Using particle monitors to minimise *Cryptosporidium* risk: a review

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ABSTRACT

Previous research has shown that reducing the amount of particulate matter in potable water can reduce the risk of human pathogens such as *Cryptosporidium parvum* entering drinking supplies. Although particle counters are a powerful tool in the amount and specificity of information they produce compared with traditionally used turbidimeters, the UK water industry has so far remained relatively cautious in embracing this new technology. This is because much doubt still remains over the value and practical use of these monitors.

The paper summarises three areas in which particle counters have been beneficial, utilising (a) their higher sensitivity to changes in water quality at low turbidities (below 0.1 NTU), (b) their higher sensitivity to changes associated with larger particle sizes, and (c) their particle-sizing ability. In general, particle counters are best used as an optional process research/optimisation tool: turbidimeters remain the preferred monitor for process control.

Key words | *Cryptosporidium*, particle counting, turbidity, water quality, water treatment

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INTRODUCTION

Cryptosporidium in drinking water

Cryptosporidium is a protozoan that can cause an acute form of gastroenteritis, known as cryptosporidiosis, in humans and animals. The first diagnosed case of cryptosporidiosis in a human was reported by Nime *et al*. (1976). Since then, the number of reported cases has risen significantly and concern has grown as a result of several high-profile outbreaks of the disease documented in Badenoch (1990, 1995), Lisle & Rose (1995), Solo-Gabriele & Neumeister (1996) and Bouchier (1998).

Cryptosporidiosis is spread by the faecal-oral route. Outside of an infected host, the parasite exists as a hard-coated, dormant form called an 'oocyst'. These are spherical, approximately 4–6 μm in diameter. If ingested in sufficient number, the organism is able to infect the small intestine where it undergoes a complex life-cycle (Casemore 1990; Smith & Rose 1990). The final stage sees an infected host typically passing millions of *Cryptosporidium* 'oocysts' in their faeces, often over a period of several weeks after initial infection (Smith *et al*. 1995). The disease is usually spread by direct contact with an infected person or animal. However, it is a particular concern in the water industry because oocysts can contaminate raw water supplies via the discharge or run-off into rivers of human and animal wastes. Indeed, LeChevallier *et al*. (1991) found oocysts in 81% of raw water samples taken from 66 works, with concentrations ranging between 0.07 and 484 oocysts per litre. If treatment plants are deficient either in design or operation, a significant number of these oocysts can pass into drinking water supplies. It is believed that only a small number of oocysts is required to infect a host: in Blewett *et al*. (1993), water containing five *C. parvum* oocysts per litre was sufficient to infect all 10 lambs drinking it. Judging by this high level of infectivity, the authors conjectured that, in some cases, infection might even have been caused by a single oocyst. Similarly, in a trial of human volunteers, Chappell *et al*. (1999) reported that half were infected by a dose of just 10 oocysts.

Particle monitors

Currently, *Cryptosporidium* oocysts are countable only by microscopy. Since the analysis procedure takes several hours to complete from collection to identification, utilities must rely on surrogate parameters for an up-to-date assessment of *Cryptosporidium* risk at their treatment plants. These include measurements given by photometric particle monitors such as turbidimeters and particle counters. A full description of these monitors has been published elsewhere (Hargesheimer *et al*. 1992; Lewis *et al*. 1992; Hunt 1993, 1995; Hargesheimer & Lewis 1995).

Turbidity is a general measure of water 'cloudiness' created by particles suspended in a water sample. It has been used to assess drinking water quality for a century and is arguably still the most important particle measurement used today in water treatment. Most modern turbidimeters measure the intensity of light scattered at 90° to an incident beam as specified by the international standard, ISO7027 (British Standards Institute 1994). In this case the instruments are termed 'nephelometric'. They are calibrated against a standard of known value (typically formazine). Unless otherwise stated, references to 'turbidity' or 'turbidimeters' will refer to conventional nephelometric instruments.

Particle (size) counters are a more recent development in the industry. These not only count but also size particles within certain predefined size bands, depending on the sensor used. Imported from other 'clean water' industries such as pharmaceuticals and semiconductor industries, they were first used on-line on a water treatment works in 1982 in South Nevada, USA (Hutchinson 1985; Hargesheimer & Lewis 1995). Several different methods are used to count particles. The most commonly used particle counters work on a light obscuration principle. These monitors detect changes in transmitted light (laser) intensity as individual particles pass through a narrow laser beam. Particles are counted and sized within different, discrete bands, usually from one or two microns (μm) upwards, depending on the type of sensor used.

Two other particle counters are also briefly mentioned here. Electrical resistance particle counters detect fluctuations in resistance created as particles pass through a small aperture (illustrated in Hargesheimer *et al*. 1992). The technique is believed to provide an accurate way of sizing particles (Van Gelder *et al*. 1999) but is not considered suitable for on-line analysis (Lewis *et al*. 1992). Another counting method, more recently imported into the industry, is the 'forward angle light scatter' (FALS) method. It is similar to the light obscuration counter except that light scatter is measured at a forward angle of 1–19° to the incident beam. Any particles passing through the sensing zone creates a change in light intensity, which can be related to particle size. The technique allows sizing of very small particles (down to 0.1 μm, Hargesheimer *et al*. 1992), and therefore is suited only to very clean water applications.

DIFFERENCES BETWEEN PARTICLE MONITORS

What particles do they see?

It is important to realise that particle monitoring is not an exact science, but that each instrument reflects a unique set of the particles' characteristics: size, shape, texture, translucency, refractive index, etc. (Hunt 1993, 1995). Turbidimeters see the widest range of particle sizes, but their reading is heavily influenced by the number of submicron particles present in the sample as shown by latex bead experiments (Gregory 1994). Conversely, particle counters usually count supermicron particles. In addition, non-spherical particles such as rod bacilli may be sized differently by light obscuration particle counters depending upon how they pass through the laser beam. Translucent particles are also undersized. According to Gregory (1994), *Cryptosporidium* oocysts, 4–6 μm in diameter by microscopy, are sized as a 2 μm latex bead. Alternatively, opaque particles such as carbon fines are sized fully, but scatter no light and so are invisible to turbidimeters (Englehardt 2000).

Reed & Mery (1986) observed that a light obscuration particle counter undersized floc particles by an order of one magnitude. This was attributed to the break-up of particles as they passed through the narrow particle counting aperture. Treweek & Morgan (1977) observed a similar result using an electric resistance counter. They

Table 1 | Comparing particle counter resolutions from latex bead experiments

Reference	Type	Resolution (%) at different bead sizes			
		2 µm	3 µm	5 µm	10 µm
Goldgrabe-Brewen (1996)	Light obscuration model 1	25	19	12	6
	Light obscuration model 2	10	3	2	—
	Light obscuration model 3	9	3	3	—
	Light obscuration model 4	15	18	—	7
		2.6 µm	3.0 µm	5.9 µm	10.0 µm
Van Gelder *et al.* (1999)	Electrical resistance model	5	8	5	8
	Light obscuration model A	77	—	17	—
	Light obscuration model B	—	32–65	—	20–30

suggested that, in this case, the undersizing was due to the particle counter not measuring the interstitial volume between aggregated particles. Conversely, Montesinos *et al.* (1983) noted that microorganisms were oversized by an electric resistance meter in comparison with microscopy methods. They attributed this to then 'shrinking' of the microorganisms during slide preparation.

Resolution

In terms of particle counting, resolution is mathematically defined as 'the minimum size difference (%) between two particles such that an instrument can consistently differentiate between them'. A sensor with a good resolution (low percentage figure) will size identically shaped spheres in a more precise band as explained in Hargesheimer *et al.* (1992) and Van Gelder *et al.* (1999).

In latex bead experiments, Van Gelder *et al.* (1999) found that electrical resistance monitors showed good resolution at all particle sizes: less than 10% for all bead sizes tested (Table 1). However, corresponding results for two light obscuration particle counters from different manufacturers were considerably less impressive especially for the smaller particle sizes. Van Gelder also found that light obscuration counters consistently underestimated the concentration of 2–5 µm particles. Goldgrabe-Brewen (1996) reported light obscuration counters in a more favourable light, with the resolution of four different sensors lying between 9–25% for the 2 µm size range. Despite the large improvement on the Van Gelder figures, these still sometimes exceeded manufacturers' specifications (typically less than 10% above 2 µm in size).

As far as turbidimeters are concerned, resolution refers to the smallest unit of measurement made by each instrument, i.e. to how many decimal places the instrument reads. Most turbidimeters read to two or three decimal places, satisfactory for potable water monitoring.

Accuracy and precision

In terms of particle measurement, 'accuracy' refers to how closely the monitors match a formazine or latex bead standard. Conversely, 'precision' refers to how closely two or more 'like' monitors match each other. It is possible to have several closely matched (high precision) instruments that do not compare favourably with their standard (low accuracy). This is discussed further, for example, in Hargesheimer *et al.* (1992).

Table 2 | Tests of particle monitor accuracy

Reference	Sample	Type	No. of units tested	Max diff in >2 µm count*	Count matched?
Goldgrabe-Brewen (1996)	Latex bead suspension	Light obscuration	8	5%	Yes
			6	7%	Yes
			3	6%	Yes
			11	35%	Yes
Other work cited in Goldgrabe-Brewen (1996)	Not specified	Not specified**	—	30%	No
Routt *et al.* (1997)	Filter effluent	Not specified**	3	Around 30%	No
	Latex suspn	Not specified**	8	Around 25%	Yes
Pickel *et al.* (1997)	Filter effluent	Not specified**	4	45%	No
				3%	Yes
Van Gelder *et al.* (1999)	Filter effluent	Light obscuration	2	32% (test 1)	No
				8% (test 2)	No
		Light obscuration	2	102% (test 1)	No
				25% (test 2)	No
		Electrical resistance***	1	113% (test 1)***	No
				63% (test 2)***	No
				170% (test 3)***	No

*In Goldgrabe-Brewen (1996) and Pickel *et al.* (1997), the % difference quoted is that from a randomly selected 'master' instrument.
In Routt *et al.* (1997) and Van Gelder *et al.* (1999) the % difference quoted is that from the mean count.
**It is likely that non-specified models are light obscuration monitors.
***Compared with the other light obscuration meters.

For particle counters, it is easier to test precision; several researchers have compared readings given by a number of like sensors (Table 2). Although most have shown that particle counters are a relatively imprecise measurement, the level of imprecision varies considerably. The harshest figures were presented by Van Gelder *et al.* (1999) who suggested that two like sensors could differ by up to 100% of their mean value. Others suggest a variation of up to 30% is more likely. Count matching is the practice of 'fixing' calibration so that a particle counter reads the same as a 'master' counter rather than calibrating it against latex bead standards. Published data indicates that this can significantly reduce counting differences between like sensors although some anomalies still occur.

The variations in particle counter resolution and precision warn against attaching too much significance too individual particle counts especially in the 2–5 µm range. Currently, it is commonly believed that particle counters are best used as a comparative tool to indicate trends in water quality rather than in 'absolute' measurement. Because of the irregularities, Van Gelder *et al*. (1999) recommended that particle counters should not be considered for regulatory purposes. Turbidimeters offer a much higher level of accuracy and precision. As shown in Sadar (1999), most turbidimeters measure accurately to within ± 2% of their formazine standard.

LINKS BETWEEN *CRYPTOSPORIDIUM* AND PARTICLE MONITORS

In the UK, the first major diagnosed outbreak of cryptosporidiosis was in 1989 in Swindon and Oxfordshire. This prompted the Government to commission an Expert Group Report, headed by Sir John Badenoch. This Group has published three reports, Badenoch (1990, 1995) and Bouchier (1998), which have advised water companies upon improving treatment design and operations. Bouchier (1998) concluded that waterborne outbreaks of cryptosporidiosis 'do not just happen' but instead are the result of inadequate treatment design or operation. These are typically marked by a rise in the number of particles in treated water, as detected by particle monitors such as turbidimeters or particle counters. For example, prior to the well documented 1993 outbreak in Milwaukee, USA, treated water turbidity rose around sevenfold from 0.25 to 1.7 NTU (Nephelometric Turbidity Units) (Lisle & Rose 1995) as a result of several process deficiencies. For ten years previous to this, the turbidity had not exceeded 0.4 NTU (Solo-Gabriele & Neumeister 1996).

Particle counters and turbidimeters are not generally credited as being able to detect or count *Cryptosporidium* in raw and treated drinking waters. Gregory (1994) described how oocysts have a similar refractive index to water and so are practically invisible to turbidity instruments. Dutari *et al*. (1999) showed that the turbidity and oocyst concentration of different oocyst suspensions correlated with each other, but the oocyst dose required to affect turbidity readings (more than 70,000 per ml) was far in excess of those found in raw or treated water supplies. This compares unfavourably, for example, with UK drinking water standards which deem 1 oocyst in 10 litres to be unacceptable (DETR 1999). This standard is similarly minuscule when compared with typical particle counts—treated water samples usually contain between 1 and 10,000 particles per ml above 2 μm.

The issue of whether particle monitors can be used to predict oocyst occurrence indirectly is more controversial. In a survey of 85 raw water samples taken from 66 different locations, LeChevallier *et al*. (1991) revealed a highly significant relationship ($p<0.01$) between positive *Cryptosporidium* concentrations and turbidity (Table 3). This suggests that there is a general association between higher oocyst concentrations and more heavily polluted watercourses. It does not necessarily mean, however, that changes in raw water turbidity or particle counts can be used to predict oocyst occurrence on a site-specific basis. LeChevallier & Norton (1992), for example, had only partial success in applying this relationship at individual works. In addition, the link with oocysts appears to be even less apparent for treated water samples: Wilson & Morse (1999), Morse *et al*. (2000) and Payne (2000) all showed oocyst occurrence to be largely independent of filter effluent particle counts (Table 3). It would appear therefore that, in general, *Cryptosporidium* risk cannot be uniquely determined from particle data.

However, given that oocysts are present in raw water, it has been widely shown that, on a site-specific basis, there often exists a direct link between oocyst numbers and turbidity/particle counts in terms of removal across a treatment process (Table 3). For example, LeChevallier & Norton (1992) demonstrated a strong link ($p<0.05$) between oocyst removal and turbidity and particle removal (>5 μm). This is important as it shows that minimising particulate passage through a works can reduce *Cryptosporidium* risk. Conversely, it also shows that an increase in treated water turbidity/particle counts can, as the Bouchier Report suggests, lead to greater risk, given that oocysts are present in the raw water.

To further assess the relationship between particle and oocyst removal figures, data from seven published oocyst-seeded process performance trials were compared (LeChevallier & Norton 1992; Nieminski & Ongerth 1995; Ongerth & Proctor-Pecararo 1995; Li *et al*. 1997; Fox *et al*. 1998; Coffey *et al*. 1999; Hamilton *et al*. 2000). Data taken

Table 3 | Published *Cryptosporidium*/particle monitor correlation tests

					Correlation			
Sample	**Reference**	**Plant scale**	**Oocysts source**	**Particle monitoring**	**Significance**	**P**	**R^2**	**Comments**
Raw water	LeChevallier *et al.* (1991)	Full	Natural	Turbidity	Very strong	$p < 0.01$		66 sites
	LeChevallier & Norton (1992)	Full	Natural	Turbidity	None	Not sig.	—	Site 1
				P. counts (> 5 μm)	None	Not sig.	—	
				Turbidity	Weak	$p = 0.06$	—	Site 2
				P. counts (> 5 μm)	Weak	$p = 0.07$	—	
				Turbidity	Weak	$p = 0.08$	—	Site 3
				P. counts (> 5 μm)	Weak	$p = 0.07$	—	
				Turbidity	Strong	$p = 0.03$	—	All 3 sites
				P. counts (> 5 μm)	Strong	$p = 0.02$	—	
Treated water	Wilson & Morse (1999)	Full	Natural	P. count (> 2 μm)	None	—	—	1 filter outlet
	Morse *et al.* (2000)	Full	Natural	Turbidity	None	—	—	3 filter outlets
				P. count (2–5 μm)	None	—	—	
	Payne (2000)	Full	Natural	P. count (> 2 μm)	None	—	—	1 filter outlet
Treatment efficiency (Particle/oocyst removal)	LeChevallier & Norton (1992)	Full	Natural	Turbidity	Strong	—	$R^2 = 0.59$	4 sites
				P. counts (> 5 μm)	Strong	—	$R^2 = 0.69$	
	Nieminski & Ongerth (1995)	Both	Seeded	Turbidity	Strong	—	$R^2 = 0.55$	2 sites
				P. counts (4–7 μm)	Very strong	—	$R^2 = 0.79$	
	LeChevallier *et al.* (1999)	Full	Natural	P. counts (> 3 μm)	Strong	—	$R^2 = 0.45$	27 sites

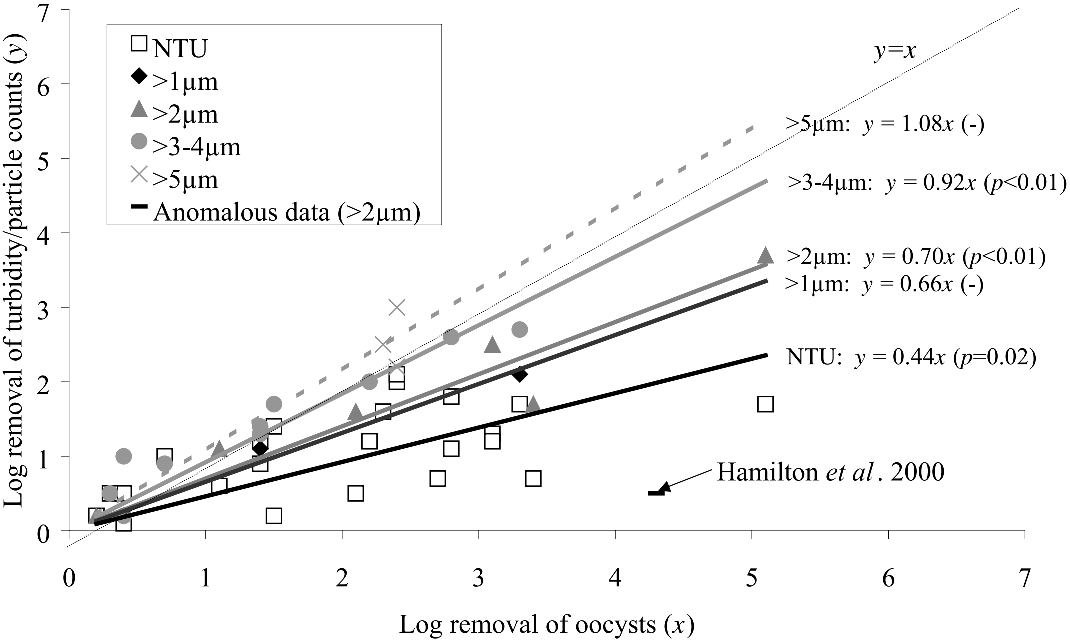

Figure 1 | A comparison of published particle and oocyst removal data.

from these studies fell along highly significant lines (Figure 1), suggesting that, in the majority of cases, particle removal statistics do provide a good indication of a plant's defences against oocysts. The removal of particles around and above oocyst size (4–6 μm) seemed to give the most accurate indication of oocyst removal. Smaller particle sizes (>1 μm, >2 μm) gave more conservative estimates, with turbidity, whose reading is based primarily on submicron particles giving the harshest estimate. In fact, turbidimeters are not ideal for assessing plant performance as they are progressively less sensitive to change in water quality at lower values, typically at some level below 0.1 NTU (discussed later) and so may underestimate plant performance.

In the model differential counts and cumulative counts have been grouped together e.g. 4–6 μm has been grouped with >4 μm, 3–6 μm with >3 μm etc. This has been undertaken as in most water samples particles have similar size distributions and are dominated, in terms of their number, by the smallest measured particle sizes. Although the model is 'observational', it at least provides a useful tool for comparing oocyst and particle removal data. Data from Hamilton *et al.* (2000) did not fit with the rest of the data and were excluded from the regression analysis. In this instance the calculated particle removal rates were unusually low compared to the high numbers of oocysts removed by the filters. Although the reasons for this are unclear, one possibility is that certain particles may have preferentially passed through the filters because of a peculiar aspect of their shape, rigidity, texture, surface charge, etc. Another possible explanation is that in the absence of filter prechlorination, bioparticles may have been generated in the filter media.

REGULATIONS AND MONITORING PRACTICES

Although it is widely believed that minimising particle numbers in drinking water can reduce *Cryptosporidium* risk, there is still much debate as to how this can be best achieved with particle monitors. In the UK and USA, for example, where treatment is tightly regulated, there are some differences in the regulatory approach.

The UK approach

The absolute turbidity standard for treated water in the UK is relatively relaxed: a standard of 4 NTU is enforced through the 1989 Water Supply (Water Quality) Regulations (DoE 1989). However, the UK does have stringent *Cryptosporidium* legislation. Following the recent amendment to this Act (DETR 1999), companies must continuously monitor for *Cryptosporidium* at works deemed to be at high risk and may be prosecuted if 1 oocyst is found per 10 litres of treated water sampled. This applies to all *Cryptosporidium* oocysts, not just the human pathogen *C. parvum*, irrespective of whether or not they have been deactivated.

A company in breach of this standard can evade prosecution if they are able to prove they have operated with 'due diligence'. The question of exactly what constitutes 'due diligence' is subject to some debate, although the Badenoch/Bouchier Expert Group recommendations are thought to be the best available guide. Although the Expert Group has set down clear recommendations for installation and use of turbidimeters, particle counters are merely 'encouraged' as an additional optimisation tool. Currently the industry has so far resisted the imposition of low turbidity or particle count standards, which contrasts sharply with USA regulations. Also, under the UK system, the level of turbidity is not viewed as being as important as anomalous data:

> 'Water utilities should define for each of their treatment works the value and duration that constitute a significant deviation in turbidity of the final water irrespective of its relationship to the regulatory standard; for example, it may be that at a large water treatment works alarms should be set to be triggered by any increase in turbidity in the final water of greater than 50% of the normal average or suitably representative level . . .'
>
> Recommendation 5.4.4 (Bouchier 1998)

The USA approach

The approach taken in the USA supports a number of key differences. In 1998, amendments to the existing Surface Water Treatment Rule (SWTR), set a zero 'maximum concentration goal' (MCG) for all *Cryptosporidium* oocysts (EPA 1998). Arguably, this standard is not as rigorously enforced as in the UK: instead, they have introduced a low regulatory standard for treated water turbidity to reduce microbial risk indirectly.

Utilities have been charged with ensuring that key works are designed to achieve a 99% or '2-log' removal of all *Cryptosporidium* oocysts. In the original SWTR (EPA 1989), particle counting was recommended as a surrogate means to verify the overall effectiveness of particle removal during treatment. In the 1998 amendments, the EPA concluded that a plant fulfilled this 2-log removal criterion if it (a) complied with a maximum treated water turbidity standard of 1.0 NTU, and (b) also achieved a target of 0.3 NTU in 95% of samples taken each month. These limits were relaxed to 5.0 NTU (max) and 1.0 NTU (95th percentile) for slow sand and diatomaceous earth filters. The EPA reached this conclusion in light of studies such as Ongerth & Proctor-Pecararo (1995), whose pilot filter plant succeeding in attaining at least 2-log removal of seeded *Cryptosporidium* oocysts until sub-optimal coagulation conditions were introduced, whereupon their filtered water turbidity rose above 0.3 NTU.

Generic particle monitor standards are, on balance, more widely accepted in the USA than in the UK. For example, Consonery *et al.* (1997) details an on-going, annual risk assessment of all treatment plants in Pennsylvania, USA, started in 1988, in which works-treated water turbidity and particle counts have been directly compared; treated water turbidity above 0.1 NTU was deemed to be an unacceptable level of risk. In many ways, the Consonery study was ahead of its time and, in light of studies such as LeChevallier & Norton (1992), any reduction of turbidity or particle counts should indeed have lead to a significant reduction in *Cryptosporidium* risk, if oocysts are present in the raw waters. However, although the setting of a low turbidity or particle count standard is convenient and may be desirable at some works, one could question the cost-effectiveness of this approach. As previously discussed, high treated water turbidity and particle counts do not necessarily correspond to high pathogen risk. This will ultimately depend upon the composition of particles in the raw water. Conversely, low treated water turbidity and particle counts do not always guarantee safe drinking water. For example, although many outbreaks have been associated with high turbidity water, others such as in Torbay (DWI

1997), Las Vegas (Roefer *et al.* 1996), and Swindon and Oxfordshire (Bouchier 1990) were linked to relatively low turbidity treated waters.

BENEFICIAL PARTICLE COUNTING APPLICATIONS

Turbidimeters are a relatively cheap, reliable and accurate measure of particles in a water sample and, as the USA and UK regulations indicate, still remain the most popular instrument for monitoring and controlling processes. Conversely, particle counter use remains a relative 'grey area'. Particle counters are relatively more expensive to buy and run, and are of questionable accuracy. In particular, the calibration of particle counters with latex bead standards can be a costly, time-consuming process, often requiring the instrument to be sent to the supplier. They will only be valuable therefore if they relate something different to turbidity.

Although turbidimeters and particle counters are quite different in design, it is surprising how frequently the different trended measurements correlate with one another (Hargesheimer *et al.* 1992; Hargesheimer & Lewis 1995; Casale *et al.* 1999; Morse *et al.* 1999; Hamilton *et al.* 2000). This is because, irrespective of their total count, particles in potable water samples tend to conform to a standard particle size distribution, their number and size varying according to an inverse power (β), as described in Bader (1970), Kavanaugh *et al.* (1980), Ginn *et al.* (1992), Hargesheimer *et al.* (1992) and Hamilton *et al.* (2001). Indeed, Morse *et al.* (2000) concluded that:

> 'Most of the information available from particle counters can be obtained from turbidimeters and other parameters that are routinely monitored in terms of increasing particle removal efficiency.'

Other researchers have revealed occasional differences between the trends, suggesting that particle counters may have some potential benefits. These relate to three specific areas. First, particle counters can be a more sensitive measure of particle numbers in low turbidity samples (<0.1 NTU). Secondly, they are more sensitive to changes in water quality associated with large particle sizes such as certain filter breakthrough events. Thirdly, they can be used to investigate anomalies in particle size distribution. Each of these benefits is now discussed in detail. (The first two of these can be achieved using only a single-channel particle counter measuring a total count, for example. Multichannel counters are needed only for the third category.)

Higher sensitivity below 0.1 NTU

Whereas turbidimeters are prone to 'flat-lining' at lower turbidities (<0.1 NTU), particle counters frequently are able to identify more clearly changes in particle numbers. This has been shown by several authors including Tate & Trussell (1978), Jacangelo *et al.* (1991), Hargesheimer *et al.* (1992), Adham *et al.* (1995) and Hargesheimer & Lewis (1995). The extra sensitivity offered by particle counters means they can be a useful optimisation tool in fine-tuning various high performance processes (Table 4). For example, Hargesheimer *et al.* (1999) used filtered water particle counts to fine-tune a plant coagulant dosing regime during stable raw water conditions. Similarly, several studies have used use them to assess alternative filter start-up strategies such as slow-start to minimise subsequent particulate passage into supply (Colton *et al.* 1996; Hall & Croll 1997; Baird & Hillis 1998).

Particle counters have also been used to detect 'small' structural and mechanical defects. Ginn *et al.* (1997), for example, found various leaks in filters at two works fitted with particle counters: namely a leaking floor tile, leaking backwash valves and a leak from a settlement tank into a filter underdrain. Similarly, Jacangelo *et al.* (1991) and Adham *et al.* (1995) showed how particle counters (with FALS sensors) can be used to detect compromised membrane filter integrity. Published particle counting applications have not just been limited to filtered water. For example, Englehardt (2000) and Hamilton *et al.* (2000) both used counters to identify subtle changes in groundwater quality resulting from surface water influence.

Although particle counters often show a higher sensitivity, this does not make them essential purchases at all works. Many works produce treated water with turbidity regularly exceeding 0.1 NTU, where particle counters

Table 4 | Selected published particle counting applications

Applications	Examples	Reference
Using filtered particle counts to optimise coagulation/filter pretreatment options	Chlorine	Goldgrabe *et al.* (1993)
		Wilczak *et al.* (1992)
	Coagulant	Hargesheimer *et al.* (1999)
		Hutchison (1985)
		Tate & Trussell (1978)
	Flocculation	Tate & Trussell (1978)
	Ozone	Bourgine *et al.* (1998)
		Chipps *et al.* (1995)
		Hall *et al.* (1999)
		Wilczak *et al.* (1992)
	Powdered activated carbon (pre-clarifier)	Standen *et al.* (1997)
Assessing filter backwash and start-up strategies	Optimising filter run-times	Morse *et al.* (1999)
		Hamilton *et al.* (2000)
	Collapsed air pulsing	Colton *et al.* (1996)
		Hall & Croll (1997)
	Slow start	Baird & Hillis (1998)
		Colton *et al.* (1996)
		Hall & Croll (1997)
	Delayed start	Baird & Hillis (1998)
		Hillis & Colton (1995)
		Saunders *et al.* (1999)
Monitoring for structural/ mechanical defects	Membrane integrity	Adham *et al.* (1995)
		Jacangelo *et al.* (1991)
	Rapid filter integrity	Ginn *et al.* (1997)

Table 4 | *Continued*

Applications	Examples	Reference
Identifying filter breakthrough	Early detection	Kavanaugh *et al.* (1980)
		Keay (1995)
		Murray (1995)
		Saunders *et al.* (1999)
	Simultaneous with turbidity	Hall & Croll (1997)
		Lewis & Manz (1991)
		Pizzi & Rodgers (1998)
Other applications	Identifying surface water influence on groundwater quality	Hamilton *et al.* (2000) Englehardt (2000)
	Using coagulant dosed and clarified water particle counts to optimise coagulant dose	Reed & Mery (1986)

appear to be of diminishing value. For example, according to Bellamy *et al.* (1993) and Consonery *et al.* (1997), the most common problem facing plant operators is the control of coagulant dosage during rapidly changing raw water conditions, as a result of which treated water turbidity can rise substantially above 0.1 NTU. So far, particle counters have not shown themselves to be especially useful in monitoring or remedying this problem.

A more detailed analysis of particle monitor sensitivity has been conducted and will be published separately (Hamilton *et al.* in press).

More sensitive to larger particle sizes

Because particle counters and turbidimeters 'see' differently sized particles, they sometimes respond differently to water quality changes where there is a marked change in particle size distribution. For example, particle counters have provided 'early' warnings of filter breakthrough (Kavanaugh *et al.* 1980; Keay 1995; Murray 1995; Saunders *et al.* 1999). In this context, 'filter breakthrough' refers to the breaking off (detachment) and passing through the filter of particles previously retained by filter media (Ginn *et al.* 1992; Moran D.C. *et al.* 1993; Moran M.C. *et al.* 1993). It is believed to occur first for large particles (>1 mm) as shown in polydiverse bead suspension experiments (Clark *et al.* 1992; Mackie & Bai 1993; Moran D.C. *et al.* 1993; Moran M.C. *et al.* 1993). Interestingly, some authors (Lewis & Manz 1991; Hall & Croll 1997; Pizzi & Rodgers 1998) all showed the 'breakthrough' of turbidity and particle counts occurring simultaneously. Whether this is because the deterioration here was due to the passage of influent particles through the filter, rather than of previously detached particles, is unknown.

In contrast, other events are believed to affect submicron particles predominantly and may be more sensitively monitored by turbidimeters, e.g. filter ripening (Clark *et al.* 1992; Mackie & Bai 1993; Moran D.C. *et al.* 1993; Englehardt *et al.* 1999). Similarly, Ginn *et al.* (1997) detailed how, on one occasion, particle counters responded less strongly than turbidimeters to the failure of a coagulant dosing pump.

The effect of particle size on monitor sensitivity has been examined in Hamilton *et al.* (2001). There it is argued that, in general, the size distribution of particles in samples remains relatively constant although it may vary from site to site. Moreover, for those sites with an abnormally coarse sample distribution, particle counters may be especially sensitive in identifying changes in particle numbers. Conversely, samples with a high proportion of very fine particles may not receive any benefits even at very low turbidities. These results support an earlier theory proposed by Kavanaugh *et al.* (1980).

Apart perhaps from filter breakthrough, which is itself a relatively rare occurrence at most treatment plants, there is currently little evidence to suggest that particles regularly undergo sudden shift-increases in size. Although particle counters can undoubtedly be useful in detecting filter breakthrough and optimising filter run-times to counter this problem, one could question whether it is cost-effective to install particle counters on every filter outlet to achieve this when a single portable instrument might suffice.

Looking at particle size distribution

Rather than focusing on changes in particle counts, as in the two previous sections, some authors have suggested that there may be advantages in monitoring specifically for anomalies in particle size distribution (Table 5). This can by done either by looking obliquely at counts in different size channels or through the use of particle size statistics such as mean particle size, β, etc.

Many of these 'sizing' applications apply to the coagulation-flocculation-clarification processes. For example, Lartiges *et al.* (1995) suggested that the optimum coagulant dose coincided with the point at which there was a sudden shift in particles in the dosed water to larger sizes. Reed & Mery (1986), on the other hand, suggested that both underdosing and overdosing coagulant led to a decrease in mean particle size, so that the optimum dose produced the lowest total particle count in dosed and clarified water samples. A third view is offered by Hutchinson (1985) who suggested that coagulated and flocculated water particle sizes could be monitored to detect the presence of excessive particle sizes which would blind filters.

Despite these interesting observations, however, these concepts have not been widely incorporated into control instrumentation or procedures, which suggests that some problems still remain in their application. Particle counters are not commonly used on dirty water samples such as raw and coagulant dosed water because of the increased risk of coincidence errors at higher counts, and because their narrow apertures can block easily (Payne 2000). As expressed previously, some authors have also voiced doubts about whether large floc particles can be sized accurately because of the force of shear applied as the particles pass through the counter aperture (Reed & Mery 1986).

Several authors have also used particle sizing to investigate the effect of various filter pretreatments on filter influent and effluent particle size and counts. For example, in a pilot plant study, Kavanaugh *et al.* (1980) showed that although flocculation increased the size of particles in a filter influent, it led to no significant change in effluent particle size or number. In the same paper, they described a process selection model whereby the most suitable treatment processes could be determined from raw water particle size measurements. They also showed that the particle size distribution of samples taken from a lake varied with depth and theorised that this could affect the suitability of certain treatment processes used for treating this water.

Particle size distribution has also been used in various studies to analyse the behaviour of particles in filters. For example, Clark *et al.* (1992) and Hargesheimer *et al.* (1992) both showed that the proportion of larger particles in filtered water increased towards the end of a filter run. Goldgrabe *et al.* (1993) tried to use a variety of particle sizing statistics as part of a study of biological filtration with, self-acknowledged, modest success.

Although these studies show that particle sizing can be a useful process research tool, it is still not commonly used in 'routine works monitoring' and arguably has much to prove in this area. Unless the role of particle sizing can be expanded, the full benefits of multichannel particle counters will not be fully realised in potable water treatment.

Table 5 | Selected published particle sizing applications

Applications	Examples	Reference
Optimising coagulation dose/flocculation energy	An optimum particle size in coagulant-dosed water was found that produced best filtered water quality	Reed & Mery (1986)
		Lartiges *et al.* (1995)
	An optimum flocculated particle size was found that increased media penetration'	Hutchison (1985)
Investigating the effect of filter pretreatments	Flocculation	Tate & Trussell (1978)
		Kavanaugh *et al.* (1980)
	Direct/contact filtration	Chipps *et al.* (1995)
	Ozone	Wilczak *et al.* (1992)
	Process selection	Kavanaugh *et al.* (1980)
Monitoring treated water for changes in particle size	Some changes in groundwater particle size distribution were visible during periods of suspected surface water ingress	Hamilton *et al.* (2000)
	Showed selective removal of different particle sizes at different stages of a particle run	Clark *et al.* (1992)
		Hargesheimer *et al.* (1992)
		Goldgrabe *et al.* (1993)
	A relatively high number of 1–2 μm particles were counted in filtered water during some periods of washwater recycling	Englehardt *et al.* (1999)

SUMMARY

Particle counters and turbidimeters do not detect *Cryptosporidium* oocysts or reliably predict their occurrence in treated waters. However, given that oocysts are present in a works' raw water then there is strong evidence to suggest that minimising treated water turbidity/particle counts will reduce *Cryptosporidium* risk.

Particle counters are not precise instruments and are therefore best used as a trend parameter only. Because of their cost, accuracy, and ease of calibration, turbidimeters remain the first-choice particle monitor for controlling potable water processes.

Often a high degree of correlation is seen between turbidity and different particle counts, effectively making the latter redundant. However, particle counters have demonstrated some benefits in three areas, namely (a) a higher sensitivity to changes in water quality at low turbidities (below 0.1 NTU), (b) a higher sensitivity to changes associated with larger particle sizes (e.g. filter breakthrough events) and (c) the ability to monitor changes in particle size distribution.

These results suggest that particle counters can be a useful process research and optimisation tool in certain site-specific instances, e.g. for filter backwash and start-up testing, to investigate suspected filter breakthrough, to optimise coagulant dosage during stable raw water conditions, to check membrane filter integrity etc. In these instances, permanently installed counters can be considered although portable instruments might suffice. Indeed the case for permanently installed counters on combined and/or individual filter outlets, for example, is still relatively unproven. Further site-specific research is still required to assess whether this is cost-effective. In particular, four key questions need to be answered.

1. Can particle counters (or suitable alternatives) be made more 'operator friendly' in terms of their resolution, precision, accuracy, ease of calibration and calibration checks?
2. In terms of *Cryptosporidium* and other pathogen risk, how important is the fine-tuning of processes (well below 0.1 NTU) relative to other treatment concerns, not least the reduction of higher turbidities?
3. How often do particle size anomalies such as filter breakthrough occur? Is the installation of particle counters on each filter a cost-effective way of monitoring this problem?
4. Although particle sizing can be an interesting process research tool, are multichannel particle counters really needed in 'routine' monitoring?

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