other organisms, is a vital step. Not only does clarification remove the obvious suspended material, it allows for subsequent effective disinfection by removing any protective haven for microbes trapped in the material. *Cryptosporidium* is not susceptible to chlorination at the concentrations and contact times normally available in drinking water treatment works. Removal of *Cryptosporidium* oocysts requires as a starting point, removal of very small particles of suspended material by the optimisation of the filtration process.

The distribution system, comprising storage reservoirs, towers, the distribution pipes and connections, whether domestic or industrial, presents numerous opportunities for contamination. However, contamination of the distribution system is generally restricted to bacteriological and chemical contaminants rather than *Cryptosporidium*.

A multiple barrier approach comprises:

- selection of a source of good quality water and its subsequent protection to minimise potential future contamination;
- all water treatment provided must be designed, operated and maintained to achieve the outcome specified i.e. product specified not process specified;

- adequate security of the distribution system to prevent contamination and the preservation of residual disinfectant after water leaves the treatment works;
- monitoring of treatment processes to ensure control of the various processes and to provide information in a timely manner on the presence of contaminants; and
- well-conceived, thorough and effective responses in the event of contamination.

Individual barriers each reduce risk rather than eliminate risk. When used together, multiple barriers act together to reduce risk by more than the sum of the individual risk reduction. Even when one barrier fails to provide the designed/desired risk reduction, the presence of other barriers maintains a reduced level of risk.

Bellamy suggested a number of strategies to reduce pathogen risk (40) covering source water, treatment works, instrumentation and control, and distribution. Source waters should be subject to a sanitary survey to establish those areas where potential contamination may be minimised. Where appropriate, treatment at source should be provided, e.g. aeration or storage. A catchment protection policy should be established and implemented.

At the treatment works, coagulant addition and mixing should be efficient and assessed regularly through the regular use of jar tests and the assessment of mixing configurations and energies. Flocculant mixing energies and hydraulic efficiency should be assessed and, where appropriate, the use of flocculant aid considered. Coagulation and flocculation should be optimised by ensuring good hydraulic conditions in clarifiers, by minimising flow disruptions and by controlling solids. The effectiveness of subsequent filtration should be ensured by optimising coagulation, minimising sudden changes in hydraulic flow patterns (including any effects from the recycling of water), routine checking of filter media and filter (41) beds, monitoring backwash operations, continuously monitoring filter inlet and outlet water quality and considering the use of filter aids. The setting of operational standards for turbidity or particle count may also be considered.

The turbidity of raw, clarified and water leaving filters should also be monitored to inform on the effectiveness of each stage of treatment. The turbidity of filtered water from individual filters should be monitored, together with enumeration of particle counts to demonstrate effective treatment and trends in quality. The use of streaming current, pH, total organic carbon and UV light monitors may also be appropriate. The Chartered Institute of Water and Environmental Management (CIWEM) consider that UV disinfection should be part of a multi-barrier approach and not used as a single stage treatment process (42).

Plant operators should be trained in the application and control of each treatment stage and records of such training should be maintained.

Although more concerned with the maintenance of chemical or bacteriological quality rather than excluding *Cryptosporidium* oocysts, areas of the distribution system which are prone to loss of disinfectant or bacterial growth should be monitored and controlled. A programme of detection of cross-connections should be established. The system should be routinely maintained by a programme of flushing and cleaning. An asset management and capital improvement plan should be established that proactively addresses system integrity and water quality.

4.3 CHANGE

Water treatment processes are designed for continuous operation and are therefore most efficient when operating under steady state conditions. Rapid or significant change in raw water quality or in operating conditions inevitably leads to a loss of efficiency. Even when storage of raw water has been provided to minimise change, usually by means of impounding reservoirs, uncontrolled change can arise from run-off or severe precipitation. These events may also introduce contaminants at the same time as the efficiency of the treatment process decreases as a result of the change itself. Hence contaminants may be presented to a system already under significant challenge.

There is therefore a need to characterise and understand "normal" conditions so that change can be detected and acted upon. Similarly, there is a need to define "normal" change (variation) such that significant deviations may be identified at the earliest possible opportunity to permit effective and timely proactive remedial actions to be taken.

4.4 OPERATOR SKILL

Ensuring that operators have appropriate skills to the extent required is vital in ensuring an effective response to any emergency. Humans invariably err and systems must be sufficiently robust to be capable of addressing such errors with minimal impact on water quality. When operators know and understand their systems and the capabilities and especially limitations of those systems, the opportunities for errors may be minimised.

Training and experience are vital assets. It is important to learn from mistakes, whether or not they led to adverse effects on water quality. Minor errors and faults can grow or accumulate into more severe problems. It has been suggested (13) that outbreaks often occur when there is a combination of events. This leads to the conclusion that there are a number of opportunities when corrective action may have been taken to prevent the subsequent development of major problems.

4.5 RISK MANAGEMENT

Every incident is unique although common themes may run through many. To identify an incipient incident requires decisions to be made with limited information. Sometimes a decision to act is made where in fact no action is required. In contrast, there may be no decision made to act even when the situation desperately needs one. It is better to make a decision on the basis of limited information and to review that decision frequently than to allow the situation to develop to the stage where any action taken is either too late or ineffective. In some cases, late action may exacerbate the problem.

The prime requirement is to recognise at all times that public health is at risk when pathogens are present in the supply system. Advice to boil water may be issued as a protective measure, before contamination is confirmed. Apart from the logistics of issuing such advice and the impact on consumer confidence, a more effective precautionary approach is to identify the incipient problem and deal with it early. This is not always easy and particularly in the case of *Cryptosporidium* when the analysis time is long. Furthermore, an increase in the number of cases of cryptosporidiosis in the community may not necessarily be associated with the drinking water supply.

Descriptive or analytical epidemiology after the event may indicate an association between an increase in the number of cases of cryptosporidiosis and the drinking water supply, but only to the extent that the evidence may be classed as strong, probable or possible. It has been suggested (43) that a number of factors should be considered when establishing a protocol with the relevant health professionals to allow a decision to be made on evidence supporting the issue of advice to boil water. These factors include quantitative criteria for interpreting the presence of microbiological contamination (E. coli, Giardia, *Cryptosporidium*); loss of residual disinfectant at the treatment works; exceedences of the operational turbidity standards; unusual conditions at the treatment works; and unusual conditions or weather that adversely affect water quality.

5 OVERVIEW OF TREATMENT PROCESSES

Water treatment works should be designed according to risk and able to handle typical peak turbidities, colour loadings and any adverse raw water conditions in the raw water. The provision and operation of effective water treatment is critical and the by-passing of any stage of treatment should be avoided. The second report by Badenoch et al (1995) (44) concluded that water treatment processes, when operated in accordance with good practice, are capable of effectively removing *Cryptosporidium* oocysts from water supplies. The importance was stressed of optimising the operation of water treatment works and considered an important element of this to be the control of the effectiveness of particle removal by reference to the turbidity of filtered and final waters (12). Log removal rates for different treatment processes have been compiled (8).

The New Zealand Ministry for the Environment consider there to be two types of treatment processes for removing protozoa from water – processes to remove particles, because *Cryptosporidium* is a particle, and disinfection to inactivate the organism (45). *Cryptosporidium* oocysts are very resistant to chlorine and control is achieved through source protection, filtration and disinfection. Effective disinfectants are UV irradiation, ozone and chlorine dioxide.

Treatment works should at all times be operated such that final water turbidity is minimised and optimised for particle removal. Provided that appropriate treatment is provided, with built-in redundancy, even wastewater can be treated to meet drinking water standards (46).

The following overview of treatment options highlights areas where water quality may be potentially compromised.

5.1 CLARIFICATION

Clarification remains one of the most significant water treatment processes and the term here refers to coagulation, flocculation and sedimentation or equivalent processes. Clarification is required to remove material contributing to the overall turbidity of the raw water and such suspended material will vary in particle size. Turbidity in water results from the presence of suspended material which includes *Cryptosporidium*. Elevated turbidity can interfere with microbiological analyses as a result of the target organisms being adsorbed onto or absorbed into the particles when particles may shield the microorganisms from disinfectants. Conversely, low turbidity does not guarantee that water is free from pathogens. Turbidity should be minimised by careful management of the catchment and storage, as well as the coagulation and filtration processes.

The smallest particles, colloids, remain in suspension since they are too small to settle in the time usually available to water passing through conventional water treatment works. These colloids also often have a surface charge which repels similar particles with a like charge, thus preventing aggregation into larger particles which might otherwise settle. The charge on such particles may be destabilised by the addition of a coagulant which may then be aggregated into larger particles by flocculation.

Charge neutralisation is achieved by addition of a coagulant aid added at the correct concentration and place with efficient and rapid mixing to form microflocs. Microflocs are then reacted with a coagulant such as aluminium sulphate, polyaluminium chloride

or ferric chloride. The resultant particles agglomerate to form macroflocs which are then separated from the body of the water by sedimentation. Polyelectrolyte flocculant aids may be used to enhance agglomeration but should not be relied upon to act alone.

There is limited knowledge on how oocysts behave during the coagulation, flocculation and sedimentation processes (47). The flocculation and sedimentation steps are both physical processes and are dependent on the coagulation step for optimisation. Recent research shows that removal of oocysts is dependent on two different processes, direct interaction of oocysts with the coagulant and entrapment in flocculated material. Floc formation was the most significant factor in the removal of oocysts by alum. The activity and age of the oocysts affect the surface charge of the oocysts, which can result in differing removal rates of oocysts during jar test experiments. Turbidity has a significant effect on floc formation and the subsequent removal of oocysts. Research continues into the effectiveness of different treatment processes and disinfection regimes (48).

Physical and chemical conditions of the water significantly affect the clarification process. pH affects the initial hydrolysis of the coagulant. Sufficient alkalinity must be present for effective coagulation when using alum and if additional alkalinity is required through the addition of other chemicals, their dose and mixing must be carefully controlled.

Formation of a floc requires an appropriate residence time with gentle mixing. Incorrect conditions can lead to the formation of a pinpoint floc that cannot be removed by sedimentation. Low water temperatures increase the settlement time and can lead to carry-over of the floc. Mixing problems can lead to the formation of a weak floc which causes overloading of the filters. Low turbidity or insufficient alkalinity of the raw water can lead to slow floc formation.

Sedimentation of aggregated flocs may be achieved in a variety of clarifiers, each having its own particular design criteria and operating procedures. In general, particles settle under the force of gravity. Flow conditions must be quiescent and short circuiting or turbulence avoided. Carry-over causes problems at the subsequent filtration stage.

An alternative process is flotation whereby microbubbles are attached to the aggregated flows which are then floated to the top of the unit and the accumulated sludge removed mechanically at intervals. Again, conditions must not be so vigorous as to result in floc carry over.

Short-circuiting, turbulence (wind induced), density currents, the presence of algae or slime may all affect the clarification process.

5.2 FILTRATION

Filtration alone without coagulation will not sufficiently remove suspended or colloidal material and is inadequate for the removal of chlorine resistant pathogens such as *Cryptosporidium* . Turbidity standards were initially introduced for aesthetic reasons with a maximum value in the UK of 4 NTU at the consumers' tap. Since the presence of suspended material may shield pathogens from the disinfectant in the bulk of the water, a turbidity of less than 1 NTU is required to ensure effective disinfection. Although suspended material may shelter pathogens, so may biofilms within the supply system itself (49).

The potential presence of *Cryptosporidium* in water requires the removal of turbidity to even lower values and often a target value of 0.1 NTU is set. The World Health Organisation has issued guidance on the level of turbidity required to allow satisfactory disinfection (50). To achieve this consistently, the operation of filters must be optimised. Flow rates through filters must be appropriate to the type of filter – slow sand, rapid or high rate multi-media filtration - and sudden changes in flow should be avoided since this can cause retained deposits to become dislodged (51). Filter washing must be carried out regularly and in accordance with manufacturers' operating procedures. Filters should be operated and maintained optimally, especially with regard to the quality and depth of media and the operation of the backwash cycle. The procedure for returning filters to service must include slow start and running the initial filtrate to waste. The operation of filters may be best monitored by continuous on-line turbidity instruments. Filtrate quality declines at the end of filter runs and identification of a deterioration in quality should initiate a backwash cycle. Supernatant backwash water should be separated from sludge and there should be no recycling without specific and stringent precautions, and preferable avoided totally.

Common problems associated with filtration include inadequate pre-treatment and clarification, fluctuating flow rates especially during backwashing of associated filters, and filter backwashing.

5.3 DISINFECTION

Disinfection using chlorine alone or chloramines is unable to inactivate *Cryptosporidium* at the concentrations normally used in drinking water treatment systems. Chlorine dioxide is slightly more effective than chlorine but requires a high CT (the product of the concentration of disinfectant in mg per litre, C, x contact time in minutes, T) of some 75 to 1000 mg.min/litre for 99% inactivation of oocysts (8).

Ozonation is more effective with a CT at 20oC of 3.5 mg.min/litre for 99% inactivation of oocysts. Low pressure UV light at 20mJ/cm2 and solar disinfection (830W/m2 at 40C for 12 h) are effective at inactivating oocysts. UV is equally effective for the inactivation of *C. parvum* and *C. hominis* (52). However, neither UV nor ozone leave a residual in the treated water entering supply and both require considerable expertise.

The use of multiple disinfectants in series has been shown to be more effective that single disinfectants alone and a synergistic effect has been observed between disinfectant and environmental stress during sand filtration (8).

Since the effectiveness of UV is dependent on the transmittance of UV through the water, adequate removal of turbidity is required. The transmissivity of the water is dependent on turbidity, total dissolved solids, iron and dissolved organic matter. Guidance on the application of UV disinfection is in preparation by the DWI. The EPA guidance on disinfection (53) also contains information the application of UV and is currently (2009) under revision.

Lamp fouling and lamp failure are potential weakness and the output of UV devices decreases in low temperatures.

UV units need to be validated for inactivation of *Cryptosporidium*. At the present time many are not (54). There is no regulatory instrument at present in the UK to guide the installation, operation and maintenance of UV disinfection systems although a number of countries have developed regulations and guidance manuals, for example the European standard ÖNORM 2001 (55) and 2003; the German DVGW 2006; and in the US the NWRI-AWWARF 2003 and USEPA 2006 (42). Several organisations associated with the water industry have produced reports that provide detailed recommendations for the proper installation, maintenance, and operation of UV disinfection systems. Petri et al identified the requirements for validating UV disinfection systems (56).

Dose monitoring and regular system maintenance are essential to maintain effective UV disinfection performance which should be validated within their intended normal operating ranges. Energy use by UV disinfection is less than that for alternative treatment options of ozonation or membrane filtration for *Cryptosporidium* control (57).

Most European countries use chlorination to disinfect drinking water although a number use ozone or UV for inactivation of oocysts. Chlorine dioxide is used in Belgium, France, Germany and Italy to inactivate *Cryptosporidium* (17). Flocculation, sedimentation and filtration can remove *Cryptosporidium* oocysts if operated correctly. However, treatment that meets or exceeds regulatory requirements does not entirely prevent outbreaks or prevent oocysts from entering drinking water supplies (52). Membrane filtration can add another treatment barrier.

6 PROTECTION OF WATER QUALITY

The operation of water treatment processes according to their design specification and in accordance with the manufacturers' procedures is vital in preserving treated water quality. However, the first actions to protect water quality start at the source. An assessment of risk should identify the potential in the catchment for oocysts to gain access to the source water. Ground water which has been historically of good quality cannot be expected to remain so indefinitely and regular monitoring should inform decisions about catchment protection and treatment. Changes in ground water levels and/or the presence of oocysts after severe weather events indicate the potential for ingress of surface water and require immediate investigation. Similarly, increases in turbidity or other microbiological indicators may give early warning of potential contamination.

Whilst continuous monitoring of water quality is reasonably straight forward for chemical and physical parameters, the continuous assessment of microbiological parameters including *Cryptosporidium*, is subject to significant delay between sampling and analytical data becoming available. In many cases, the results of analysis only become known after the water has been consumed and the value of such analysis as a preventive measure is minimal, other than to inform as to whether contamination has occurred and is still occurring.

The volume of a sample of water examined represents a small fraction of the total volume supplied. The issue of limited volume grab samples was addressed in the UK by requiring continuous sampling under well defined conditions as part of the implementation of the *Cryptosporidium* monitoring regulations (58).

The Drinking Water Inspectorate issued guidance in October 2008 on the 2000 Regulations and the 2007 Amendment Regulations and confirmed that specific monitoring for *Cryptosporidium* was no longer required although the expectation was that where a risk assessment of a water treatment works and associated supply chain identified a risk from *Cryptosporidium*, appropriate remedial action should be taken to mitigate that risk[2]. There is now no standard for *Cryptosporidium* but monitoring should be undertaken to ensure the safety of water supplies (59).

Badenoch et al (1990) (51) considered that early detection of conditions that favour the breakthrough of oocysts into the treated water would be helped by the ability to determine the turbidity of the filtrate from every filter. Continuous measurement of turbidity or particle count monitoring can indicate at an early stage particle break though with the associated possibility of the presence of oocysts.

Bouchier et al (12) considered that there were four broad ways that a water utility could become aware of oocysts in the water supply:

- detection of oocysts in a sample of water;
- detection of a change of operational circumstances which leads to the risk that oocysts could contaminate drinking water;
- local health authority is notified of an increase in stools containing *Cryptosporidium* oocysts; or
- the national disease surveillance centre detects a cluster of cases.

2 See also Section 9

The report concluded that there was an apparently strong correlation between outbreaks and inadequacies in the treatment or operation of the treatment process or where there was overloading of the treatment process. It was concluded that turbidity monitoring through the water treatment process was vital to check that treatment barriers were working properly. The failure to recognise turbidity events could reflect inadequacies in the continuity of turbidity monitoring, the interpretation of results or in the calibration and control of the equipment. It was noted that the quality of ground waters was not always high or consistent. Furthermore, given the lack of an appropriate disinfection system to which *Cryptosporidium* is susceptible, effective protection through physical barriers and conventional treatment is essential and such treatment must be operated within its design capacity and not bypassed.

Significantly, the report recommended that water companies should carry out a risk assessment for each source and update it regularly. For sites at which *Cryptosporidium* might be a high risk, monitoring should include 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. Individual companies should define their own operational limits and responses to exceedences of those standards. It was noted that particle count monitors provide additional information to that provided by turbidity measurements. Random spot sampling was considered unlikely to be effective for operational monitoring and continuous sampling for *Cryptosporidium* with analysis times linked to turbidity monitoring results should be considered.

Careful management of the catchment and temporary abandonment of water sources have helped reduce contamination of source waters. The World Health Organization (WHO) Water Safety Plans are being widely used to improve drinking water quality.

7 RISK ASSESSMENT

The Swindon outbreak led Bouchier et al (12) to identify in three main areas the factors to be considered in the risk assessment of groundwater contamination: the source, hydrological features and catchment factors. Means by which these factors could be verified were identified.

Factors affecting the source included shallow flow systems such as springs and adits; adits with vertical shafts; unsealed linings above rest water levels; defective casing integrity; sewers, septic tanks or slurry pits near wells heads or above adits; defective fencing around spring heads or catchpits; and poorly documented construction details.

Hydrogeological features included the presence of known or suspected connection between the aquifer and an adjacent river; unconfined shallow water table; karst conditions or rapid macro-fissure flows; patchy inconsistent drift cover; solution features in the catchment; shallow flows to springs; and fissure dominant flow.

Catchment factors included high volumes of returned wastewater including sewage discharges; rearing of livestock in the catchment near the abstraction point; likely sources of *Cryptosporidium* such as abattoirs; urban areas; and livestock grazing adjacent to sources or hard standings.

The Walkerton incident led to 93 recommendations for the implementation of a multi-barrier approach including improved source protection and obligations to manage water quality from source to tap (60). It included recommendations to establish sound management and operational systems with accreditation designed to ensure operators have systems in place to ensure the delivery of safe water as well as development of an operational plan for the water supply system. Such systems would include adoption of best practices; process control through continuous monitoring of turbidity, residual disinfectant, and disinfectant contact time; effective operation of robust multiple barriers; preventive strategies to identify and manage public health risks; and effective leadership.

The report into the North Battleford incident (61) considered issues associated with water supply to a small rural community. It recommended particularly the establishment of a safe drinking water policy and the undertaking of biennial inspections of treatment works by knowledgeable inspectors to document the implementation and maintenance of best practices in key operational areas.

A number of schemes have been developed by the AWWA for the achievement of drinking water safety. QualServe programmes provide for a self-assessment of an organisation, a peer review through site visits, and a benchmarking exercise. The International Water Treatment Alliance uses self-assessment and peer review to optimise the performance of works treating surface water. The Composite Correction Programme is a coalition of organisations with the aim of improving treatment and safety of drinking water and represents the USEPA's contribution.

Basic principles of the Hazard Analysis and Critical Control Point (HACCP) system may be applied to the operational control of treatment processes and comprises seven principles: identification of hazard and preventive measures; critical control points; critical limits; monitoring procedures; corrective actions procedures; verification/validation; and documentation and record keeping. Hrudey suggests that a sensible and pragmatic approach is needed for the HACCP principles to be applied to the water industry (13).

The New Zealand Ministry of Health (NZMH) developed a programme for encouraging Public Health Risk Management Plans, an approach which focussed on events that may lead to hazards being

introduced into water or not removed from it. Four barriers were identified that could control hazards; prevention of contamination of source water; removal of particles from water; inactivation of microorganisms present; and maintenance of the quality of water in supply. NZMH has produced a number of specific practical guides for various parts of the water treatment and supply system.

Australia has developed a total quality management approach based on a fundamental commitment to drinking water quality management. The approach focuses on three main areas. System analysis and management includes an assessment of the supply system, preventive measures, operational procedures and process control, verification of quality and management of incidents and emergencies. Support is required through employee awareness and training, community involvement and awareness, research and development and documentation and reporting. The whole process is subject to review and continual improvement through evaluation and audit. This has led to a complete restructuring of the Australian Drinking Water Guidelines and guidance has been issued on hazard identification and risk assessment (62).

After the Walkerton incident, Canada developed guidance that describes a multi-barrier approach to drinking water safety covering the cycle from source to tap and suggests approaches to its implementation (63).

The World Health Organisation, in its third edition of WHO Guidelines for Drinking Water Quality, described in detail the water safety plan approach to ensure water quality between source and consumers' tap (50). Careful management of the catchment and temporary abandonment of water sources have helped reduce contamination of source waters. The World Health Organization (WHO) Water Safety Plans are being widely used to improve drinking water quality.

A quantitative microbiological risk assessment (QMRA) approach has been proposed (64) to complement the traditional verification of drinking water safety as determined by the absence of indicator bacteria. Although there is generally a lack of appropriate data on the fate and behaviour of pathogens limits the application of the technique, data is available from statutory monitoring for *Cryptosporidium* in the UK. Application of QMRA allowed estimation of the risk of infection at the 216 assessed treatment sites. Additionally, *Cryptosporidium* monitoring data in source water at eight treatment works was assessed to determine how *Cryptosporidium* removal could be quantified for QMRA purposes. Removal varied between 1.8 and 5.2 log units and appeared to be related to the concentration of *Cryptosporidium* in the source water.

Two risk assessment approaches are generally used. One approach uses quantitative risk assessment using exposure and reference dose data and includes the selection of assessment and measurement endpoints and the comparison of endpoint water quality measurements or distributions to a guideline value. Current research in this approach considers the comparison of multiple contaminants and how to compare these, and the use of stochastic models to understand the origins of risk. A second approach is qualitative and involves the use of expert groups to assess water quality issues and their priority. The Scottish Executive proposed a semi-quantitative method (65) which requires calculation of a risk score for catchment factors and for treatment, operational and management factors. The score is then weighted according to population. The approach used by the EPA is based on this methodology (66).

A more detailed discussion of risk assessments for drinking water sources is available elsewhere (67) where different risk assessment methods based on these generic approaches and case examples are outlined. The risk assessment method used by the Ministry of Health in New Zealand method has been reviewed and is considered a benchmark of well-recognised global approaches.

8 WATER SAFETY PLAN APPROACH

The WHO considers that a WSP approach is achieved through a number of steps:

- **An understanding of the system an its capability to supply quality water;**
- **Identification of potential sources of contamination and their control;**
- **Validation of control measures to manage risks posed by identified hazards;**
- **Implantation of a system to monitor control measures and initiate timely responses to problems;**
- **Verification of water quality**

The UK Drinking Water Inspectorate (68) and others have issued guidance on drinking water safety plans which must be based on a comprehensive risk assessment and risk management approach to all the steps in a water supply system from catchment to consumer. The primary objectives are to minimise contamination of sources, reduce or remove contamination by means of appropriate treatment processes and prevent contamination in the distribution system and in consumers' properties. Ideally, each water supply chain should have its own WSP although a generic or model plan may be appropriate for small systems that are similar in nature. A WSP is considered to be a fully documented framework of hazard identification, risk assessment, risk management, control measures, monitoring and incident and emergency plans. Sanitary surveys are the means to collect site specific information on hazardous events and are the basis for effective strategies for the prevention of hazards and their control (8).

The initial step in establishing a WSP is the establishment of an appropriate team of experts with appropriate knowledge, experience and understanding to prepare the WSP according to published guidance. Once established, a WSP should be reviewed regularly and particularly if there have been any significant changes in circumstances in the water supply chain or if there have been failures in water quality to meet regulatory or operational standards.

A source to tap approach for the establishment of a WSP necessarily includes consideration of source water and the catchment, treatment works, distribution system and consumers' installations and a brief consideration of each is presented here. Although the latter two aspects are not strictly relevant to a consideration of *Cryptosporidium*, they are included for completeness.

8.1 CATCHMENT

Factors which might affect the catchment include geology, hydrology, weather patterns, nature of the land and it use, industrial activities, farming practices, degree of natural land and its wildlife, quarrying and mining, competing water uses such as irrigation and river compensation flows, planned future activities and any existing catchment control or protection zones.

For surface water, potentially significant factors include the type of water source (river, direct abstraction, storage reservoir, impounding reservoir or lake), point discharges (sewage effluents, industrial effluents, mine water), water quality and seasonal and weather variations, flow and reliability of source and its retention time, recreational or other human activity and any existing source protection systems.

For groundwater, factors include whether the aquifer is confined or unconfined, the hydrology and recharge area of the source, flow rate, direction of flow and dilution characteristics in the aquifer,

the speed of response to surface activities and events, the depth of casing and water level, wellhead protection and any activities in the recharge area that could potentially affect water quality.

Potential hazards include rapid variations in raw water quality arising from weather events, activities within the catchment, pollution of raw water from point discharges such as sewage, septic tank and industrial effluents, storm water overflows, overflows from active and closed mines and landfill sites, pollution from agricultural activities including chemicals and fertilisers from arable land/forestry and wastes from animal rearing, pollution from human recreational activity and wildlife, inadequate protection of the source and its point of abstraction, short-circuiting, stratification and eutrophication of raw water storage reservoirs

Control measures to reduce or eliminate the risk in the catchment or abstraction point may include implementing a catchment management plan to protect surface and groundwater (including control of all point sources of discharges, limitation and control of specific activities and regular inspection of the catchment), planning regulations to protect water resources against future activities, protection at the point of abstraction and reservoir management to minimise eutrophication, short-circuiting and stratification. For many control measures, monitoring will be by regular inspection of the catchment and potential polluting sites and regular inspection of the point of abstraction and associated works.

Codes of agricultural good practice should be promoted and reviewed regularly to ensure their continued applicability.

8.2 TREATMENT WORKS

Information on treatment works and a flow diagram of existing processes and their controls is essential. Such information will includes details of each treatment process and what they are designed to achieve and details of the control of each treatment process including monitoring arrangements and whether monitoring is discrete, continuous, automatic, manual. Criteria for determining whether or not each process is in control and working efficiently should be established together with disinfection contact time and disinfection residuals. Information on operational control and monitoring of the final treated water is required that demonstrates that treatment is working efficiently. Details are required of all chemicals used in the treatment processes together with any hazards identified in the catchment assessment that cannot be controlled therein or that might not be removed by treatment

Hazards that might arise during the treatment process include contaminants identified in the catchment that are not controlled within the catchment and may not be removed by existing treatment processes, flow and quality variations outside design limits, failure of any treatment process, inappropriate or insufficient treatment, insufficient back up equipment, failure of process monitoring equipment and alarms, natural disasters and power failures and contamination of treatment chemicals and materials.

A common hazard and risk is intermittent high turbidity in the raw water which can overwhelm the treatment processes, including disinfection. Control measures that could reduce or eliminate the risk include new or upgraded treatment processes, optimisation of each treatment process, ceasing abstraction during periods when the quality of the source water deteriorates, using only approved chemicals and materials, ensuring that process or equipment failures are detected

and alarmed and for serious failures result in the shut down of the works. Control measures might include treatment systems to remove substances that cannot readily be controlled within the catchment and are difficult to monitor routinely such as *Cryptosporidium*.

Each monitoring system should have preset limits which if exceeded trigger an alarm and in appropriate cases isolate the works.

8.3 DISTRIBUTION SYSTEM

Relevant information regarding the distribution network will include how the system operates and schematic diagrams of the network, service reservoirs, towers etc and their controls. The position and status of associated equipment, such as valves and hydrants is also required. Records are required of service reservoir design, including capacity, number of compartments, position of inlets and outlets, materials of construction and retention time. Information is required on the means to protect installations from unauthorised access. Materials of construction of the network, the normal ranges of pressures, flows, water age and retention time and the normal method of operation should be recorded.

Potential hazards include ingress of contaminated water through structural defects in service reservoirs. Ingress in the network may occur at times of low or no pressure, when a reservoir or network is opened for repair or may be associated with back flow of contaminated water from consumers' premises. Chemicals may leach from the use of inappropriate materials and deposits and microbiological growths may occur. Unauthorised access at service reservoirs or in the distribution system may occur and petrol and other solvents can migrate through plastic pipes Disturbance of mains deposits often causes discoloured water

Typical control measures include operating the network such that sudden changes in flow are minimised. Routine flushing programmes can control some discoloured water problems. Network pressure must be maintained and there should be written procedures in place for repairs that involve opening the network that include disinfection before returning the system to service. A disinfectant residual should be maintained. The status of all valves should be known and recorded. A risk assessment of the consequences of any major change in the operation of the network must be made before any such actions are authorised.

Control measures might include determination of flow, pressure and disinfectant residual at various points within the network with an investigation initiated when the result is outside specified limits. Periodic internal audits should be carried out to ensure that staff are following procedures for the repairs of burst mains. Service reservoirs and the distribution system should be regularly inspected and maintained and potential sources of contamination regularly inspected.

8.4 CONSUMERS' INSTALLATIONS

It is recognised that it is not possible to create or maintain information about individual properties although some generic information can be useful, such as the number of industrial, commercial and domestic connections. Other information might include details of major industrial and commercial

sites which include on-site information on the distribution system within the site and estimates of the proportions of major plumbing materials likely to be found within domestic households.

Two major hazards are recognised. There is a possibility of backflow of contaminated water from a consumer's installation into the distribution network resulting in the supply of contaminated water to consumers downstream. The second is the effect of the pipe work and fittings within the property on the quality of water.

Control measures include treatment of the water at the treatment works to reduce the tendency for water to leach metal for the consumers' pipe work and an education campaign to inform consumers of the risks to their own water supply from their pipe work materials and from unhygienic taps. Validation and monitoring may include regular inspection of premises to check that appropriate back flow prevention devices are fitted. When treatment is installed to reduce metal solvency, appropriate parameters should be monitored in the water leaving the works and within distribution to check that the water is properly treated.

8.5 WSP VALIDATION

Once the WSP has been prepared for the whole supply chain, it is necessary to prepare a routine validation monitoring programme which specifies what should be monitored and at what frequency. Sampling points for validation should be those normally used for human consumption and representative of the properties within that supply chain. Once it has been demonstrated that the distribution system and consumers' properties do not affect the value for a parameter, the sampling point for that parameter may revert to the point where water leaves the treatment works or other appropriate point. Apart from monitoring required by regulation, additional requirements may be derived from the water safety plan.

8.6 SUPPORTING PROGRAMMES

Supporting programmes may include the training of staff in preparing and implementing a WSP. Operational procedures should be written as standard operational instructions and as much of the WSP as possible should be subject to a quality control system.

8.7 DOCUMENTATION

Full documentation must be maintained and reviewed immediately whenever there is a significant change of circumstances within, or a problem with, the water supply chain. A WSP should also be reviewed from time to time, taking into account the results of implementing the WSP. Any changes made to a WSP as a result of a review should be documented.

8.8 SURVEILLANCE AND VERIFICATION

Independent verification at intervals is required at intervals by an independent person or organisation.

9 REGULATORY APPROACHES

Generally, European countries based their individual mandatory standards on the World Health Organisation Guidelines for Drinking Water Quality (50) with, in some cases, additional national standards. The US, Australia and New Zealand have also issued mandatory standards. Canada has voluntary national guidelines, some or all of which become mandatory only in individual provinces and territories. The World Health Organisation has no law-making authority but has established guidelines for the use of individual countries. Most European countries now follow or intend to follow WHO guidance from which derived the EU Drinking Water Directive 80/778/EEC.

THE UK

In the UK, following the inability of the legislation at the time to allow a successful prosecution following the outbreak in South Devon in 1995, the DWI amended in 1999 the Water Supply (Water Quality) Regulations 1989 (69). These amended regulations (70) required water companies to carry out an assessment of risk of all sources containing *Cryptosporidium* oocysts. Where a risk is identified water companies were required to either install treatment to remove continuously all particles greater than 1µm in diameter (i.e. membrane filtration) or implement continuous sampling under specified conditions (70). Sampling and analysis are complicated and time consuming requiring concentration and identification and enumeration of oocysts by immunofluorescent microscopy. Initial testing does not inform whether the oocysts are viable nor does it identify the sub-type. Accordingly there is no specific standard for *Cryptosporidium* in the EU Drinking Water Directive nor the UK national standards. However, the 2000 Regulations specified a treatment standard of less than 1 oocyst per 10l in a sample taken over a 24 hour period under specified conditions. The UK Government's approach was subject to considerable criticism from experts and authorities abroad (71). In general, a risk based approach to the management of *Cryptosporidium* has been preferred over prescribing a specific limit on numbers of oocysts. There is also a general requirement that drinking water shall not contain any organism at a concentration that would constitute a potential danger to human health.

Guidance was issued in 1999 (72) following the distinction between *C. hominis* and *C. parvum* and further guidance on reviewing risk assessments was issued in 2000. Water companies were advised to consider and document risk not only on an overall basis but also on a seasonal basis (73). In December 2005, DWI issued Information Letter 17/2005, the purpose of which was to ensure that, following outbreaks in England and Wales, water companies had in place an appropriate and proportionate level of risk management. In summary, companies were required to identify:

a. identify the location of all sewage discharges in relation to the location of intakes to water treatment works;

b. identify the presence of communities without sewerage services which are reliant on, for example, cess pits or septic tanks in the catchment upstream;

c. assess the ability of each intake to shut down in the event of heavy rainfall;

d. assess the sufficiency of information about source water quality to allow identification of the works being affected by occasional or short duration sewage pollution events;

e. assess the reliability of information about source water storage times and whether it is appropriate in the overall risk assessment; and

f. update information held on raw waters for E.coli, *Cryptosporidium* and other microbiological parameters and assess the capability of the water treatment processes to remove oocysts from the raw water under worst case conditions.

The risk assessment should make clear if water treatment is only "basic" in microbiological terms. In these situations other control measures should be in place and these should be documented. For example, appropriate and frequent, preferably continuous, monitoring of the source water quality for relevant (named) operational indicators. Basic treatment in this context would include any or all of the following: screens, roughing and pressure filters, filtration designed or optimised for non microbiological treatment purposes such as manganese or taste/odour control, reliance on residence time in downstream treated water storage structures or distribution mains to achieve adequate chlorination (deficiencies in measured C_t).

The current regulations do not require monitoring specifically for crypto but where a risk assessment of that water treatment works and associated supply chain identifies a risk from crypto appropriate remedial action needs to be taken to mitigate the risk. There is now no standard as such and monitoring would need to determined in order to ensure the safety/quality of supplies – this would be informed by, and inform the review of, the risk assessment, taking into account the various barriers put in place to mitigate that risk.

Guidance issued by the DWI addresses the changes to the crypto aspects of the regulations (59) and the relevant sections (7.4, 7.6 and 7.7) are reproduced here.

7.4 *Prior to being amended Regulation 27 required a risk assessment that was specific to Cryptosporidium. The regulation now requires a comprehensive risk assessment for each treatment works and connected supply system which covers all hazards and hazardous events. These risk assessments shall be undertaken using the water safety plan approach published by WHO in the Drinking Water Guidelines 2004, taking into account subsequent updates and associated guidance manuals published by WHO. Water Safety Plans require documentation of the hazards and hazardous events that potentially could arise in the catchment area for the source, during treatment, within the distribution system and within building plumbing systems (up to the consumers cold water tap). The methodology requires risk to be characterised for each hazard/hazardous event using a scoring system based on likelihood and consequence criteria. An example of such criteria has previously been published by DWI in relation to PR09 submissions (as Annex B to Information letter 2/2008). Risks should be characterised before and then after taking account of the existing permanent control measures in place. The scoring method should be capable of identifying "residual risks" which require further steps of mitigation (control measures) to be put in place. Residual risks may be either acceptable or unacceptable in nature. DWI considers that where "residual risks" as identified through water safety plan methodology are unacceptable in nature these should be interpreted as having the same meaning as the term "significant risk….of a potential risk to human health" in Regulation 27. This would therefore identify the need for further action to be taken to control or mitigate the risks. Existing Cryptosporidium Risk Assessments and associated notices and monitoring arrangements remain in force until these new risk assessments have been completed and the Regulation 28 reports assessed by DWI.*

7.6 *Regulation 29 which amongst other things described the monitoring requirements for Cryptosporidium has been revoked. However DWI has agreed to retain on its website the following Standard Operating Protocols until such time as methods have been published through SCA or another recognised body. It is expected that companies will continue to carry out monitoring for Cryptosporidium using these protocols within the context of Regulation 27 risk assessments and Regulation 16A monitoring programmes. However, the forensic audit trail requirements no longer apply. The recommended source of advice relating to oocyst typing methods is the UK Cryptosporidium Reference Unit at NPHS, Swansea.*

7.7 The revocation of Regulation 29 means that companies can address a significant risk from Cryptosporidium by the use any appropriate water treatment technology. However the Inspectorate has agreed to retain its guidance on membrane filtration on its website and this will be enhanced in the near future by guidance on the use of UV for oocyst inactivation.

SCOTLAND

In Scotland, new directions (The *Cryptosporidium* (Scottish Water) Directions 2003) (74) were issued in 2003. These require every treatment works in Scotland to be tested at least once a month from June 2004. The aim is to provide information on existing background levels of *Cryptosporidium* in raw water sources and the effectiveness of treatment. Results will be reported to NHS Boards, local authorities and to the Drinking Water Quality Regulator. The additional information will help to track background levels of the parasite over time and enhance public health risk assessment. More frequent and widespread testing will also give an indication of the effectiveness of existing filtration equipment and help identify plants for improvement. It is likely that the existing Directions will be repealed and incorporated in new Regulations dealing with risk assessments and other matters towards the end of 2010.

NETHERLANDS

In Holland the Dutch Drinking Water Decree Act 2001 specifies that the risk of infection by *Cryptosporidium* should be below 10-4 per person per year. Under the rolling revision of Water Safety Plans, the concept of risk assessment. When surface water is to be used as a source of drinking water, risk should be assessed by monitoring the source for *Cryptosporidium* and also by assessing the efficacy of treatment processes provided. Sampling frequency is dependent on the volume of water produced per day but during normal and peak flow conditions, sources should be monitored every three weeks (75).

AUSTRALIA

Australia revised in 2004 its drinking water guidelines (38). The Guidelines include detailed guidance on risk assessments, risk management, multiple barriers and monitoring. No guideline value is set for *Cryptosporidium* because of the lack of a method to identify human infectious strains in drinking water. It is also considered that current risk assessment models suggest that impossibly large volumes of water would need to be tested. Routine monitoring of distribution systems is not recommended although investigations may be required following events which could increase the risk of contamination by *Cryptosporidium*.

NEW ZEALAND

In New Zealand, Drinking-Water Standards were revised in 2008 (76). For protozoa, the compliance criteria are based on the probability that the treatment process will inactivate or remove and protozoa present. The criteria are:

- The use of risk based criteria that are more stringent for contaminated sources than for clean sources;
- Acknowledgement of additive effects of successive treatment processes;
- Use of log-removal efficiency data (derived from USEPA) for a range of treatments;
- Specification of the use of validated equipment, monitoring programmes and treatment performance measures; and
- The requirement to take appropriate remedial measures.

A risk based approach is used to assess overall risk to the catchment. The concept of log credits is applied to ensure that for each catchment and groundwater category, appropriate and sufficient treatment is applied to reduce the risk of *Cryptosporidium* presence in treated water. Catchment risk must be reassessed every five years.

A monitoring programme is defined which specifies sampling frequencies dependent on population supplied and catchment factors. The analytical method to be used is that produced by the USEPA. Tables are included that list log credit data for different treatment processes.

There is no requirement to monitor sources for protozoa which supply fewer than 10,000 population; a surrogate process comprising inspection and monitoring of source protection, abstraction, treatment and network protection is required.

CANADA

In Canada, the use of a multi-barrier approach is recommended and the first defence is considered to be catchment protection (5). An MAC for *Cryptosporidium* was not proposed because of the low recovery rates during analysis and a lack of information on viability or infectivity. Because of the widespread occurrence of *Cryptosporidium* in Canadian surface waters, the guidance states that minimum treatment should comprise coagulation, flocculation, clarification and filtration as well as disinfection.

The standard for turbidity was revised in 2004 and is dependent on the type of filtration. The general recommendation is that for water derived from surface water sources or from groundwater sources under the direct influence of surface water, filtration should reduce the turbidity to the lowest level possible with a target of <0.1NTU at all times. Where this target cannot be met, other conditional targets have been established. Where chemically aided filtration is used, turbidity should be ≤0.3NTU in 95% of the measurements made each month and shall not exceed 1NTU at any time. Where slow sand filtration is used, turbidity shall be ≤1NTU in 95% of the measurements made each month and shall not exceed 1NTU at any time. Where membrane filters are used, turbidity shall be ≤0.1NTU in 99% of the measurements made each month and shall not exceed 0.3NTU at any time.

It has been recommended (41) that the Canadian Guidelines be replaced by a set of health-based long-term objectives for drinking water quality together with legally binding standards.

THE UNITED STATES

The USEPA introduced in 1998 an Interim Enhanced Surface Water Treatment Rule (77). One part of this requires that systems supplying populations larger than 10,000 that are required to filter under the Surface Water Treatment Rule must achieve a 2-log removal of *Cryptosporidium*. Treatment works with conventional or direct filtration which produce water with turbidities of 0.3NTU or less for 95% on monthly samples in which turbidity never exceeds 1NTU are deemed to meet this requirement.

The Long Term 1 Enhanced Surface Water Treatment Rule (2002) strengthens controls for small systems serving a population of less than 10,000 (78).

The Long Term 2 Enhanced Surface Water Treatment Rule (2006) (79) applies to systems deriving water from surface sources or from groundwater sources influenced by surface waters and requires enhanced monitoring and treatment where elevated numbers of oocysts may be present. This rule links the level of required water treatment to the degree of source water contamination. Current regulations require filtration systems to provide a 2-log (99%) reduction in *Cryptosporidium* levels. This is appropriate for works that have little or no *Cryptosporidium* in their source water but additional treatment is required where high levels of *Cryptosporidium* pertain and for all unfiltered PWSs.

The objective of monitoring is to determine the concentration of *Cryptosporidium* in source water and for works with high levels of *Cryptosporidium* in their source water to require additional treatment. LT2 also seeks to examine the correlation between *Cryptosporidium*, E. coli and turbidity for smaller systems.

Sampling frequencies are determined by the size of the treatment works. Populations greater than 10,000 are considered to be large systems and less than 10,000 are small. Ground water systems which are not influenced by surface water are exempt from LT2, as are surface water systems that already provide ≥5.5 log treatment for *Cryptosporidium*. The start date of monitoring is dependent on the size of the population served with monitoring for the largest populations starting in October 2006 and for the smallest in 2010. Further details are given in Appendix A.

Larger populations will require at least monthly sampling for two years. Source water samples must be collected prior to treatment. Treatment plants utilizing pre-sedimentation, raw water off-stream storage or bank filtration may sample water after these processes. No treated water sampling is required.

Middle sized works will be required to initially conduct 12 months of monitoring for E. coli followed by an additional 12 – 24 months of monitoring for *Cryptosporidium* if E. coli trigger levels are exceeded.

Small works for which exceeding the trigger levels may be anticipated may omit initial E. coli monitoring and monitor for *Cryptosporidium* at a frequency of either twice per month for a period of one year or monthly for two years. For those systems deriving water from lakes or reservoirs or from ground water which is under the direct influence of surface water and where the nearest surface water body is a lake or reservoir, the trigger level is a mean annual E.coli concentration greater than 10 E. coli/100ml. For systems using flowing stream sources, or from ground water which is under the direct influence of surface water and where the nearest surface water body is a flowing stream, the trigger level is a mean annual E. coli concentration greater than 50 E. coli per 100ml.

Samples for *Cryptosporidium* analysis must be at least 10L in volume or as much volume as two approved filters can accommodate before clogging or adequate volume to generate at least 2.0 ml of packed pellet volume.

Different treatments are required for different concentrations of *Cryptosporidium* in the final water.

The USEPA does not consider routine monitoring for disease-causing organisms to be feasible, hence the establishment of treatment technique requirements. Because of the establishment of the Long Term 2 Surface Water Treatment Rule, the USEPA did not consider it appropriate to include *Cryptosporidium* in the latest revision of the final potable water contaminant candidate list (80).

The Groundwater Rule (2006) addresses risk using a risk based strategy requiring periodic surveys of systems and identification of significant deficiencies; source water monitoring when a system identifies the presence of coliforms in treated water; corrective action for systems with serious deficiencies or faecal contamination of source water; and compliance monitoring to show inactivation or removal of viruses

USEPA standards require that turbidity must never exceed 1NTU and must not exceed 0.3NTU in 95% of daily samples in any one month.

ISRAEL

Israel places no requirement for the monitoring of *Cryptosporidium* in its consolidated Public Health Regulations (81), but tabulates sampling frequencies for other microbiological parameters based on population served (Tables 4 and 5).

Table 4 Frequency of Water Supply System Sampling and Microbiological Testing

Population size	Frequency of testing	Number of samples per test
Up to 1,000	Once in 4 weeks	2
1,001 to 5,000	Once in 4 weeks	4
5,001 to 10,000	Once in 4 weeks	6
10,001 to 20,000	Once in 4 weeks	8
20,001 to 30,000	Once in 2 weeks	5
30,001 to 40,000	Once in 2 weeks	6
40,001 to 50,000	Once in 2 weeks	7
50,001 to 60,000	Once a week	4
70,001 to 90,000	Once a week	6
90,001 to 110,000	Twice a week	4
110,001 to 140,000	Twice a week	5
140,001 to 170,000	Three times a week	4
170,001 to 200,000	Three times a week	5
200,001 to 250,000	Five times a week	4
250,001 to 300,000	Five times a week	5
300,001 to 400,000	Five times a week	6
400,001 to 500,000	Five times a week	7
Over 500,000	Five times a week	8

Table 5 Microbiological testing of Treated Water and Microbiological testing at Entry Points into a Water Supply System

Size of population served	Test frequency
Less than 20,000	Once in 4 weeks
20,001 to 50,000	Once in 2 weeks
50,001 to 100,000	Once in 4 days
Over 100,001	5 days a week

OTHER COUNTRIES

In Brazil, following outbreaks of cryptosporidiosis, Federal Legislation Law 1649, December 2000, required investigation for the presence of oocysts in drinking water (82). In Nigeria and Pakistan for example, no mention is made of *Cryptosporidium* although there is a general requirement to follow the WHO guidance (83). South Africa has no specific guidance for *Cryptosporidium*. Japan follows the WHO guidelines.

IRELAND

In the current Drinking Water Regulations (S.I. No. 278 of 2007) routine testing for *Cryptosporidium* is not required. However Clostridium perfringens is specified as an indicator organism and is subject to regular monitoring in supplies with surface water sources. The parametric value for *C. perfringens* is 0/100ml and where there is non-compliance the supply is investigated to ensure that there is no potential danger to human health arising from the presence of pathogenic micro-organisms such as *Cryptosporidium*. It is possible that the position of Clostridium may be clarified in the future review of the Annexes of the 1998 EC Directive (84).

The EPA has introduced a risk screening methodology (66) methodology for *Cryptosporidium* based on the model produced by the Scottish Executive (65). It has also adopted the Water Safety Plan approach (85).

10 SAMPLING AND ANALYSIS

Water sampling for *Cryptosporidium* may be by individual grab samples or continuous sampling. However, for reliable results continuous samples should be taken of treated water with a volume of 1000L over a 24 hour period (Bouchier, 1998). Sampling of raw waters should be related to an assessment of catchment risk and the degree and type of treatment available i.e. it should be site specific. It may be possible to develop template arrangements although these should be used with care and validated. Turnaround time for *Cryptosporidium* results varies from a few days to more than a week depending on transport arrangements and laboratory location and the analytical costs are significant. There is no *Cryptosporidium* reference laboratory in Ireland.

The measurement of turbidity in treated water is important in the daily management of water quality, particularly as there is an established relationship between elevated turbidity and the presence of *Cryptosporidium* oocysts. The standard for turbidity is 1 NTU (previously 4 NTU). High turbidity, variation in turbidity or a rapid rate of increase in turbidity are early indications of a possible problem and turbidity itself may adversely affect the sampling process. Of potential microbiological surrogates, only spores of *Clostridium perfringens* were initially reported to correlate with *Cryptosporidium* concentrations (8). Turnaround time for *C. perfringens* testing is 2-3 days.

However, the rates of removal of the two organisms by different treatment processes differ as does their susceptibility to disinfection and the relationship between them has been challenged on the basis that the inactivation kinetics of Clostridium showed it to be more susceptible to disinfection (with chlorine dioxide) than *Cryptosporidium* (86). Research commissioned by the Drinking Water Inspectorate showed that there was no relationship between the two organisms either pre-treatment or post-treatment and that Clostridium was not a good surrogate for *Cryptosporidium* (84).

The AWWA (3) has produced a detailed review of the detection of waterborne pathogens. Initially, the analysis of *Cryptosporidium* relied upon concentration of particulate matter by filtration or centrifugation followed by direct microscopic examination. Sample concentration was accomplished by filtration through a 1 µm porosity wound filter or membrane. Subsequently, tangential flow filters and centrifugal cream separators were used. Detection of oocysts follows filtration and the separation of the resultant pellet by IMS. Microscopic examination of oocysts after staining with DAPI confirms the presence of *Cryptosporidium*.

Until 1998 the most common method of sample analysis was the ICR Method specified by the USEPA using string wound cartridges (87). This method required the trapping of cysts and oocysts and other suspended material either on a filter or in a concentrated pellet. Sewage samples containing large numbers of cysts and oocysts could be analyzed by centrifuge concentration of a small sample. For raw water or treated drinking water, approximately 1000 L were pumped through a 1 µm wound filter. Particulate matter was recovered by backflushing, rinsing, handwashing, or machine processing (using a stomacher bag) and concentrated into a pellet. Although filtration through membranes resulted in higher recovery efficiencies, filter clogging remained a problem. The amount of background material in the pellet may be reduced by discontinuous density gradient centrifugation using either zinc sulphate, 1.0 M sucrose, or a mixture of Percoll and sucrose. *Cryptosporidium* oocysts float on the surface of the density medium and recovered material was then concentrated again by centrifugation and the final pellet was examined microscopically.

The relative advantages of ultrafiltration and capsule filtration to separate oocysts from surface waters have been compared. The disposable hollow fibre ultrafilter system was compatible

with the USEPA Method 1622 and recovered *C. parvum* oocysts from seeded surface waters with significantly greater efficiency and reliability than the currently approved filter (88).

The ICR method has been replaced by the USEPA Method 1623 (87). This method involves the use of different filters and magnetic beads coated with antibodies specific for *Cryptosporidium* oocysts. Immunomagnetic particles are trapped using a magnet and the oocysts are dissociated using acid to produce a purer product with reduced background. Misidentification in reduced by this method and the recovery and precision of the analysis is increased.

Immunofluorescent staining is usually performed by trapping a portion of the pellet on a small membrane and rinsing antibodies through but can also be carried out in centrifuge tubes. Algae that are similar in size and staining characteristics to oocysts may be misidentified. Final identification often requires additional light, phase, and differential interference microscopy. Direct and indirect fluorescence kits are available. Immunofluorescence analysis requires specialized equipment and a high degree of skill. It is time consuming and expensive and only semi-quantitative. Continuous improvements are being made by the USEPA, Health Canada, industry and academia to before the methodology is fully quantitative and cost-effective.

One alternative technique is flow cytometry which again requires concentration and recovery stages but the detection procedure is automated. Expensive and specialized equipment is required. However, the method has been shown to be least variable and most accurate for spiking specified numbers of oocysts into samples. The most effective of the methods tested for detection in both environmental and reagent water was solid phase cytometry (89).

Internal controls should include both positive and negative samples and antibodies must be used at the correct dilution. Clancy (1994) found that recovery of *Cryptosporidium* oocysts ranged from 1.3 to 5.5% (average 2.8%). A Health Canada study of commercial, government, and research laboratories in Canada found that recovery of *Cryptosporidium* oocysts ranged from 0 to 43% (av. 5.3%). LeChevallier et al. (1995) conducted a critical analysis of the method and concluded that major losses of *Cryptosporidium* occur during centrifugation and clarification. Recovery efficiencies are considerably better using Method 1623 and average some 40 - 50% range.

Method optimisation is necessary for detecting small numbers of oocysts in environmental samples consistently, and further work is required to (i) optimise IMS recovery efficiency, (ii) quality assure performance-based methods, (iii) maximise DNA extraction and purification, (iv) adopt standardised and validated loci and primers, (v) determine the species and subspecies range in samples containing mixtures, and standardising storage and transport matrices for validating genetic loci, primer sets and DNA sequences.

Health Canada refers to a method involving filtration and IMS (5) and also mentions flow cytometry with fluorescence activated cell sorting, PCR with or without restriction fragment length polymorphism. Developments and refinements to the analytical methodology continue for example to establish infectivity (90).

Methods under development include PCR, real time PCR, microsatellite and microarray systems. Although molecular methods require extensive sample processing and purification, they are potentially very sensitive, specific multiple genes can be targeted to increase confidence in positive results, high sample number throughput via automated analyses, quantifiable, instrumentation costs comparable with other lab equipment.

11 CONCLUSIONS AND RECOMMENDATIONS

Conclusions

There are numerous animal vectors whereby *Cryptosporidium* may gain access to water sources, and in some instances, to treated water. Key features of some 51 incidents involving cryptosporidiosis in the community between 1984 and 2009 are summarised and common issues identified. It should be remembered that outbreaks of other microbiological waterborne disease may offer learning opportunities. Most incidents arose through contamination of source waters, deficiencies in treatment or ignorance of relevant factors leading to a deterioration in water quality.

Multiple barriers are essential in preventing the occurrence of *Cryptosporidium* in treated water supplies. Initial selection of a source of good quality water should be followed by active efforts to establish and maintain a catchment protection policy. Although initially of good quality, a source may not necessarily remain so and routine operational monitoring is required to inform of any deterioration. Appropriate treatment must be in place and operated according to design criteria.

Significant changes in water quality either at source or during or after treatment must be detected by appropriate monitoring and operators must be informed of any significant change in quality that might require intervention. Similarly, operators need to be aware of other factors that might impinge adversely on water quality, including environmental, hydrological or climatic conditions.

An overview is presented of treatment processes, including clarification and filtration, identifying critical points. Efficient removal of particulate matter is considered particularly important given that *Cryptosporidium* oocysts are small particles and are not susceptible to many of the disinfection systems currently installed. The application of alternative disinfection systems are summarised and include ozonation, UV light, membrane filtration and chlorine dioxide.

Continuous monitoring for bacteriological and other microbiological parameters, including Cryptosporidium, is not possible. Grab samples are of small volume when compared with the normal output of treatment works. For these reasons, continuous sampling of large volumes under defined conditions using a filtration method have been proposed. The determination of other parameters indicating the presence of particles, such as turbidity or particle counts, may act as appropriate surrogates giving information on the effectiveness of particle separation processes.

Risk management plans are vital in the identification of potential sources of contamination. Factors potentially affecting sources, hydrological features and catchment factors are considered. The risk assessment method developed by the Ministry of Health in New Zealand is recognised as a benchmark of well-recognised global approaches.

The water safety plan approach as proposed by the World Health Organisation has been adopted by many countries. The Australian framework for management of drinking water quality is one useful example. Application of the approach to water catchments, treatment works, distribution systems and consumer installations could be considered part of the multiple-barrier approach.

The regulatory approach of other countries is presented. Generally, European countries follow the WHO approach. The US, Canada, New Zealand and Australia have their own standards. Most

countries do not require regulatory monitoring for *Cryptosporidium* because analysis times are long, grab samples are of limited representation of the total output from a works, the infective dose has not been unequivocally established and it is difficult to establish the viability of any oocysts detected. Accordingly, treatment criteria have been adopted with monitoring of surrogate parameters.

The USEPA has introduced a robust analytical system based on filtration, magnetic bead separation and antibody recognition.

Ireland has specific issues attributable to the nature of the hydrogeological situation combined with high stocking rates of livestock and the absence of filtration from regular water treatment (21). In many parts there is only a shallow layer of soil and subsoil over karst limestone whilst in other areas there are heavy soils that can be prone to either rapid surface runoff after rainfall or channelling of water along large pores. These situations can result in rainwater that may hold a significant contaminant load rapidly reaching surface water reservoirs or groundwater. There is a need to reduce the potential contamination of sources and to ensure that treatment and control of treatment is robust.

RECOMMENDATIONS

1. Reports into individual outbreaks of cryptosporidiosis are an essential source of information allowing the identification of deficiencies leading to that particular incident. Incidents involving other pathogens show similar deficiencies and failings. Reviews of past outbreaks of cryptosporidiosis and other pathogens highlight often repetitive failings.

   I recommend that key lessons learnt from such events should be used to inform and guide water suppliers.

2. Many of the failings leading to outbreaks are associated with a lack of awareness of factors affecting source waters or a lack of appropriate treatment barriers to address changes in source water quality. Changing conditions may not only affect source water quality but also the efficiency of subsequent treatment. A lack of expertise may lead to an inability to either recognise such changes or the significance of those changes. Even when staff have those skills and awareness, they must have delegated responsibility to act appropriately and in a timely manner to mitigate the effects of such changes.

   I recommend that honest self assessments of the vulnerabilities of water treatment and supply systems are undertaken and appropriate action taken to rectify any deficiencies identified.

3. Water safety plans aim to understand the whole water supply chain and identify potential sources of contamination and control them. WSPs should validate and monitor any control measures that are introduced and ensure that timely responses are instigated to address any developing problems. Subsequent verification of water quality is achieved through appropriate sampling and analysis. In many ways, WSPs formalise what suppliers should be achieving through the adoption of the recommendations above to completely understand and control the water supply system from source to tap.

   I recommend that the existing Water Safety Plan approach is expanded and implemented by all suppliers.

4. The quality of ground water sources is generally less variable than that of surface water sources although continued good quality can never be guaranteed. Surface water sources are very prone to weather related and environmental events leading to extreme and rapid changes in water quality. When sudden and severe deterioration in quality occurs, the effectiveness of treatment works designed and installed to cope with average conditions, may be compromised. Such challenges to treatment occur at the very time when higher concentrations of *Cryptosporidium* may be expected to be present in the source water.

   I recommend that an assessment is made of the treatment available at each site and the ability of that treatment to cope with the worst possible conditions of source water quality.

5. All stages of treatment must be operated within their design parameters. The control of treatment processes relies on robust information about the performance of each stage, which is usually provided through the interpretation of analytical data. Such data may be generated by regular grab sampling and analysis or by continuous on-line monitors. The establishment of a routine sampling regime allows the setting of alarm limits to indicate when a process is out of control or approaching that point. Clearly defined responses are then required to allow operators to respond appropriately.

   I recommend that appropriate monitoring carried out at each stage of treatment and that appropriate alarm levels are established to identify when treatment processes are out of control or approaching that situation.

   I also recommend that robust procedures are put in place to ensure an appropriate and timely response to developing or actual out of control situation.

6. Removal of small particles, including *Cryptosporidium* oocysts, is dependent on well operated separation processes. Filtration systems are an essential part of the clarification process and must be operated within their design parameters. Turbidity monitoring or particle analysis allows an understanding of the condition of filters and their operating efficiency through continuous real-time information.

   I recommend that continuous turbidity monitors or particle counters be used to monitor the effectiveness of particle removal for each filter.

7. The routine analysis of treated water for *Cryptosporidium* is carried out in few countries and then under specific conditions, for example when inadequate treatment is available to remove *Cryptosporidium* oocysts. More often, sampling of treated water is carried out when there is evidence for treatment being compromised. Such evidence may come directly from analytical data such as turbidity or microbiological analysis, or indirectly through observation of filter performance, awareness of significant weather events or loss of control of treatment process.

   I recommend that sampling of treated water for Cryptosporidium be carried out when oocysts are, or are likely to be, present in the raw water and when the treatment provided is not suitable for the removal of oocysts from water. The sampling programme should be established by the relevant professionals to ensure that adequate information is made available to protect public health.

8. The use of UV for the inactivation of *Cryptosporidium* is becoming more common. However, fouling of lamps and lamp failure are potential weakness. The output of UV devices decreases in low temperatures and the effectiveness of UV is dependent on the transmissivity of the water. Many UV units are not validated for removal of *Cryptosporidium* and guidance is limited.

   I recommend that where UV systems are installed for the inactivation of *Cryptosporidium*, that they are validated for each site.

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APPENDIX A1 SAMPLING AND ANALYSIS IN SOURCE WATERS AND TREATED WATERS

1 SOURCE WATERS

GENERAL

This appendix summarises the approach to sampling and analysis of source waters in the US and, where appropriate, has been modified to reflect the requirements of the EPA.

All surface water sources and ground water sources under the influence of surface water must be characterised to determine what treatment is required to reduce *Cryptosporidium* in the treated water leaving the works. Initial sampling and analysis should be carried out to confirm whether or not ground water sources are under the influence of surface water.

Source water monitoring will allow the determination of the average concentration of *Cryptosporidium* and allow classification of the source according to risk.

Unfiltered systems may be divided into those systems that do or do not require additional treatment to provide two forms of disinfection.

SAMPLING REQUIREMENTS

Sampling schedules are based on the size of the population served:

- Schedule 1: Systems supplying 100,000 population or more
- Schedule 2: Systems supplying 50,000 – 99,999 population
- Schedule 3: Systems supplying 10,000 – 49,999 population
- Schedule 4: Systems supplying fewer than 10,000 population.

Large systems (supplying more than 10,000 population) that provide filtration (or that are at present unfiltered but are required to provide filtration) should monitor source water for *Cryptosporidium*, E coli and turbidity at least once per month for two years.

Small systems (supplying fewer than 10,000 population) that provide filtration (or that are at present unfiltered but are required to provide filtration) should first monitor source water for E coli or an alternative indicator approved by the EPA (such as turbidity) at least once every two weeks for one year.

Cryptosporidium monitoring should be carried out at a frequency of at least two per month for one year or at least monthly for two years if one of the following trigger events occurs:

- The annual mean concentration of E.coli exceeds 10 E coli per 100ml for systems deriving water from lakes or impounding reservoirs;
- The annual mean concentration of E.coli exceeds 50 E coli per 100ml for systems deriving water from flowing water sources (rivers, streams);
- The value of the approved alternative indicator exceeds the approved trigger level; or
- The system does not carry out monitoring for E.coli at least one every two weeks for one year.

Small systems may choose to monitor for *Cryptosporidium* immediately instead of for E. coli.

All systems should repeat source water monitoring after six years to determine whether a significant change in source water quality has occurred.

SAMPLING POINT

Source water samples should normally be taken prior to any treatment but the EPA may relax this if collection of such a sample is not feasible and if treatment is unlikely to have an effect on sample analysis. Samples should be taken after pre-sedimentation or impoundment reservoir.

2 TREATED WATERS

Most countries do not require monitoring for *Cryptosporidium* in treated water. The UK initially required continuous sampling under specified conditions and daily analysis at treatment works where a risk assessment of sources had identified a particular risk and where inadequate treatment is provided. Continuous sampling is not required where water suppliers have installed treatment capable of removing all particles greater than 1 µm in diameter. Where no risk has been identified in the raw water or where a potential risk has been identified but appropriate treatment and control systems have been installed, routine monitoring may not be required.