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CRANFIELD UNIVERSITY

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Using particle monitors to minimise *Cryptosporidium* risk

SCHOOL OF WATER SCIENCES

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Using particle monitors to minimise *Cryptosporidium* risk

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ABSTRACT

Over the last two decades, there has been much interest in whether particle counters hold any significant benefit over conventional nephelometric turbidimeters in monitoring potable water treatment processes. Southern Water, which supplies drinking water to two million customers living in Kent, Sussex, Hampshire and the Isle of Wight first used particle counters at one of its works in 1992. This study presents the key results of a three-year study, conducted in conjunction with Cranfield University to find the most beneficial use of these monitors, so that a sensible investment can be made.

This study comprised a series of monitoring trials, conducted at different ground and surface water treatment works. In many instances, there was a strong similarity between turbidity and particle count trends, effectively making one of monitors redundant. However, particle counters were shown to be beneficial in three ways: (a) they could be more sensitive to changes in water quality at low turbidities (below 0.1 NTU), (b) they could be more sensitive to changes associated with larger particle sizes and (c) they could also provide useful information on particle size distribution.

This issue of monitor sensitivity has been analysed using a regression model built from experimental data. For a given water sample, this model predicts how many more times sensitive particle counters will be, in detecting changes in water quality, compared to nephelometric turbidimeters. This indicated that whereas turbidimeters typically 'flat-line' at low values, particle counters are frequently more sensitive and so can be used as a fine-tuning optimisation tool below 0.1 NTU. However, this sensitivity is also proportional to the particle size distribution of the sample; particle counters are more suited to samples containing a high proportion of large particles (>10μm). This explains why particle counters are not always 'more sensitive' below 0.1 NTU.

Although no links could be found between particle counts (and turbidity) and *Cryptosporidium* oocysts, it appears that if oocysts are present in the raw water then inferior particle removal across a treatment process can lead to increased risk. Cryptosporidium oocysts were found even in very low turbidity (<0.1 NTU) treated water samples. This shows the need for fine-tuning treatment processes below 0.1 NTU and highlights a potential optimisation role for particle counters.

The study concludes, however, that particle counters are best used as an optional process research/optimisation tool only: turbidimeters remain the preferred monitor for process control. Indeed, the study finds no overwhelming evidence to justify the permanent installation of particle counters at treatment works. However, an increased use of portable particle counters in optimisation work is recommended.

Consideration is given to other practical concerns such as where and how to use particle counters and what parameters to measure. The value of particle counters' sizing ability has also been assessed. In addition to sensitivity modelling, particle size distribution data revealed a large difference in the volume of particles passed by two sludge treatment plants. The study concludes that, where particle counters are used, there may be some value in monitoring particle size distribution using a particle size ratio or a similar statistic.

ACKNOWLEDGEMENTS

Firstly I like to thank my academic supervisor Simon Parsons for his impeccable support throughout my three years, and also to my original industrial supervisor Guy Standen for his aid beyond the call of duty. I hope your health problems are behind you now.

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Finally I like to thank my parents, for putting up with me during my final months of writing-up.

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Chapter 1: INTRODUCTION

Like the air we breathe, the water we drink also contains many particles invisible to the naked eye. Although treatment works usually remove most particles above 1 micron (µm) in size no affordable filtration system can practically remove all particles from drinking water. For this reason, in most developed countries, the water is chlorinated to deactivate any potentially harmful pathogens that may have passed into supply, thus rendering it safe to drink.

Recently, concern has grown over a specific human pathogen, *Cryptosporidium parvum,* which has exhibited some resistance to traditional disinfection methods. Water companies have therefore to sought to minimise *Cryptosporidium* risk by reducing the number of particles in drinking water by improving plant design and operation.

At the same time, interest has grown in on-line particle (size) counters, which count and size particles in a water sample, and whether they hold any significant benefit over conventional nephelometric turbidimeters in optimising potable water treatment processes.

The 1998 Bouchier Report, commissioned by the UK Government to advise companies on minimising *Cryptosporidium* risk, encouraged the use of particle counters to provide additional information to turbidimeters but fell short of giving specific recommendations on their use. This is because, despite the high level of information provided by particle counters, there is still some doubt as to their real value.

Southern Water, which supplies drinking water to two million customers living in Kent, Sussex, Hampshire and the Isle of Wight first used particle counters at one of its works in 1992. This thesis presents the key results of a three-year study, conducted in conjunction with Cranfield University to find the most beneficial use of these monitors, so that a sensible investment can be made.

This study comprised a series of monitoring trials, conducted at different types of water treatment works: groundwater and surface water treatment works. In addition, some interesting results were obtained from monitoring at two washwater/clarifier sludge recycling plants.

Much information has already been published on particle counters. In the main, however, these have largely focused on aspects such instrument design and calibration. Although these are important issues, this study aimed to focus more on practical applications of the monitors, looking at what they actually say about treatment processes, if and where to install monitors, how to use the information provided, what parameters to use, etc.

Chapter 2: LITERATURE REVIEW

A revised form of this chapter has been accepted for publication by the '*Journal of Water Supply, Research and Technology – Aqua*' under the title 'Using particle monitors to minimise *Cryptosporidium* risk: a review'.

2.1 CRYPTOSPORIDIUM IN DRINKING WATER

Cryptosporidium is a protozoan that can cause an acute form of gastroenteritis, known as cryptosporidiosis, in humans and animals. A history of the organism is given in Warrell (1990): the parasite was first discovered at the start of the century by Tyzzer (1907); in the peptic glands of laboratory mice. At that time, it was thought to be harmless. 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), Bouchier (1998), Lisle and Rose (1995), Solo-Gabriele and Neumeister (1996).

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, some 4-6μm in diameter, as shown by microscopy (Figure 2.1). If ingested in sufficient number, the organism is able to infect the small intestine where it undergoes a complex lifecycle (Casemore 1990, Smith and 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). According to Blewett *et al.* (1989), an infected calf shed 10^{10} oocysts within a fortnight. Although debilitating, the disease is self-limiting in most cases: symptoms, which include diarrhoea, abdominal cramping, nausea and feverishness, usually persist for a period of one week (Smith *et al.* 1995). However, in the case of immuno-compromised patients such as AIDS sufferers or the elderly, cryptosporidiosis can be life threatening.

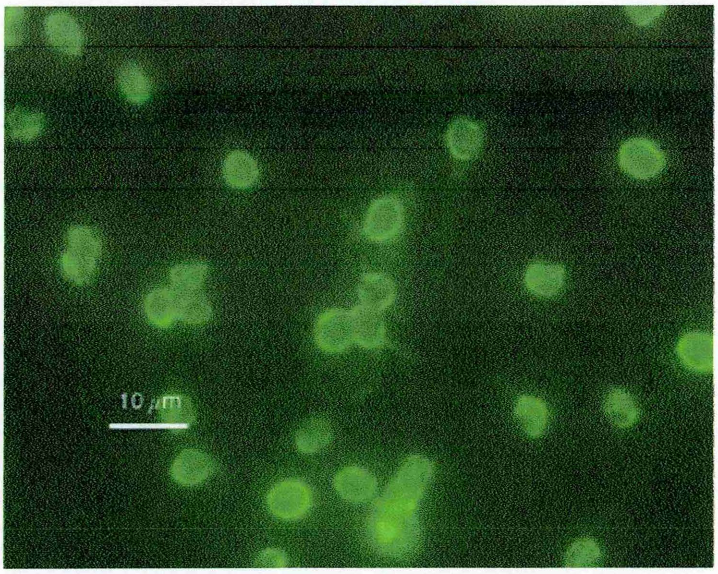


Figure 2.1 *Cryptosporidium parvum oocysts, stained with a fluorescent antibody, seen under microscopy (taken from Lindquist, 2000).*

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. *Cryptosporidium* is found in low concentrations in many raw waters. For example, LeChevallier *et al.* (1991) found oocysts in 81% of raw water samples taken from 66 works, with concentrations ranging between 0.07 to 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.

Several high profile outbreaks of the disease have been linked to contaminated drinking water supplies. Most reported outbreaks have occurred in the United States (US) and the United Kingdom (UK) (Table 2.1) although several others have been reported in Australia, Canada and Japan (Baudin and Laine 1998). The largest reported outbreak occurred in Milwaukee (United States) in 1993 (Fox and Lytle 1996, Solo-Gabriele and Neumeister 1996). This outbreak was believed to have been responsible for up to 400,000 cases, of which some 69 immuno-compromised patients died. After the outbreak, several deficiencies in treatment design and operation in the plants supplying the area were highlighted. These included (i) inappropriate coagulation control during periods of high challenge to the works, (ii) and the recycling of untreated, used filter washwater back to the head of the works.

Although traditional disinfection methods such as chlorination, ozonation, and ultra-violet (u-v) light treatment are usually adequate for deactivating most waterborne pathogens, *Cryptosporidium* oocysts have shown a relatively high resistance to these treatments. For example, Chauret *et al.* (1999) showed that *Cryptosporidium* oocysts are approximately 67 and 14 times more resistant to chlorine dioxide than are MS2 bacteriophages and *Giardia* cysts respectively. The efficiency of these disinfectants is a contentious issue. Smith *et al.* (1990) concluded that with 4 hours contact time a free chlorine concentration of more than 16,000 mg/l was required to completely inactivate all oocysts. This is far in excess of levels that can be practicably obtained in water. Similarly, ultra-violet light (u-v) trials conducted by Clancy *et al.* (1998) suggested that very high (4,000-8,000 mJ cm^{-2}) u-v dosages were required. However, these figures have been thrown into question by authors such as Finch *et al.* (1993) and Bukhari *et al.* (1999) who showed that the *'in vitro'* method of excystation used in the previous two studies underestimates inactivation when compared with *'in vivo'* animal infectivity studies. With the *in vivo* method Bukhari *et al.* for example, demonstrated >4 log (99.99%) inactivation of oocysts with a lower u-v dosage. Whatever the exact effectiveness of each of these disinfectants, perhaps the most crucial factor remains that several large outbreaks of cryptosporidiosis have occurred despite the presence of chlorine and, in at least one case, ozone disinfectants (Table 2.1). Suppliers have therefore had to rely more heavily upon physical barriers such as clarification and filtration to remove the organism.

Table 2.1 *Suspected major outbreaks of waterborne cryptosporidiosis (Adapted from Solo-Gabriele and Neumeister 1996).*

					Treated turbidity NTU			*Suspected causes*					
Outbreak (Year)	*Estd. no. of cases*	*Ref*	*Raw water source*	*Treatment*	*Average before outbreak*	*Peak during outbreak*	*Oocysts detected in treated water (per l)*	*Coagulation Problems*	*Washwater recycled*	*Wastewater plant u/s*	*Animal waste*	*Increased river flows*	*Surf. water intrusion*
Bexar County, US (1984)	2,000	Badenoch (1990)	Ground	Chlorination	n/r	n/r	Not detected			●			●
Carroll County, US (1987)	12,960	Badenoch (1990), Bellamy *et al.* (1993), Solo-Gabriele and Neumeister (1996)	Surface	Conventional*	0.5	<1.0 (up to 5.0 on indiv. filter.)	7 of 9 +ve Mean 0.63 Max 2.2	●		●	●	●	
Swindon and Oxfordshire, UK (1989)	516	Lisle and Rose(1995), Badenoch (1990), Bouchier (1998)	Surface	Conventional*	n/r	0.2-0.4	0.002–77 (dist) 0.002–5 (treated)		●		●	●	
Loch Lomond, UK (1989)	244	Badenoch (1990), Bouchier (1998)	Surface	Chlorination	n/r	n/r	0.008 – 0.4 (dist)			●	●		
North Humberside, UK (1989)	477	Badenoch (1990), Bouchier (1998)	Surface	RGF, SSF and chlorination	n/r	n/r	2 of 3 samples positive					●	
Isle of Thanet, UK (1990/1)	47	Lisle and Rose (1995)	Surface/ Ground	Conventional* + GAC filt.	<1	2	14 samples all negative	●			●	●	
Jackson County (Talent), US (1992)	15,000	Leland *et al.* (1993), Solo-Gabriele and Neumeister (1996)	Surface	Conventional*	0.5	2.2	Not detected****	●		●	●	●	
Milwaukee County, US (1993)	403,000	Fox and Lytle (1996), Solo-Gabriele and Neumeister (1996)	Surface	Conventional*	< 0.4**	1.7	Not monitored	●	●	●	●	●	
Clark County (Las Vegas), US (1994)	78	Solo-Gabriele and Neumeister (1996) Roefer *et al.* (1996)	Surface	Conventional*	<0.1	<0.2	Not detected		●	●			
Torbay, UK (1995)	575	Bouchier (1998), DWI (1997)	Surface/ Ground	Conventional* (Sirofloc)	0.2-0.3	0.55	Some 'low numbers'			●	●	●	●
North London and Hertfordshire, UK (1997)	345	DWI (1998), Bouchier (1998)	Ground	Ozonation, GAC filt + chlorination	n/r	>4***	11 of 562 positive 0.03-0.2		●	●	●	●	●

'n/r' = 'not reported'; 'u/s' = 'upstream'

* Coagulation/Clarification/Filtration/Chlorination.

** Not exceeded for 10 years prior to outbreak.

*** The result is queried in DWI, (1997). This high on-line measurement was not confirmed by separate laboratory analysis.

**** It was difficult to analyse samples fully because of the presence of algae and other debris.

2.1.1 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 brief description of these monitors is now presented.

2.2 PARTICLE MONITOR DESCRIPTIONS

For the purposes of this study, only on-line, photometric (light measuring) instruments are being considered. Off-line particle analytical methods such as suspended solids analysis or microscopy are discussed elsewhere (e.g. Hunt 1993).

2.2.1 Turbidimeters

2.2.1.1 <u>Transmitted light methods</u>

Turbidity is a general measure of water 'cloudiness' created by particles suspended in a water sample. The parameter 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. Originally turbidity was considered to be a measure of light attenuation within a water sample as defined by the Beer-Lambert Law:

$$I_z = I_0 e^{-\lambda z} \tag{2.1}$$

where I_0 = Light intensity at initial depth

I_z = Light intensity at optical path length, z

λ = Light attenuation coefficient or 'turbidity'

Turbidity can be measured either using a photometric device, described in Black and Hannah 1965, ABB 1998 (Figure 2a) or by visual techniques e.g. transparency test-tubes or Secchi discs (both described in British Standards Institute 1994). These visual methods are still used today to analyse 'dirty' water samples e.g. waste or surface waters where only an approximate reading is required.

2.2.1.2<u>Light scatter method (Nephelometry)</u>

However, most modern on-line instruments are based on light scatter rather than light transmission (Figure 2b). Scattered light intensity is usually detected at 90° to the incident beam as specified by the international standard, ISO7027 (British Standards Institute, 1994). In this case the instrument is referred to as 'nephelometric'. ('Nephelometry' is to the scientific name for the study of clouds). Turbidimeters are calibrated against a standard of known value (typically formazine) and readings are usually expressed in NTU (Nephelometric Turbidity Units).

According to Hunt (1993), the 90° angle is preferred because it allows smaller particles to be detected. Although turbidimeters can sense particles of any size (0.01μm to any size, Hunt 1993), their readings are biased towards the number of submicron (<1μm) particles present in the sample, as shown by latex bead experiments conducted by Gregory (1994). This is because, as described in Black and Hannah (1965) and Huber and Frost (1998), forward light scattering dominates for larger particles (5μm), whereas for submicron (0.05μm) particles, it is more evenly distributed.

More information can be found on nephelometric turbidimeters in Hunt (1993). Unless otherwise stated, references to 'turbidity' or turbidimeters will refer to conventional light scatter instruments.

2.2.2 Particle counters

Particle (size) counters are a more recent development in the Industry. These instruments 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, US (Hargesheimer *et al.* 1998, Hutchinson 1985). Although they are a powerful tool in the amount and specificity of information they produce compared with turbidity, there still remains much debate as to (a) how useful such data is, and (b) how to interpret the data.

2.2.2.1Light obscuration

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 the narrow beam (Figure 2c). Each particle creates a 'shadow', the peak of which is related to particle size. Particles can be counted and sized within different, discrete bands, usually from one or two microns (µm) upwards, depending on the type of sensor used.

Light obscuration particle counters are volume dependent. Sample flow must be kept at or close to a known constant. This is usually achieved through a constant head weir, which also debubbles the samples. Particle counters can count only a limited number of particles before a significant number of them pass in front of the sensor and are counted simultaneously. This effect is known as coincidence error (described in Hargesheimer *et al.* 1992, Sommer and Kleine 1999). Manufacturers typically quote a maximum total particle count for which there is a 10% degree of coincidence error. Above this count, sample dilution is required for accuracy. Light obscuration particle counters are also described in more detail in Hargesheimer *et al.* (1992), Hargesheimer and Lewis (1995), Lewis *et al.* (1992), Hunt (1993), and Van Gelder *et al.* (1999).

2.2.2.2Electrical resistance (electrical zone sensing)

These monitors detect fluctuations in electrical resistance created as particles pass through a small aperture within a sample container (Figure 2d). The technique is believed to provide an accurate way of sizing particles (Van Gelder *et al.* 1999). However, the method is not considered suitable for on-line analysis (Lewis *et al.*

1992) and is not commonly used in the Industry. The monitors are further described in Hargesheimer *et al.* (1992), Hunt (1993), Van Gelder *et al.* (1999).

2.2.2.3Forward angle light scatter (FALS)

Another, less commonly-used counter is the 'forward angle light scatter' (FALS) method. This has been imported into the Industry only in the last 10 years. It is similar to the laser turbidimeter except that light scatter is measured at an angle of 1-19° (Figure 2e). Any particles passing through the sensing zone creates a change in light intensity, which is related to particle size.

The technique allows sizing of very small particles, (down to 0.1μm, Hargesheimer *et al.* 1992). However, on a given sample, the likelihood of significant coincidence error is higher than for obscuration counters. Hargesheimer *et al.* (1992) provides some examples of maximum particle concentration limits for a FALS monitor: 5,000 particles greater than 0.5μm per ml. These monitors are therefore appropriate only for very clean water samples. Recommended reading for further information on these particle counters include Lewis and Manz (1991), Lewis *et al.* 1992, Hargesheimer *et al.* (1992), O'Shaunessy *et al.* (1997).

2.2.3 Particle index monitor

Another type of particle monitor, recently introduced into the Industry, is the 'particle index monitor' or 'photometric dispersion analyser'. This uses a turbidity fluctuation technique detailed in Gregory (1994). These meters are essentially transmitted light turbidimeters but return a measurement based upon the noise detected in the signal (the AC component) rather than the usual average (the DC component) (Figures 2f and 3).

They do not count or size individual particles. They are, however, especially sensitive to larger particles (Kirby *et al.* 1998). In this way it is believed that particle index trends may mimic particle count trends. As with particle counters, particle index meters are calibrated with a latex bead suspension. This is a relative difficult exercise.

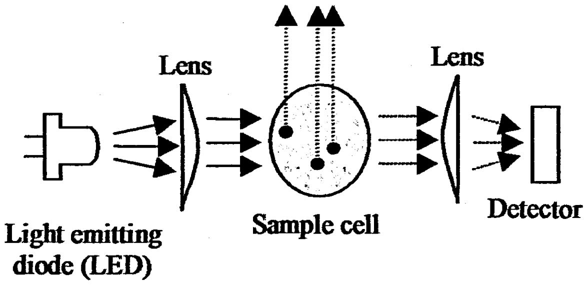


Fig. 2.2a *Transmitted light turbidimeter (ABB 1998).*

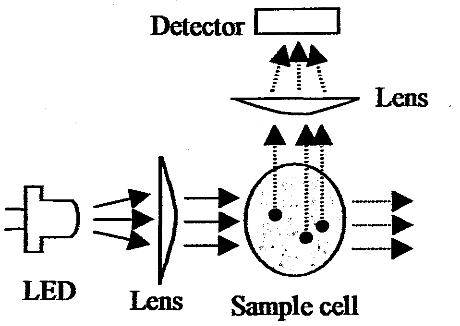


Fig. 2.2b *Nephelometric turbidimeter (ABB 1998).*

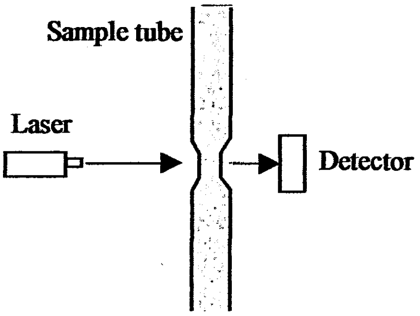


Fig. 2.2c *Light obscuration particle counter (Lewis et al. 1992).*

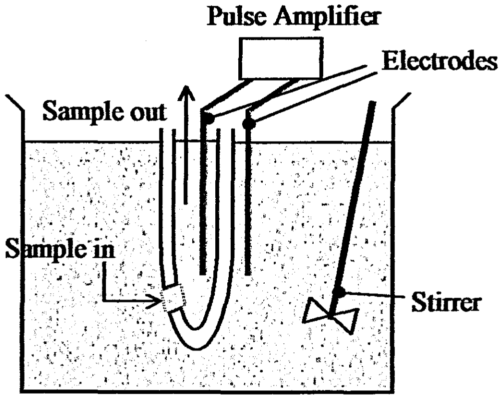


Fig. 2.2d *Electrical resistance particle counter (Hargesheimer et al. 1992).*

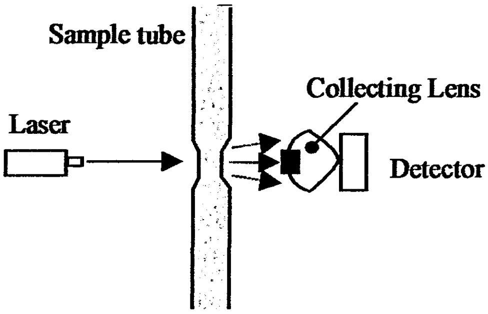


Fig. 2.2e *FALS particle counter (Lewis et al. 1992).*

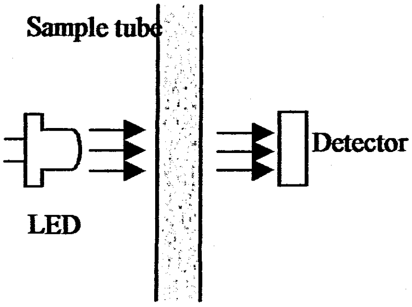


Fig. 2.2f *Particle index monitor (Kirby et al. 1998).*

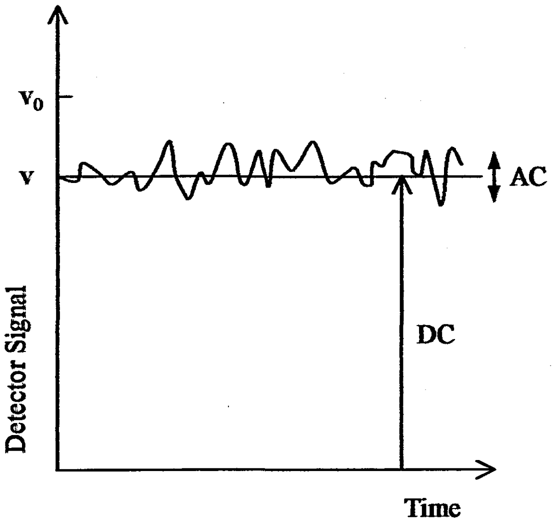


Figure 2.3 *DC and AC components of a turbidity signal (adapted from Kirby et al. 1998)*

2.3 DIFFERENCES BETWEEN PARTICLE MONITORS

This section reviews the relative strengths and weaknesses of each monitor in terms of as cost, resolution, accuracy/precision, sensitivity etc.

2.3.1 Cost

Turbidimeters and particle index meters are generally the cheapest instruments available. Particle counters are generally more expensive, the exact cost depending on the required specifications: e.g. resolution capability, the number of size channels etc. (Lewis *et al.* 1992). Certain instruments may also incur higher running costs e.g. the calibration of particle counters can be a costly, time-consuming process, often requiring the instrument to be sent to the supplier.

2.3.2 Level of information

Of all the instruments considered, particle counters supply the highest level of information: providing a breakdown of particles counted in a number of discrete size channels. The other monitors are single-value instruments. If size information is considered to be unimportant, then a simple, one or two channel particle counter, or a particle index monitor may suffice.

2.3.3 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, 95). 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. Particle index monitors are especially sensitive to very large particles (>20μm) as shown by latex bead experiments (Kirby *et al.* 1998).

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. Particles with a low refractive index can also be undersized. According to Gregory (1994), *Cryptosporidium* oocysts, 4-6μm in diameter by microscopy are sized as a 2μm latex bead. Alternately, particles such as carbon fines are sized fully but scatter no light and so are invisible to turbidimeters (Englehardt 2000).

Reed and 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 and Morgan (1977) observed a similar result using an electric resistance counter. They 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 to microscopy methods. They attributed this to the 'shrinking' of the microorganisms during slide preparation.

2.3.4 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 2.2). 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 2-5μm 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 2μm size range. Despite the large improvement on the Van Gelder figures, these still sometimes exceeded manufacturers' specifications (typically less than 10% above 2μm 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 does the instrument read. Most turbidimeters read to two or three decimal places, satisfactory for potable water monitoring.

Table 2.2 *Comparing particle counter resolution data from latex bead experiments.*

		Resolution (%) at different bead sizes			
Ref	*Type*	*2μm*	*3μm*	*5μm*	*10μm*
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

		Resolution (%) at different bead sizes			
Ref	*Type*	*2.6μm*	*3.0μm*	*5.9μm*	*10.0μm*
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

2.3.5 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).

For particle counters, it is easier to test precision; several researchers have compared readings given by a number of like sensors (Table 2.3). 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 2-5μm 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 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.

2.3.6 Sensitivity to water quality changes

It is widely believed that particle counters are more sensitive when monitoring low turbidity samples. Below 0.1 NTU, turbidimeters are frequently observed to be insensitive to changes in water quality and turbidity trends often appear flat. This subject is discussed further in (Section 2.6.1).

Table 2.3 *Tests of particle monitor accuracy.*

Ref	*Sample*	*Type*	*No. of units tested*	*Max diff in $>2\mu m$ 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)	Filt. 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 and Pickel, the % difference quoted is that from a randomly selected 'master' instrument.
In Routt and Van Gelder, 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.

2.4 LINKS BETWEEN *CRYPTOSPORIDIUM* AND PARTICLE MONITORS

In the UK, the first major diagnosed outbreak of cryptosporidiosis was in 1989 in Swindon and Oxfordshire (Table 2.1). 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, US, treated water turbidity rose around sevenfold from 0.25 to 1.7 NTU (Nephelometric Turbidity Units) (Lisle and 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 and 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 1-10,000 particles per ml above 2μm.

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 2). This suggests that there may be 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 at a particular works. LeChevallier and 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 and Morse (1999), Morse *et al.* (2000) and Payne (2000) all showed that oocyst occurrence to be largely independent of filter effluent particle counts (Table 2.4). 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 2.4). For example, LeChevallier and Norton (1992) demonstrated a strong link ($p<0.05$) between oocyst removal and turbidity and particle removal (>5μm). This is important as it shows that minimising particulate passage through a works can reduce *Cryptosporidium* risk. Conversely, it also shows that deterioration in treatment performance can, as the Bouchier Report suggests, lead to greater risk, given that oocysts are present in the raw water.

Particle monitors are commonly used to assess the oocyst removal efficiency of a particular treatment process (Table 2.5). This efficiency is often quoted as a 'log' removal figure (Equations 2.2 and 2.3). For example, a particle removal rate of 90% is equivalent to '1-log removal'; 99% is equivalent to '2-log'; 99.9% is equivalent to '3-log' etc. Care must be taken if different particle counters are used to monitor feed and filtrate sample lines, because small calibration differences can have a large effect on removal statistics. Ideally, the same instrument should be used to measure both feed and filtrate concentrations. In addition, significant coincidence error in the feed measurement can lead to highly misleading results. These problems are further described in Section 2.4.2.1.

$$Percent\ removal = \frac{Influent\ concentration - Effluent\ concentration}{Effluent\ concentration} \times 100\% \quad (2.2)$$

$$Log\ removal = \log_{10}(100 - Percent\ removal) \quad (2.3).$$

To further assess the relationship between particle and oocyst removal figures, data from seven published oocyst seeded process performance trials were compared (LeChevallier and Norton 1992, Nieminski and Ongerth 1995, Ongerth and Proctor-Pecararo 1995, Li *et al.* 1997, Fox *et al.* 1998, Coffey *et al.* 1999, and Hamilton *et al.* 2000). Data taken from these studies fell along highly significant lines (Figure 2.4), suggesting that, in the majority of cases, that particle removal statistics do provide a good indication of a plant's defences against oocysts. The removal of particles around and above oocyst size (4-6µm) seemed to give the most accurate indication of oocyst removal. Smaller particle sizes (>1µm, >2µm) gave more conservative estimates, with turbidity, whose reading is based primarily on submicron particles (Section 2.3.1.2) 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. This was also seen in Bellamy *et al.* (1993).

In the model differential counts and cumulative counts have been grouped together e.g. 4-6µm has been grouped with >4µm, 3-6µm with >3µm 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 was 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 in 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.

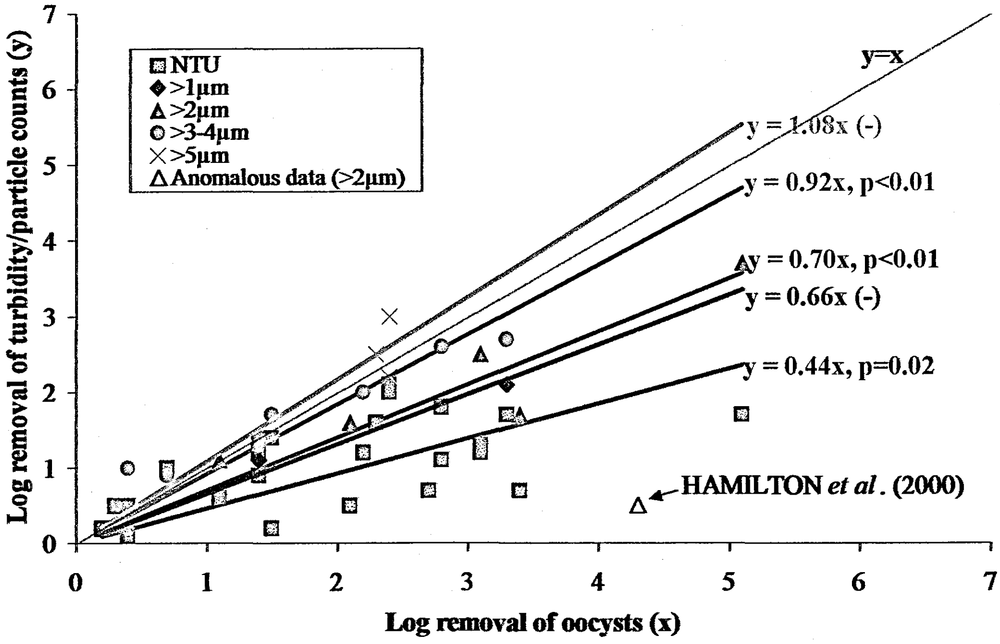


Figure 2.4 *A comparison of published particle and oocyst removal data.*

Table 2.4 *Published Cryptosporidium/particle monitor correlation tests.*

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

Table 2.5 *Published plant performance trials comparing different Cryptosporidium surrogates.*

Ref	*Process*	*Plant Scale*	*Oocyst Source*	*Filter Pre-Cl?*	*Log removal*							*Comments*
					Oocyst	*Turb*	*>1µm*	*>2µm*	*>3µm*	*>4µm*	*>5µm*	
LeChevallier and Norton (1992)	Conventional	Full	Natural	Yes	>2.4	2.0	-	-	-	-	2.2	Site 1
					>2.4	2.1	-	-	-	-	3.0	Site 2
					>2.3	1.6	-	-	-	-	2.5	Site 3
Ongerth and Proctor-Pecararo (1995)	Flocc - Filt	Pilot	Seeded	No	3.1	1.3	-	-	-	-	-	Optimum coag
					2.8	1.1	-	-	-	-	-	Sub-optimum coag
					2.7	0.7	-	-	-	-	-	Sub-optimum coag
					1.5	0.2	-	-	-	-	-	Sub-optimum coag
Hamilton et al. (2000)	MF (2 stage)	Pilot	Seeded	No	4.3	-	-	0.5	-	-	0.8	Second stage
Li *et al.* (1997)	3 Bag filters	Pilot	Seeded	No	1.4	0.9	1.1	-	-	1.3[a]	-	Bag 1
					0.4	0.1	0.2	-	-	0.2[a]	-	Bag 2
					3.3	1.7	2.1	-	-	2.7[a]	-	Bag 3
Fox et al. (1998)	Coag - Settlement	Pilot	Seeded	No	1.5	1.4	1.4	-	1.7[b]	-	-	Optimal coag
					0.7	1.0	1.3	-	0.9[b]	-	-	Optimal coag
					0.4	0.5	0.7	-	1.0[b]	-	-	Under dose coag
					0.3	0.5	0.5	-	0.5[b]	-	-	Under dose coag
					1.4	1.2	1.4	-	1.4[b]	-	-	Over dose coag
Nieminski and Ongerth (1995)	Conventional	Full	Seeded	No	2.2	1.2	-	-	-	2.0[c]	-	Contact filt
					2.8	1.8	-	-	-	2.6[c]	-	Direct filt
		Pilot	Seeded	No	3.0	2.0	-	-	-	2.9[c]	-	Contact filt
					3.0	2.0	-	-	-	2.9[c]	-	Direct filt
Coffey *et al.* (1999)	Conventional	Pilot	Seeded	Yes	5.1	1.7	-	3.7	-	-	-	Site 1 Optimised
					3.4	0.7	-	1.7	-	-	-	Site 1 Sub- optimised
					2.1	0.5	-	1.6	-	-	-	Site 1 No coagulant
					3.1	1.2	-	2.5	-	-	-	Site 2 Optimised
					1.1	0.6	-	1.1	-	-	-	Site 2 Sub- optimised
					0.2	0.2	-	0.2	-	-	-	Site 2 No coagulant

Unless stated otherwise, figures shown represent optimum operating conditions. Only studies that compared particle removal and oocyst removal have been included.

[a] 4-6um
[b] 3-6um
[c] 4-7um

2.5 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 US, for example, where treatment is tightly regulated, there are some differences in the regulatory approach.

2.5.1 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 US regulations. Also, under the UK system, the level of turbidity is not viewed to be 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)

2.5.2 The US approach

The approach taken in the US is 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 lower 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 and 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 US than in the UK. For example, Consonery *et al.* (1997) details an on-going, annual risk assessment of all treatment plants in Pennsylvania, US, 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 and 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.

2.6 BENEFICIAL PARTICLE COUNTING APPLICATIONS

Turbidimeters are a relatively cheap, reliable and accurate measure of particles in a water sample and, as the US 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 and Lewis 1995, Hamilton *et al.* 2000, Casale *et al.* 1999, Morse *et al.* 1999). 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), 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. Firstly, 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 benefit.)

2.6.1 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 and Trussell (1978), Jacangelo *et al.* (1991), Hargesheimer *et al.* (1992), Adham *et al.* (1995) and Hargesheimer and 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 2.6). 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 (Baird and Hillis 1998, Colton *et al.* 1996, Hall and Croll 1997).

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 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 reported separately (Chapter 5).

2.6.2 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 (>1μm) as shown in polydiverse bead suspension experiments (Mackie and Bai 1993, Clark *et al.* 1992, Moran D.C. *et al.* 1993, Moran M.C. *et al.* 1993). Interestingly, some authors (Lewis and Manz 1991, Pizzi and Rodgers 1998, and Hall and Croll 1997) 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, Englehardt *et al.* 1999, Mackie and Bai 1993, Moran D.C. *et al.* 1993). 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 is it argued that, in general, the size distribution of particles in samples remains relatively constant although 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.

Table 2.6 *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) Hutchinson (1985) Tate and Trussell (1978)
	Flocculation	Tate and 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 and Croll (1997)
	Slow start	Baird and Hillis (1998) Colton *et al.* (1996) Hall and Croll (1997)
	Delayed start	Baird and Hillis (1998) Hillis and 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)
Identifying filter breakthrough	Early detection	Kavanaugh *et al.* (1980) Keay (1995) Murray (1995) Saunders *et al.* (1999)
	Simultaneous with turbidity	Hall and Croll (1997) Lewis and Manz (1991) Pizzi and 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 and Mery (1986)

2.6.3 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 2.7). 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 at the point where there was a sudden shift in particles in the dosed water to larger sizes. Reed and 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 and 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, he described a process selection model whereby the most suitable treatment processes could be determined from raw water particle size measurements. Kavanaugh 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 multi-channel particle counters will not be fully realised in potable water treatment.

Table 2.7 *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 and Mery (1986) Lartiges *et al.* (1995)
	An optimum flocculated particle size was found that 'increased media penetration'	Hutchinson (1985)
Investigating the effect of filter pretreatments	Flocculation	Tate and 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 1-2μm particles were counted in filtered water during some periods of washwater recycling.	Englehardt *et al.* (1999)

2.7 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, five key questions need to be answered:

1. How useful is the extra sensitivity provided sometimes by particle counters at low turbidity?

2. 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?

3. 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?

4. Although particle sizing can be an interesting process research tool, are multichannel particle counters really needed in 'routine' monitoring?

5. Can particle counters (or suitable alternatives) be made more 'operator friendly' in terms of their resolution, precision, accuracy, ease of calibration and calibration checks?

Chapter 3: OBJECTIVES

The overall objective of the work was to determine the best uses of particle counters at water treatment works, especially in light of the *Cryptosporidium* problem.

As described in Chapter 1, this study has concentrated on the practical application of the monitors, looking at what they actually say about treatment processes, if and where to install them, how to use the information provided, what parameters to use, etc.

The work has comprised a series of site-specific monitoring trials conducted at three types of treatment works: namely surface water treatment works, groundwater works, and two sludge treatment plants. In some cases, this work was undertaken with a specific aim e.g. the testing of a delayed start at Hardham WSW. In other cases, the aims were a more general exploration of works believed to be of relatively high *Cryptosporidium* risk.

Along with these site-specific studies, two other areas of research were included in this thesis. Firstly, literature and experimental data was analysed to see if the response of particle counters and turbidity to changes in water quality could be modelled thereby providing a way of assessing the best uses of particle counters. Secondly, particle monitor and *Cryptosporidium* data was compared to see if any links between the two could be determined. All these studies provided some answers to the first four key questions posed in Section 2.7.

Chapter 4: MATERIALS AND METHODS

In each of the following Results chapters, descriptions of treatment works and particle monitoring set-ups have been given separately. This chapter, therefore, deals with more general particle counting issues such as calibration and maintenance.

4.1 PARTICLE COUNTER SETUP

4.1.1 Particle counters used

Two types of particle counters have been used in this study: PMS Liquilaz E20 and Met-One PCX. Monitoring specifications for these monitors are shown below (Table 4.1). Both these instruments are volumetric, light obscuration sensors that count particles above 2μm. [In volumetric particle counting, the laser beam is shone across a sample cell (usually 1mm x 1mm cross sectional area) to a detector on the opposite side of the cell. The advantage of this method is that every particle in the sample can be counted. The disadvantage is that because it looks at every particle, the chance of coincidence error is increased. Conversely, in in-situ counters, a light source is focused on the centre of the sample stream. Because the focus is only around the middle 12-20% of the sample (Process Instruments, 2000a), this reduces the chance of coincidence error. However, only a fraction of the sample is analysed compared to volumetric counters.

Table 4.1 *Particle counter specifications.*

	PMS *Liquilaz E20*	*Met-One* *PCX*
Monitor type	Light obscuration	Light obscuration
Volumetric or in-situ?	Volumetric	Volumetric
Particle size range	2-150μm	2-750μm[a]
Liquid flow rate	80ml/min	100ml/min
Resolution	Less than 10% at all sizes	Less than 10% at all sizes[b]
Capillary dimensions	0.5 x 1.0 mm	0.75 x 0.75 mm
10% coincidence limit	12,000 particles per ml[c]	12,000 particles per ml[b]

[a] Larger particles may be counted but not sized correctly

[b] Data supplied by manufacturer.

[c] Data taken from Hargesheimer and Lewis (1995).

4.1.2 Particle monitoring rig

Early in the trial, it was observed that the relationship between particle counts and turbidity would be a major point of interest within the study. A mobile rig was therefore constructed to aid the comparison of these monitors (Figures 4.1-4.3). The rig comprised three monitors: a Met-One PCX particle counter, an ABB 7997/202 turbidimeter and a Diverse FPM particle index monitor. These monitors were set-up to run parallel to each other upon an 'L-shaped' plywood board (Figure 4.1). This shape could fit into the various sample kiosks located around the company (Figure 4.2). The rig was held in position by hanging it from hooks through a chain attached to the top of the board. Where necessary, ropes were used as an additional fastening.

Readings from all three monitors were logged on a laptop computer running Met-One Water Quality Software (WQS) (Figure 4.3). This laptop was located next to the rig, and was contained in a customised NEMA enclosure, which protected it from splashes and minor flooding.

Tubing materials used are shown in Table 4.2. The Met-One PCX inlet and outlet tubes consisted of a polyester-lined PVC material (Bev-a-line®) provided by the manufacturers. Otherwise Tygon® R3603 was mostly used for all external tubing. (The internal tubing in the Met-One PCX is also made from Tygon®). Tubes were kept as short as possible in order to minimise biofilm growth and particle settlement within them. For this reason, the external Tygon® tubing in the mobile rig was changed at the start of each site study (typically every 1-2 months). It was observed that the tubing in front of the Diverse FPM particle index monitor's sensor was prone to fouling. This was changed on a regular basis (every 1-2 weeks) as a precautionary measure, by sliding the tubing up through the monitor.

Table 4.2 *Tubing materials used.*

PMS Liquilaz E20 (Hardham/Burham)	
From tap to CHD	Tygon® R3603
From CHD to sensor	Tygon® R3603
Mobile Rig	
From tap to CHD's	PVC
From CHD to Met-One PCX	Bev-a-line®
Through Met-One PCX	Tygon®
From CHD to ABB	Tygon® R3603
From CHD to Diverse FPM	Tygon® R3603
Met-One PCX (Burpham WSW)	
From tap to CHD	Bev-a-line®
From CHD to sensor	Bev-a-line®
Through Met-One PCX	Tygon®

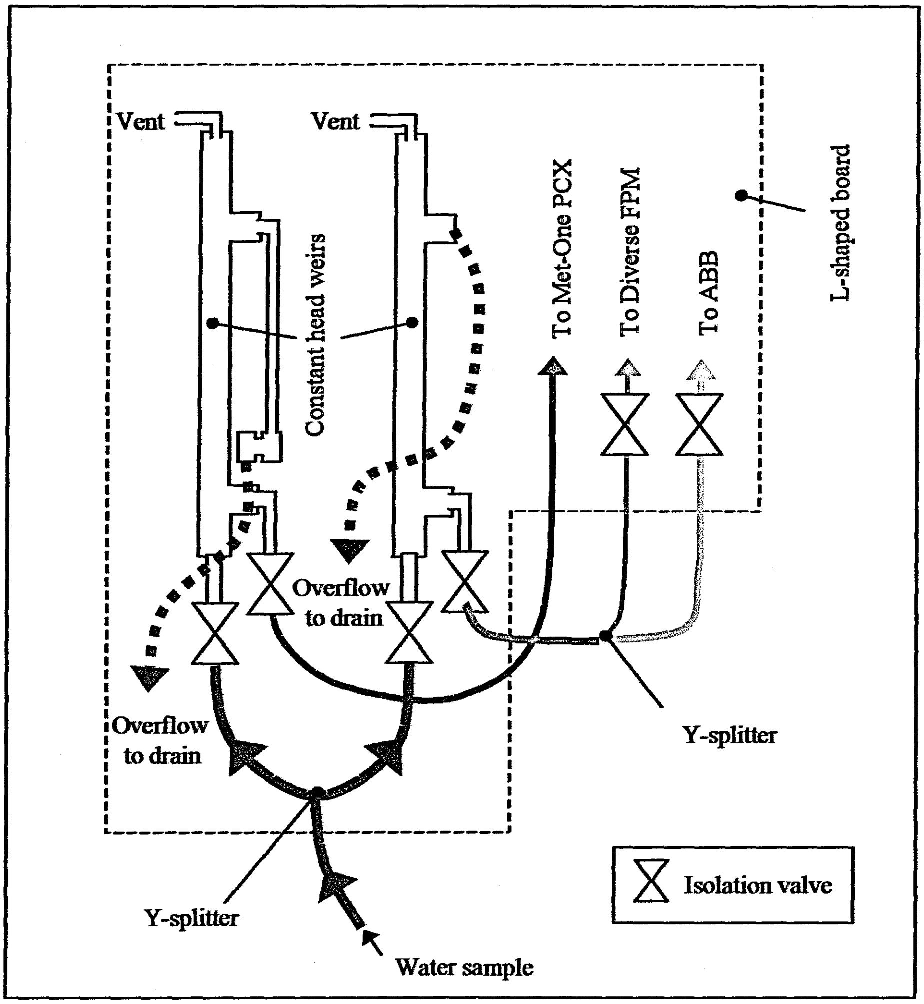


Figure 4.1 *Simple schematic of the mobile particle monitor rig.*

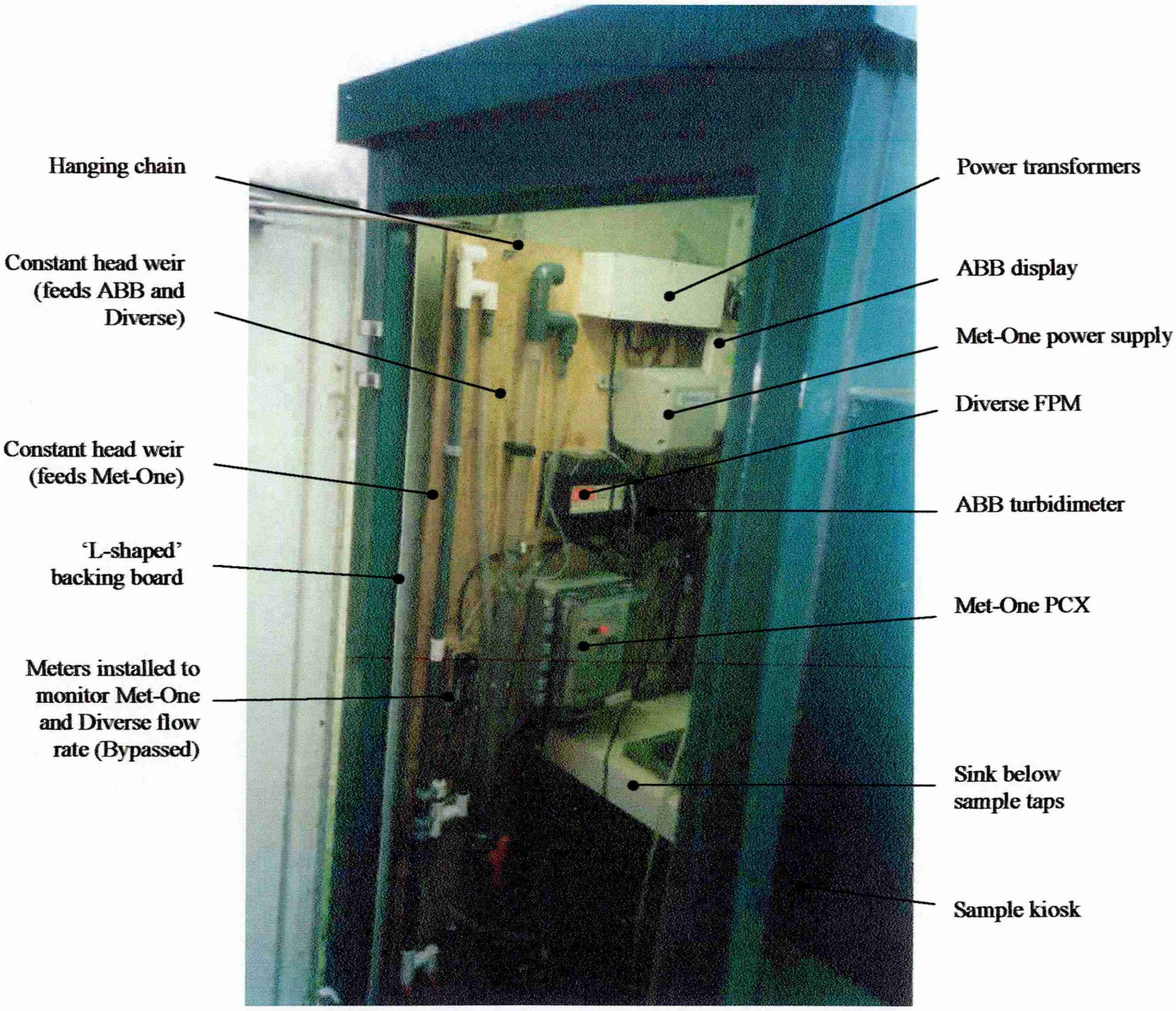


Figure 4.2 *Mobile particle monitor rig set up in sample kiosk at Newmarket WSW (1).*

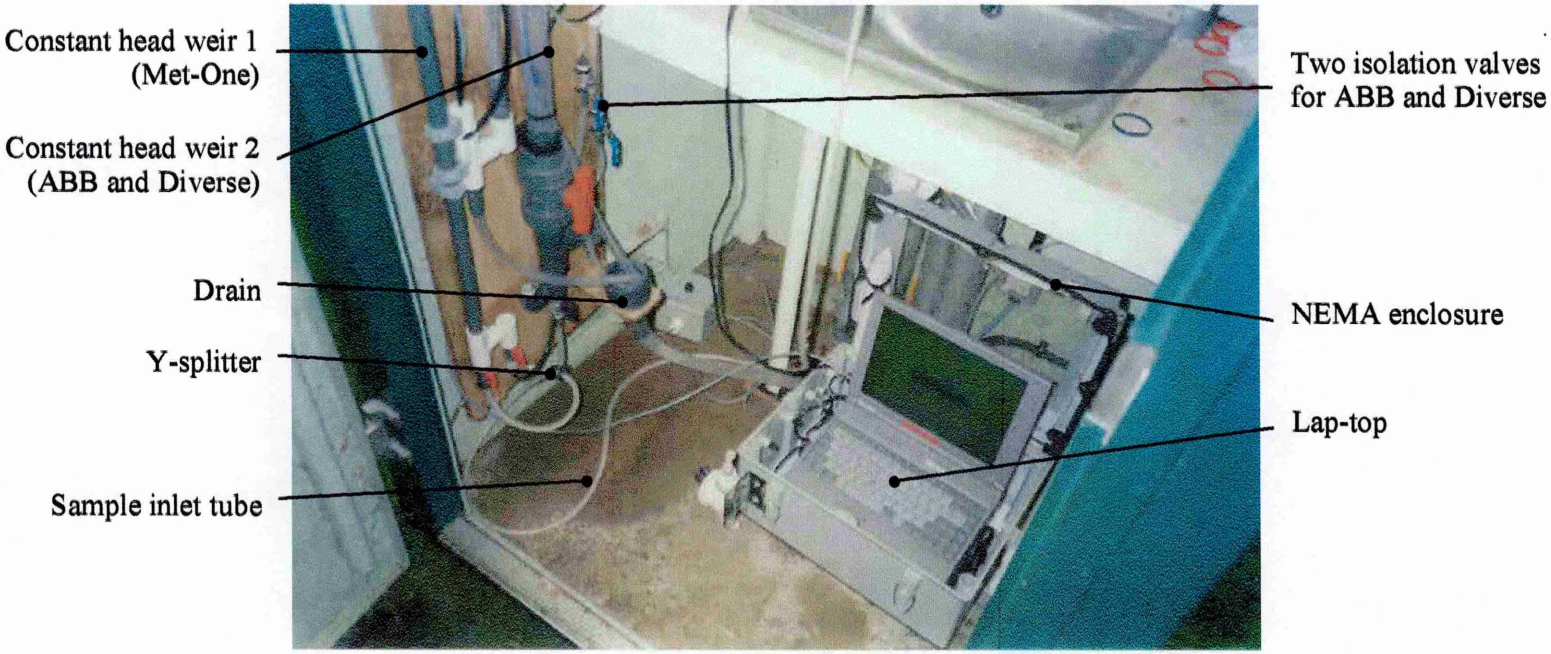


Figure 4.3 *Mobile particle monitor rig set up in sample kiosk at Newmarket WSW (2).*

4.2 MAINTENANCE ISSUES

4.2.1 Particle monitor flows

The Met-One PCX particle comes with a standard constant head weir to regulate flow to the instrument and to debubble the sample. In order to directly compare particle counts with the other particle monitors on the rig, it was decided that a similar device be fitted upstream of the turbidimeter and particle index monitor. The PCX manual states that 4ft of head pressure at the constant head weir inlet will maintain a sensor flow of 100ml min^{-1}. Flow rates between the turbidimeter and particle index monitor were controlled by partially closing the valves fitted on their respective inlets.

Regular flow checks were conducted to see if the monitors were receiving the specified rates of flow (Table 4.1). As long as there was sufficient sample pressure to fill both constant head weirs, flow rates generally remained within their specified bounds. Initially the mobile rig was fitted with flow meters downstream of the particle monitor sensors. However, it was found that these created resistance, which restricted flow through the instruments and so were disconnected. Instead flows were checked manually using a measuring cylinder.

A few problems were experienced during the study. For example, an attempt was made to sample from several rapid gravity filters at Testwood WSW. A description of this works is provided later. For this, the rig was lowered into a pit, which ran below the filter gallery. Initially there was just enough pressure to supply the required volume of sample to the instruments. However, as the headloss in the filters increased towards the end of their run, the sample pressure dropped critically. This trial was therefore scrapped and the rig moved to a second filtration plant located on the site (Enelco filters 13 and 14) where filter outlet samples were being pumped. For the former filter plant, it would have been possible to obtain a continual sample (a) either by locating the particle counter beneath the filter gallery, if possible, or (b) by installing a pump upstream of the particle counter. A similar sample pressure deficit was encountered when trying to install the rig downstream of a Kalsep microfiltration plant at Burham. This work was also abandoned in favour of monitoring at Beauport WSW.

Only on one occasion did significant sensor blockage occur. This was seen during the monitoring of the washwater recycling plant at Burham and was thought to be due to two main factors. Firstly, the analysed sample contained a high proportion of large aluminium floc particles. Secondly, the PMS Liquilaz E20 counter used at this works has a very narrow aperture (Table 4.1). Sensor blocking was evidenced by (a) a drop in sample flow rate and (b) by a simultaneous decline in measured particle count, which would start typically some 12-48 hours after cleaning. Frequently, particle counters that were left running overnight would have to be unblocked when returning to the site the next morning. This was done using a combination of blowing through the sample tube, reversing the flow through the counter, and in more extreme cases, of passing a 10% hydrochloric acid solution through the sensor. At Burham WSW, only data was used for which the flow rate could be verified. At all other works, once the particle counters had been installed correctly, flow rate was not perceived to be a significant problem.

4.2.2 Sensor cleaning

Particle counter sensors were cleaned at the start of each trial and then every 1-2 months as part of a programme of routine maintenance. The PMS Liquilaz E20 units were cleaned using a 10% hydrochloric acid solution. This was pumped into the system then allowed to stand for a period of 15 minutes before being reconnected to the sample. For the Met-One PCX sensors, a 'brush' cleaning procedure used as described in the PCX instruction manual (Met-One, 1997) using a 5% dilution of the Micro®-90 cleaning fluid provided.

Opinions are divided on how regularly sensors need cleaning. It is generally recognised that this will depend upon the type of sample being analysed. Murray (1995) stated that, *'The particle counting system for filtered water should be flushed out at intervals of six months, but more regularly for raw water particle counters.'*

However, Pickel *et al.* (1997) suggested that sensors should be cleaned on a weekly basis as a precaution.

From experience, particle counters seem able to run for several months with little adverse effects. In this study, particle counters were washed every 1-2 months as a precaution as advised by Met-One (*pers. comm.*). In various experiments now detailed, particle count readings were compared 'before' and 'after' cleaning, in order to assess any impact that the cleaning might have had.

4.2.2.1 Experiment 1: Burpham WSW (4th Jun 1999)

This experiment was carried out at a groundwater supply works described in Chapter 7. Two Met-One PCX particle counters had been installed up and downstream of a microfiltration plant situated there.

On the 4th June, 2001, the particle counters were washed (Section 4.2.2) and the effects noted. Prior to this, these sensors had not been washed for 98 days. The data was to be presented as a trend, but unfortunately was lost as the software had not been set-up correctly to archive the data. Instead, the data is limited to the following 'spot' readings taken at the time. The very large change in feed particle count is extremely unexpected. Without being to examine the underlying trend, it is not possible to say whether this change is genuinely the result of cleaning the sensor. The result is also counter-intuitive in that one would expect, if significant blockage had occurred, that the particle count and mean particle size would increase as seen in the filtrate readings. It is difficult therefore to draw any firm conclusions from this data.

Table 4.3 *Burpham WSW: Treated water - 4th Jun 2001 (Sensor had not been cleaned for 98 days).*

Sensor	Status	*>2μm*	*>3μm*	*>5μm*	*>10μm*	*>10μm(%)*	*β**
Feed	Before Cleaning	796	393	103	31	3.89	2.9
	After Cleaning	294	151	39	11	3.74	2.8
Filt	After Cleaning	40	15	1.4	0.08	0.20	4.2
	Before Cleaning	35	14	1.9	0.10	0.28	3.7

Listed particle counts are per ml.
* This particle size distribution statistic is described later.

4.2.2.2 Experiment 2: Burpham WSW (8th November, 1999)

The sensors were recalibrated, reinstated and then cleaned again on the 19th October. The above experiment was then repeated on the 8th November some 20 days later. This time a trended data set is available (Figures 4.4 and 4.5). Both feed and filtrate particle count results gave a same response to the filtrate i.e. a small increase in particle count and mean particle size.

In the 'filtrate' sensor data a couple of unusual anomalies can be seen. Firstly there is a relatively high degree of noise in the >10µm(%) trend (Figure 4.6). The exact reason for this is unknown at the time of study, although a similar degree of noise was also seen in Hardham counts where the number of >10µm counts were similarly very small.

Secondly, for around an hour after having cleaning the 'filtrate sensor', a relatively high number of >10µm particles were seen. Again the reason for this is also unknown. One possible explanation is that during the cleaning process, the brush dislodged some very large particles, which took a relatively long time to pass through the narrow sensor aperture. The anomaly is exaggerated on the log-scaling used. Any similar occurrence in the feed example would be masked because of the higher number of >10µm particles in that sample stream.

These figures provide a useful way of determining an optimal sensor cleaning frequency. From the work presented here, it would appear that monthly cleaning intervals are sufficient. It is recommended that where particle counters are used over a long period of time, records should be kept as shown in Figures 4.4 and 4.5 each time a sensor is cleaned.

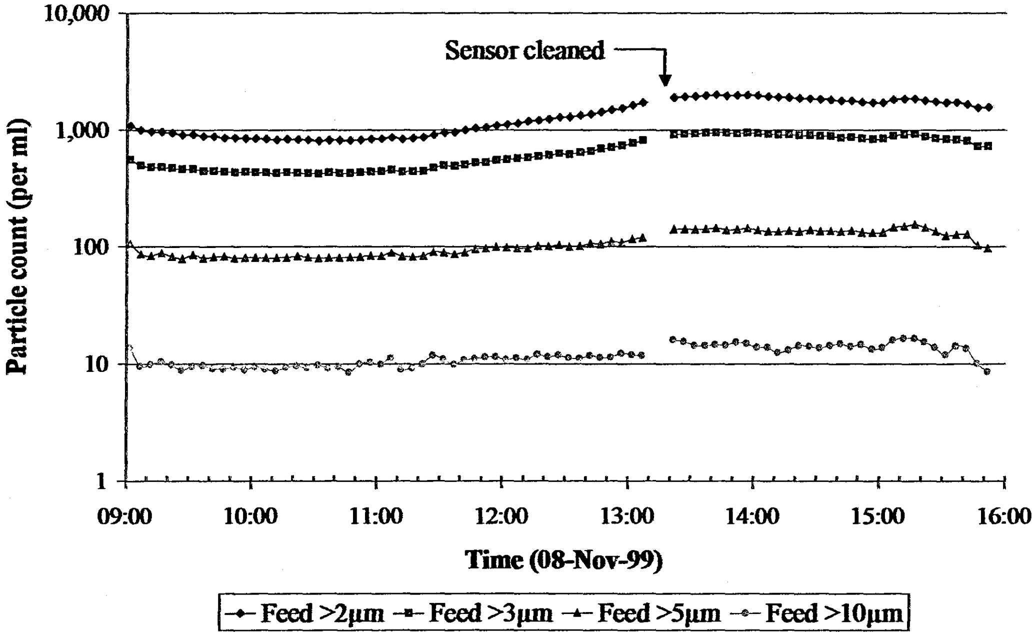


Figure 4.4 *Burpham WSW: 'Feed' particle counter sensor cleaned after a period of 20 days.*

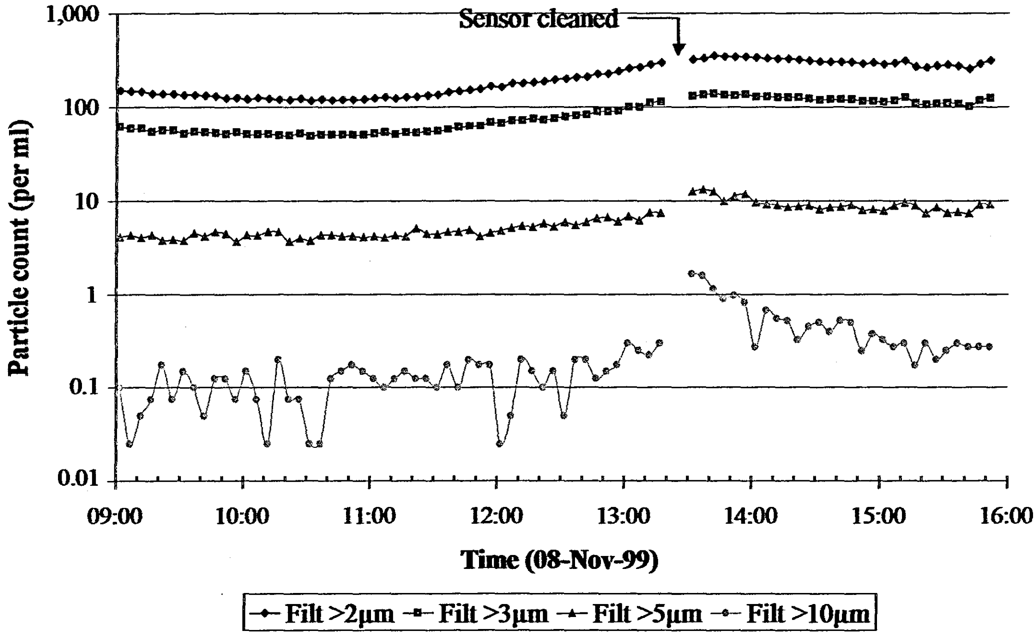


Figure 4.5 *Burpham WSW: 'Filtrate' sensor cleaned after a period of 20 days.*

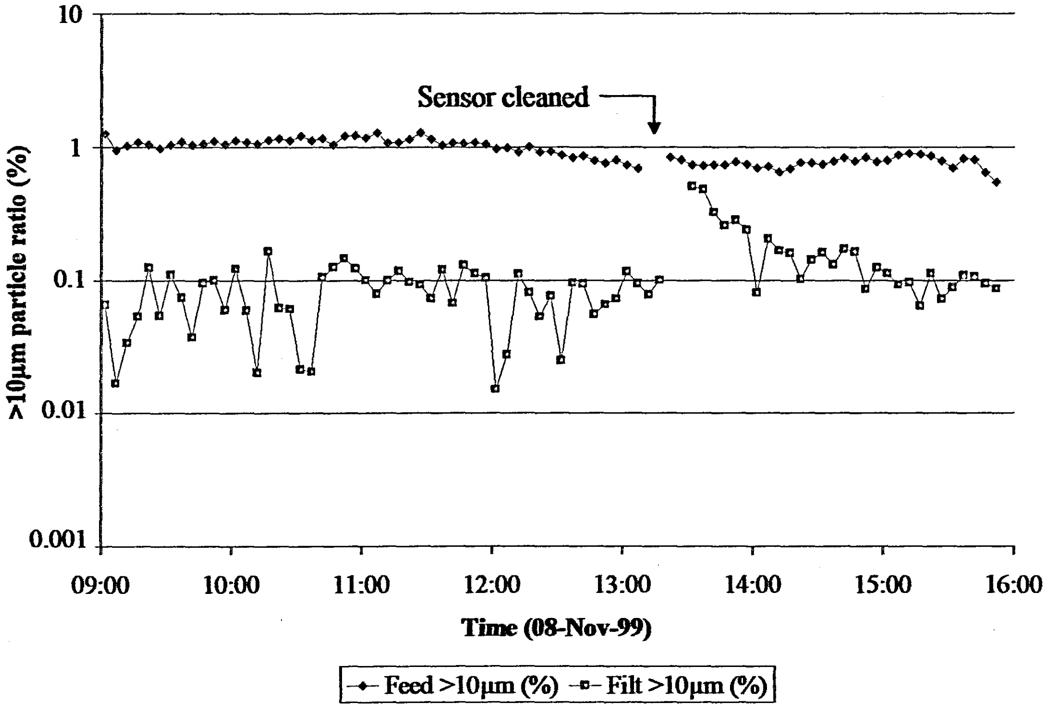


Figure 4.6 *Burpham WSW: Examination of the effect of cleaning on particle size distribution*

4.2.3 Sensor calibration

All the particle counters used in the trial were calibrated every twelve months at the manufacturers using monodisperse latex bead suspensions.

As discussed in Section 2.3.5, particle counting is a relatively imprecise technology. Readings given by two different particle counters can vary significantly. To counter this, several researches such as Lewis *et al.* 1999, Pickel *et al.* (1997) have advocated count matching (Section 2.3.5). This is where particle counters are 'fixed' to read the same as a 'master' counter across all size channels. The relative pro's and con's of count matching is discussed in Pickel *et al.* Count-matching improves monitor precision, but as that paper acknowledged, such particle counters '*do not have calibrations that are traceable to any known standard.*' It is interesting that both Pickel *et al.* and Lewis *et al.* attach much importance to absolute particle count values. For example, Lewis *et al.* required that all rapid gravity filters at a specific works produce an effluent with total particle count below 50 per ml (>2μm). For that use of particle counters, count matching is arguably a more attractive proposition.

In this study, however, interest was directed more towards using particle counters as a trend facility i.e. to look for changes in particle size/number rather than adherence to a particular standard. Monitor accuracy was therefore judged to be more important than precision. A similar 'trend analysis' approach was adopted by Ginn *et al.* (1997) who also decided not to count-match particle counters.

On-line instruments have been preferred here to 'grab' (or 'batch') analysers, which count particles in bottled samples. Previous experience with latter type of analysis revealed that samples collected in containers could be easily contaminated. This is reinforced by grab analyser data sets presented in Adham *et al.* (1995), Goldgrabe *et al.* (1993) and Hargesheimer and Lewis (1995), all of which contain a relatively high degree of noise.

One problem with using on-line instruments is that it is very difficult to check their calibrations using latex bead suspensions. Hargesheimer and Lewis advocated the use of latex bead standards to verify particle size and particle count but found that

'Standards to verify the counting accuracy are available but can be used in batch (grab) sampling configuration only...No way was found in this project to introduce calibration spheres to the particle count sensor while the sensor was still connected on-line.'

On-line calibration checks were not run during this study. This decision was taken because, as discussed in Chapter 3, the main focus of this study was the application of particle counters, and not to investigate possible improvements in their calibration. It is believed, however, that this would be a worthy area of study in future. One possible way forward, for example would be to purchase a grab sampler, on which regular calibrations checks could be made, and then compare this instrument with on-line counters. Another option would be to conduct a simple size test using a latex bead suspension. A method for performing this operation this is given in Process

Instruments, 2000b. In this method the particle counter is drip fed from a container suspended above the counter.

As a simple precision check, particle counters were regularly switched to see how their readings compared. An example of this was described in Hamilton *et al.* (2000) (Appendix A). In that case, >2μm readings given by a Met-One PCX and a PMS Liquilaz E20 particle counter were virtually identical.

A similar experiment was conducted at a washwater/clarifier sludge recycle plant at Burham WSW (Figures 4.7 and 4.8). [Burham and Burpham WSW are very different works; the former being a large surface water treatment works in Kent, and the latter a relatively small groundwater supply works in West Sussex]. At Burham WSW, two PMS Liquilaz E20 particle counters were set-up to monitor microfilter feed and filtrate (as detailed later). The filters were not running as the time of this experiment, the particle counters analysing remnant water in the mains. It was thought that this would provide stable readings, which would be ideal for comparing the two sensors.

In fact, the filtrate readings obtained were not stable, with total particle counts in the filtrate sample rising from 17 to 170 across the monitoring period (Figure 4.7). In terms of turbidity there appeared to be a slight increase in from 0.07 to 0.10 NTU across this period (not shown). The exact reason for this was unknown. Although this comparing of the two sensors was not ideal, a reasonable similarity was still apparent between the two particle counters, both in terms of particle count (Figure 4.7) and size distribution (Figure 4.8).

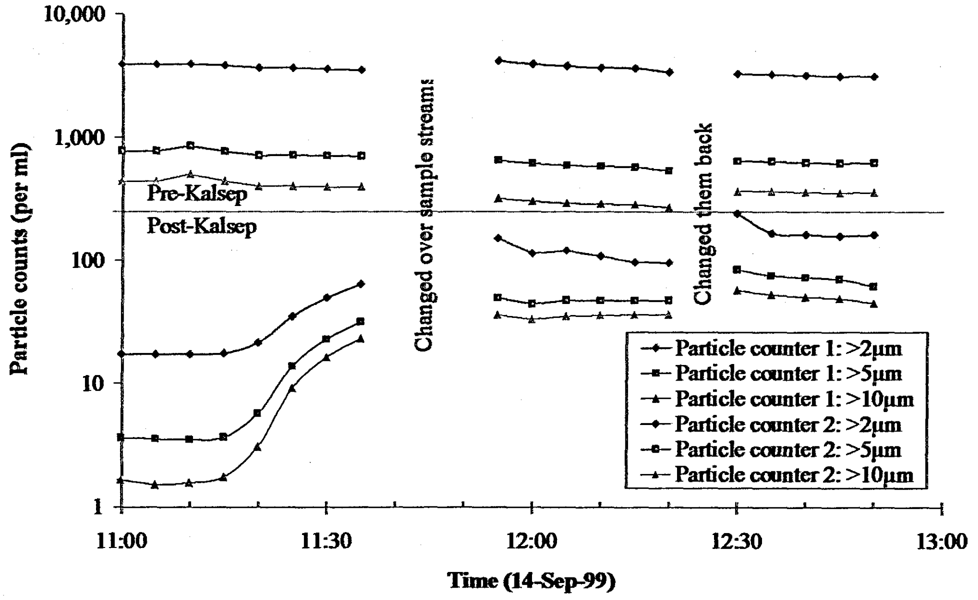


Figure 4.7 *Comparing the counting precision of two PMS Liquilaz E20 particle counters installed at Burham WSW.*

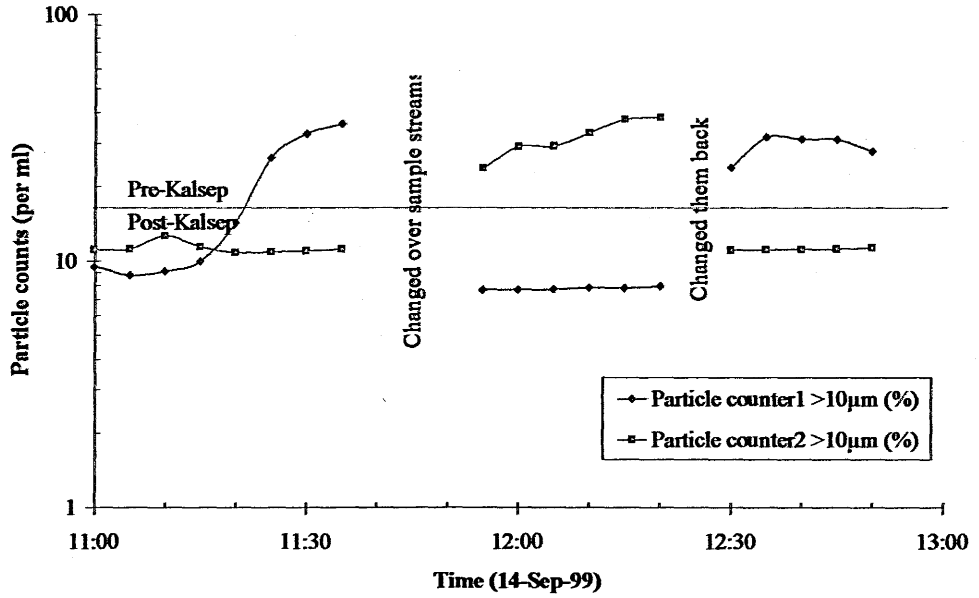


Figure 4.8 *Testing the sizing precision of two PMS Liquilaz E20 particle counters installed at Burham WSW.*

4.2.4 Coincidence error

Most particle counting in this study has been conducted on relatively clean-water samples with counts falling well short of 10% coincidence limits, specified by the manufacturers. In the rare instances where the risk of coincidence error was thought to be significant, (seen especially in the washwater/sludge recycling monitoring), this subject is raised and discussed separately.

Sommer and Kleine (1999) reported that two factors are responsible for limiting counters to a certain particle concentration, electronic saturation (i.e. the inability of particle counters to process the detected signal) and optical coincidence. The same paper suggested that 10% coincidence limits specified by manufacturers might underestimate the problem because they ignore the effects of electronic saturation.

A latex bead experiment, conducted to verify the coincidence limits, is detailed in Hamilton *et al.* (2000) (presented in Appendix A). The 10% coincidence limit of the PMS Liquilaz E20 particle counter used was estimated at around 12,000 per ml counts per ml. This was in exact accordance with the manufacturers own data.

Chapter 5: PARTICLE MONITOR SENSITIVITY MODEL

A revised form of this chapter has been accepted for publication by the '*Journal of Water Supply, Research and Technology – Aqua*' under the title '*An analysis of particle monitor sensitivity in potable water treatment*'.

5.1 INTRODUCTION

Studies have shown that reducing particulate matter in treated water samples can reduce the number of *Cryptosporidium* oocysts in drinking water (LeChevallier and Norton 1992). For this reason, water suppliers are keen to ensure that their works are optimised to minimise the number and size of particles present in treated water.

Three types of monitor are currently being evaluated in a long-term trial at Southern Water: conventional 90° light scatter (nephelometric) turbidimeters, light obscuration particle counters and a particle index monitor (photometric dispersion analyser). A more detailed description of these monitors has been published elsewhere, (Hargesheimer *et al.* 1992 Lewis *et al.* 1992, Hargesheimer and Lewis 1995, Hunt 1993, 95, Gregory 1994, Kirby *et al.* 1998). In this study the term 'particle monitor' has been used as a generic term, representing all types of photometric particle analysers such as turbidimeters, particle counters and particle index monitors.

In brief, turbidimeters measure the amount of 90° light scatter from particles in a sample cell. This reflects the 'cloudiness' of water sample, relative to a known standard, and is usually expressed in NTU (Nephelometric Turbidity Units). Conversely, most on-line particle counters measure a change in light intensity as particles pass through a laser beam. The 'shadow' (light obscuration) cast by each particle is proportional to its size within a defined size range. Particles can be counted and sized within different, discrete bands, usually from one or two microns (μm) upwards, depending on the type of sensor used. Particle index monitors use the 'turbidity fluctuation' technique (Gregory 1994, Kirby *et al.* 1998). These return a single-value measurement called a 'particle index' based upon the amount of fluctuation seen in a transmitted light signal.

All these monitors can obviously differ in their detection of individual particles, which will have different light scattering and blocking properties depending on their shape, texture, translucency etc. (Hunt 1993, 95). In addition, the size of particles in a sample can also affect monitor readings. In the case of turbidimeters, for example, although they 'see' particles in a wide size range, typically 0.01μm upwards (Hunt 1993), they respond optimally to particles in the submicron (<1μm) size range as shown by latex bead experiments (Gregory 1994). Most particle counters, on the other hand, count supermicron particles (>1μm). Particle index monitors are especially sensitive to very large (>20μm) particles (Kirby *et al.* 1998).

Despite these differences, however, when monitoring 'real' water samples, a strong degree of correlation is often seen between different particle count and turbidity trends (Hargesheimer *et al.* 1992, Hargesheimer and Lewis 1995, Casale *et al.* 1999, Morse *et al.* 1999, Hamilton *et al.* 2000). This is because particles (as sized by particle counters) tend to follow a characteristic size distribution (Bader 1970, Ginn *et al.* 1992, Hargesheimer *et al.* 1992, Kavanaugh *et al.* 1980), described by an inverse power relationship (Figure 5.1, Equation 5.1), and to vary in similar proportions across all size ranges. The similarity between particle count and turbidity trends can seriously limit the value of using particle counters at many treatment works: particle counters are usually more expensive to buy and to maintain than turbidimeters and will only be beneficial if they relate something different.

$$\textit{Particle size distribution, } N_i = Ax_i^{-\beta} \qquad (5.1)$$

where 'normalised' count, $N_i = \dfrac{\text{particle count (per ml)}}{\text{channel width } (\mu m)}$ in size channel i,

x_i = particle size, midpoint of channel i (μm),

A and β constants.

One difference is that particle counters can provide a more sensitive measure of particle numbers in low turbidity samples (<0.1 NTU). For example, Jacangelo *et al.* (1991) and Adham *et al.* (1995) both noted that particle counters were around three hundred times more sensitive than turbidimeters in detecting compromised fibres on a membrane filter. Tate and Trussell (1977), Hargesheimer *et al.* (1992) and Hargesheimer and Lewis (1995) also showed a similar, if less pronounced effect when monitoring high quality rapid gravity filtered water. However, this heightened sensitivity is not always observed. For example, in two filter ripening curves presented in Hargesheimer *et al.* (1992), turbidity appears to be the more sensitive technique even when measuring well below the 0.1 NTU level. Similarly in Goldgrabe *et al.* (1992), an increase in filtered water turbidity from 0.08 to 0.10 NTU was mirrored by an increase particle counts from 82 to 101 per ml (>1μm) i.e. both instruments showed an almost identical percentage increase.

A second difference is that particle counters can be more sensitive to changes associated with larger particle sizes. For example, they can provide an early indication of filter breakthrough (Kavanaugh *et al.* 1980, Keay 1995, Murray 1995, Saunders *et al.* 1999), which is believed to occur first for large particles. Kavanaugh *et al.* (1980) suggested that monitor response might be directly proportional to a sample's particle size distribution. That study theorised that a critical point exists at $\beta=3$ such that when $\beta>3$, a sample is dominated by smaller light scattering particles. In this case, that turbidimeters might be preferable for detecting changes in particle numbers. However, when $\beta<3$, the sample is dominated by larger, light obscuring particles whereupon monitors such as particle counters might be more useful.

The following study set out to investigate more rigorously the question of monitor sensitivity to changes in water samples by building an observational regression model from published and unpublished data sets. This could be used to assess the value of using particle counters at different treatment works.

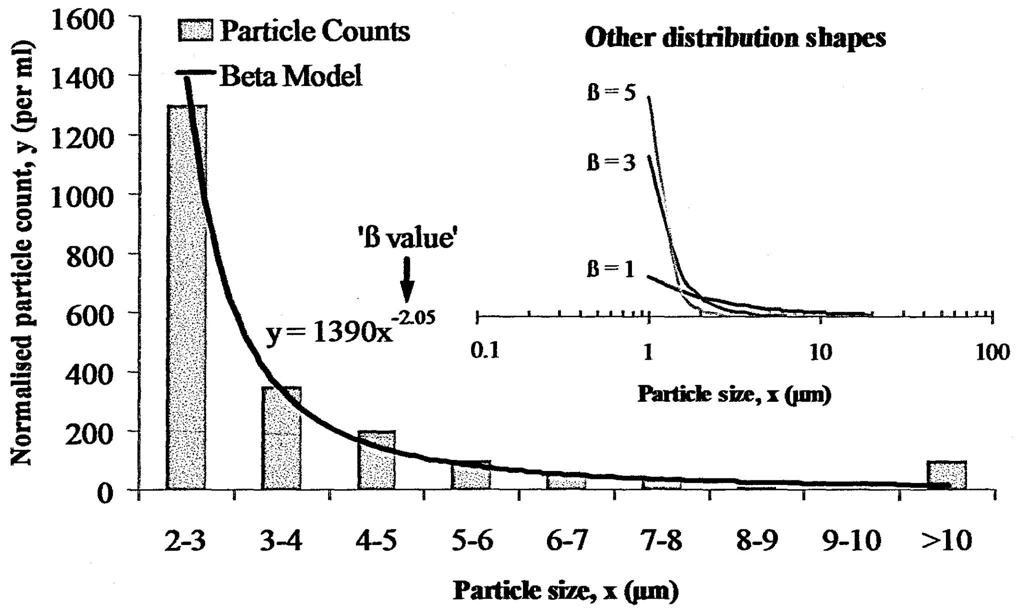


Figure 5.1 *Typical size distribution of particles in water as measured by light obscuration particle counters.*

5.2 METHODS

5.2.1 Sensitivity Modelling

The data analysed in this study has been taken from various stages of potable water treatment processes: e.g. raw surface and groundwaters, filter outlets, recycled washwaters etc. Where a change in particle number has been detected, a comparison has been made between the size of change in turbidity readings and in corresponding particle counts and/or particle index. To this end, the sensitivity statistic, S has been defined as follows:

$$S_{pc} = \frac{\Delta_{pc}}{\Delta_{ntu}}, \quad S_{pi} = \frac{\Delta_{pi}}{\Delta_{ntu}} \tag{5.2}$$

$$where\ \Delta_{monitor} = \frac{high\ monitor\ reading}{low\ monitor\ reading} \tag{5.3}$$

('pc', 'pi' and 'ntu' subscripts refer respectively to particle count, particle index and turbidity data).

As an example, in the case of the Jacangelo *et al.* (1991) data, a change in turbidity from 0.03 to 0.05 returned Δ_{ntu} = 1.7. At the same time, particle counts (>1μm) increased from around 2 to 1000 per ml, giving Δ_{pc} = 500. Dividing Δ_{pc} by Δ_{ntu}, gave S_{pc} = 300 which indicated that, in this instance, the particle size counter was 300 times more sensitive than turbidity to the change in particle number. Although small errors in turbidity readings can lead to large differences in S, these have only a small effect in the inverse power model: there is relatively little difference between S=200 and S=500, say when shown on a $\log_{10}$-scale. By defining sensitivity as a ratio between a high and low reading, the analysis is also relatively robust to instrument calibration differences.

5.2.2 Experimental data

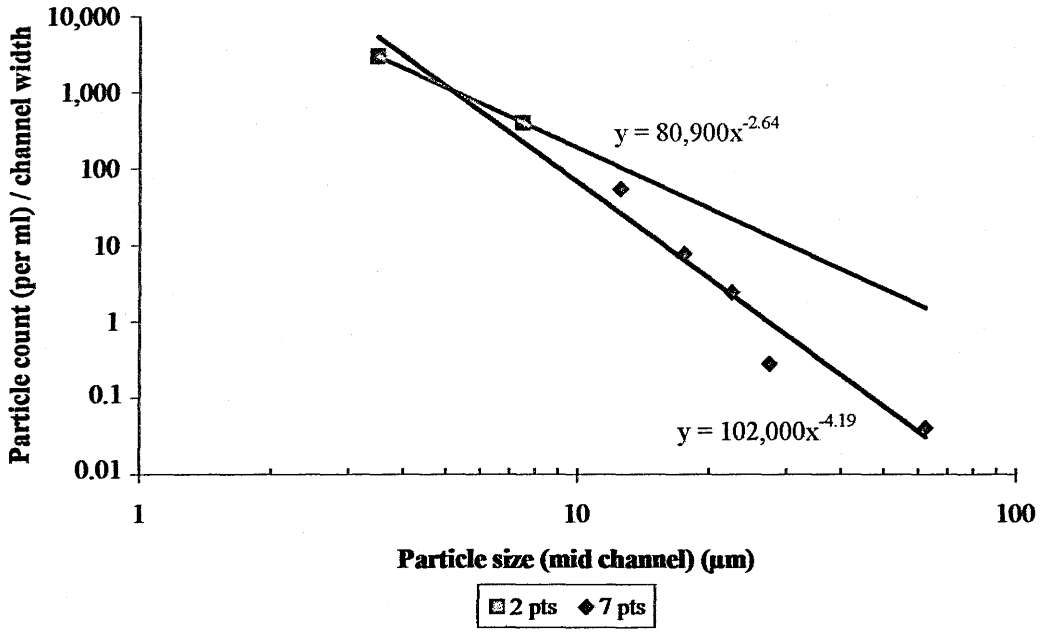
The experimental data has been extracted from 5 different sites using two types of light obscuration particle counter (PMS Liquilaz E20 and Met One PCX) and two different turbidimeters (ABB 7997/202 and Hach 1720C).

5.2.3 Validating β

The effect on sensitivity of a sample's particle size distribution as defined by the inverse power law coefficient β has also been analysed. The process for calculating β is not straightforward. Its value can vary significantly depending on which size intervals are used. Hargesheimer *et al.* (1992) observed that β sometimes varied significantly depending on whether 5 or 10 or more points were used to calculate it. In order to investigate this further, a number of size distributions have been compared, two of which are shown (Figures 5.2 and 5.3).

The analysis confirmed that β can vary greatly depending on which size ranges are used. This is shown by the different line gradients obtained when 2 or more size channels are used. The difference is especially apparent in Figure 5.2 data with a 'knee' clearly visible around the 10μm gradation. Interestingly, in latex bead experiments, Van Gelder *et al.* (1999) observed that, compared to electrical resistance particle counters, light obscuration instruments tended to underestimate the number of particles in the 2-5μm size range. Whether these observations are linked is unclear.

Figure 5.2 shows that the inclusion in the calculations of particle counts above 20μm in size can have a large effect on β. However, it could be argued that the β estimate should not be so heavily influenced by particles, which in this case form less than 0.2% of the total count. In Figure 5.2, a point of relative equilibrium is reached when using 4 size channels; in Figure 5.3 this is reached with 3 channels. To standardise its calculation in this study, β has been derived from normalised particle counts in the following ranges: 2-3μm, 3-5μm, 5-10μm, and 10-20μm.



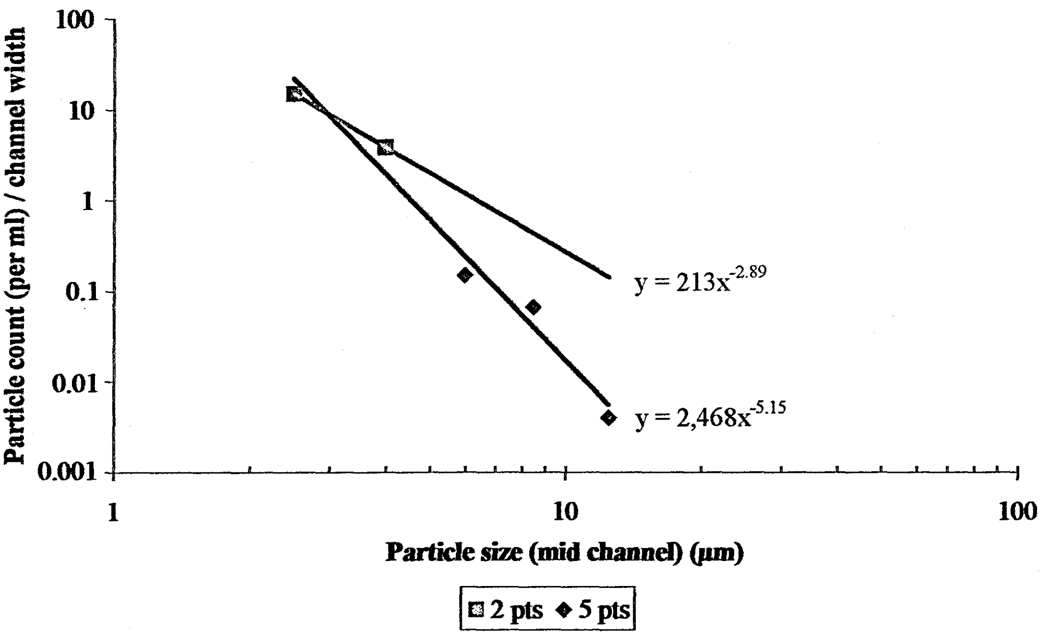
Size channels used	2-5µm	5-10µm	10-15µm	15-20µm	20-25µm	25-50µm	50-100µm
Particle counts*	2974	399	54	7.6	2.4	0.28	0.04
Beta (n=2)**	2.6 [n/a]						
Beta (n=3)	3.1 [0.07]						
Beta (n=4)	3.6 [0.01]						
Beta (n=5)	3.9 [0.002]						
Beta (n=6)	4.3 [0.0008]						
Beta (n=7)	4.2 [0.00005]						

Figure 5.2 *Beta estimates calculated using different size channels (Light obscuration sensor, surface water sample, data taken from Hargesheimer and Lewis 1995).*

* Normalised particle count (i.e. divided through by channel width).

** n = number of indicated size channels used to calculate beta.

The significance level [p] associated with each β calculation is shown in square brackets.



Size channels used	2-3µm	3-5µm	5-7µm	7-10µm	10-15µm
Particle counts*	15	3.9	0.15	0.07	0.004
Beta (n=2)**	2.9 [n/a]				
Beta (n=3)	5.2 [0.10]				
Beta (n=4)	4.8 [0.04]				
Beta (n=5)	5.1 [0.005]				

Figure 5.3 Beta estimates calculated using different size channels (Light obscuration sensor, filtered groundwater sample).

* Normalised particle count (i.e. divided through by channel width).

** n = number of indicated size channels used to calculate beta.

The significance level [p] associated with each β calculation is shown in square brackets.

5.2.4 Particle ratios

Because of the discrepancies seen when calculating β, an alternative size distribution parameter was also used, namely the proportion of 'large' particles (>10μm) in a sample expressed as a percentage of the total count, denoted here by $Q_{>10\mu m}$ (Equation 5.4). This is easier to calculate than β and is appropriate for all particle size distributions. To provide a more suitable scaling of this parameter, logarithms were taken, and this new statistic denoted by *a* (Equation 5.5).

$$Q_{>10\mu m} = \frac{>10\mu m\ particle\ count}{>2\mu m\ particle\ count} \times 100\% \tag{5.4}$$

$$a = \log_{10}(Q_{>10\mu m}) \tag{5.5}$$

5.3 RESULTS

5.3.1 Initial sensitivity model

The models were built by plotting monitor sensitivities (S_{pc} and S_{pi}) against baseline turbidity values (NTU_{low}). For the literature data set (Table 5.1a and 5.1b), a strong inverse power relationship between particle monitor sensitivity (S) and turbidity (T) was apparent (Figure 4), given by

$$S = 0.18\,T^{-1.35}, \quad p < 0.01 \tag{5.6}$$

(Applies to both particle counters and index monitors)

This observational model suggests that, in general, particle counters are relatively more sensitive at lower turbidities (especially below 0.1 NTU), whereas turbidimeters are as sensitive as, if not more sensitive than particle counters at higher values.

This initial model is built from data taken many different types of particle counter (Table 5.1a), including various forward angle light scatter (FALS) sensors (described in Hargesheimer *et al.* 1992, Lewis *et al.* 1992). In terms of accuracy, therefore, it is superseded by subsequent models that use data only from two light obscuration counters. However, this model does at least demonstrate a novel way in which different monitors can be compared. Although only five data points were generated, particle index monitors appear to be as sensitive to changes in water quality as particle counters. Statistically, the 'particle count' and 'particle index' data were indistinguishable from each other (p>0.99).

Several data points fell outside the 99% confidence interval shown in Figure 5.4. Some of the points below the line (e.g. Hargesheimer *et al.* 1992) represent deteriorations caused by filter ripening, during which time relatively more smaller particles are believed to pass through the filter. Conversely, some of the points above the line correspond to filter breakthrough (Kavanaugh *et al.* 1980, Murray 1995), which is frequently associated with an increase in particle size.

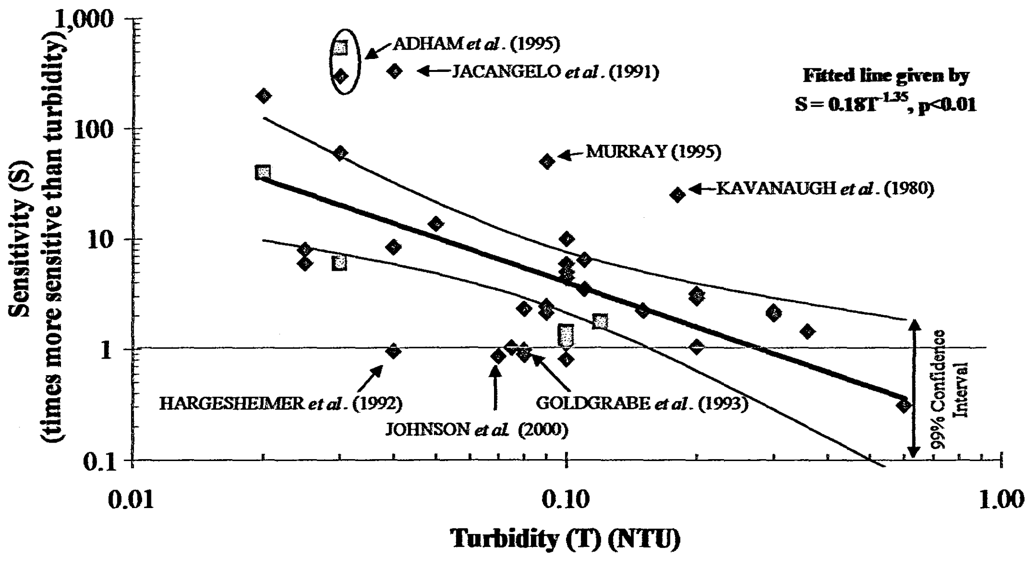


Figure 5.4 *Particle monitor sensitivity model (Literature data).*

5.3.2 Improved model using beta

The model was reconstructed to see if the particle size distribution, as defined by β, could be integrated into the model. To preserve consistency in the β estimates, only experimental data (Table 5.2) was used. As can be seen in Figure 5.5, the effect of particle size was successfully modelled; both turbidity ($p<0.01$) and β ($p<0.01$) were significant inclusions in this model.

$$S_{pc} = 3.71 T^{-0.50} (0.66)^{\beta}, \quad p < 0.01 \tag{5.7}$$

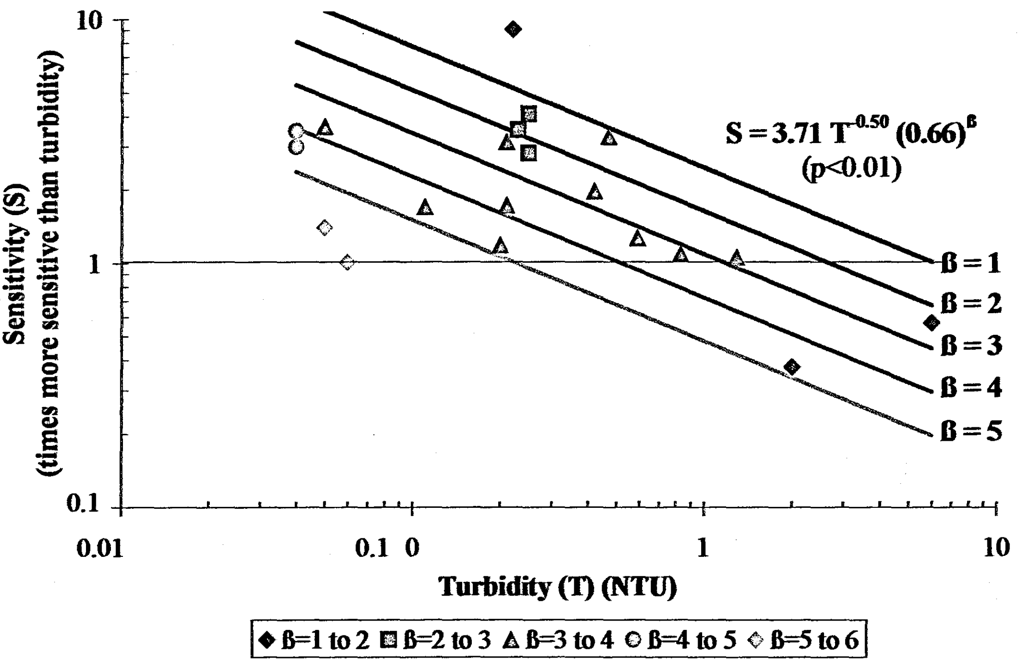


Figure 5.5 *Particle counter sensitivity model with β (Experimental data).*

5.3.3 Alternate model using particle ratio

Because of discrepancies surrounding the calculation of beta, an alternate model was also built. This used the >10μm particle ratio defined previously. As can be seen in Figure 5.6, a similar pattern was seen linking particle counter sensitivity with turbidity and particle size.

$$S_{pc} = 0.87\,T^{-0.49}\,(0.58)^{-a}, \quad p < 0.01 \qquad (5.8)$$

Once again turbidity (p<0.01) and *a* (p<0.01) were both significant inclusions in this model. Of the three models derived so far, this is arguably the most accurate. The similarity between this and the β model further substantiates the use of β in this study.

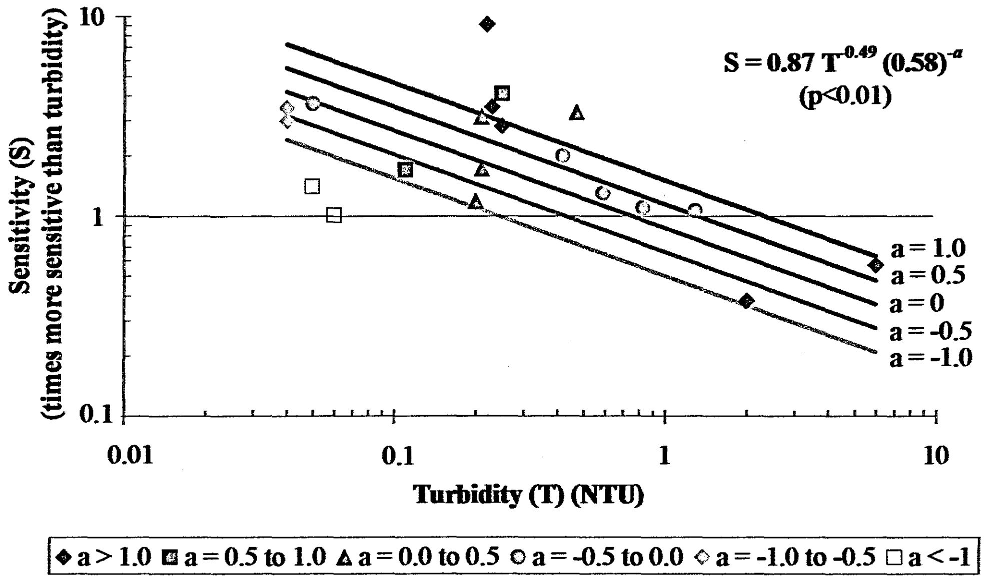


Figure 5.6 *Particle counter sensitivity model with particle ratio (Experimental data).*

5.4 DISCUSSION

5.4.1 Particle counting below 0.1 NTU

Aside from particle sizing applications, particle counters (and index monitors) appear to be most useful when monitoring high quality water with turbidity at or below 0.1 NTU. As such, they can be used to evaluate and fine-tune high performance treatment plants in respect of coagulant dose, filter start-up and backwashing strategy etc. (reviewed in Hamilton *et al.* 2001). Here, for example, experimental data (Newmarket WSW) showed that particle counters were more capable of detecting surface water intrusion at a low turbidity groundwater works.

In the UK, the level of treated water turbidity is not generally considered to be as important as anomalies in that data. The government commissioned Bouchier Report (1998) recommends on large treatment works that '*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 some suitably representative level.*' It is evident from the model that in some instances, a small change in turbidity e.g. from 0.05 to 0.06 NTU, for example, can represent a large increase in particle numbers. A water company might therefore consider using particle counters to control processes that consistently produce very low turbidity water such as membrane or certain rapid gravity filter plants.

In the main, however, turbidity remains a more sensitive monitor at higher values and arguably is more important as far as detecting large deteriorations in water quality, which may be more significant in terms of *Cryptosporidium* risk. For example, the largest problem in water treatment is controlling coagulant dose under rapidly changing raw water conditions (Bellamy *et al.* 1993, Consonery *et al.* 1997). On these occasions, turbidity may rise substantially above 0.1 NTU where particle counters would seem to be of diminishing value.

5.4.2 Effect of particle size distribution

The models also show how particle size distribution affects monitor sensitivity. As theorised by Kavanaugh *et al.* (1980), for samples containing a high proportion of submicron particles ($\beta>3$), particle counting will typically be less sensitive than expected for a sample of a given turbidity. Conversely particle counting will be more sensitive for samples containing proportionally more larger particles ($\beta<3$).

This has several implications. Firstly, where there is an anticipated shift increase or decrease in particle size, the sensitivity of particle counters (>2µm) will vary accordingly. More generally, though, particle size distribution appears to remains fairly constant at individual works. This is shown in the lack of variability in a and β values in Table 5.2. Some processes may produce samples with an unusually fine particle size distribution, and so may not benefit from on-line particle counters even at low turbidities; conversely other samples may have an abnormally coarse distribution and so may be especially suited to particle counting.

An unusual demonstration of this was seen in experimental data taken from a water recycling process at a surface water treatment works (Burham WSW). Here, a blend of filter washwater and clarifier sludge is dosed with polyelectrolyte, undergoes settlement and microfiltration (Kalsep Fibrotex AX300) before being returned to the head of the works. The microfilter feed and filtrate water has an unusual particle size distribution because it comprises a very high amount of large aluminium floc particles, ($\beta = 1.7$-2.0; $a = 1.0$-1.2). Unfortunately, under a high solids challenge, the particle counters monitoring this process have shown a tendency to clog, which has restricted their use thus far. With better monitor design and/or sampling arrangements, it is hoped that the situation could be improved. It is possible that an adapted technology might be useful in other sludge treatment processes e.g. in wastewater treatment.

5.5 SUMMARY

The sensitivity model is a useful comparative tool that can be used to determine the best applications of particle counters at different water treatment works.

Particle counter sensitivity varies according to an inverse power relationship with turbidity. Particle counters are therefore generally best used to fine-tune processes below 0.1 NTU. For processes that consistently produce very low turbidity water e.g. membrane filters, there may be some value in using particle counters in process control.

The work also shows the value of existing turbidimeters. These are usually as sensitive as particle counters around 0.1 NTU and remain more important in terms of minimising *Cryptosporidium* risk.

The size distribution of particles in water samples, as defined by particle ratios or the inverse power law β coefficient, has a significant effect on monitor sensitivity and can affect the suitability of using particle counters at some works. This can be assessed using the sensitivity model.

The model can also be used to compare new high sensitivity instruments. There is limited evidence to suggest that particle index monitors are as sensitive as particle counters below 0.1 NTU. If particle sizing is not required then these may be useful as a cheap alternative to particle counting.

It can also be used to compare unusual changes in on-line particle count and turbidity trends. For this purpose, it is recommended that where particle counters are being used, a particle size ratio or a similar size statistic be trended alongside turbidity and particle counts.

Table 5.1a *Literature data set (Particle counters vs. turbidity).*

*Reference**	*Sample*	*Reason for change*	*Particle counter/sensor*	NTU_{low}	NTU_{high}	Δ_{ntu}	PSC_{low}	PSC_{high}	Δ_{psc}	S_{psc}
Adham *et al.* (1995) Fig. 9,11	Post membrane	Damaged fibres	Met-One 250/211 (FALS, >1μm)	0.02	1.00	50.0	1	10000	10000	200
Saunders *et al.* (1999) Fig. 1.8	Post RGF	Filter breakthrough	Not specified	0.025	0.026	1.0	20	125	6.3	6.0
Pizzi and Rodgers (1998) Table 3	Post RGF	Filter breakthrough	Not specified	0.025	0.042	1.7	9	121	13	8.0
Adham *et al.* (1995) Fig. 9,11	Post membrane	Damaged fibres	Met-One 250/211 (FALS, >1μm)	0.03	0.50	16.7	2	10000	5000	300
Adham *et al.* (1995) Fig. 9,11	Post membrane	Damaged fibres	Met-One 250/211 (FALS, >1μm)	0.03	0.50	16.7	5	5000	1000	60
Jacangelo *et al.* (1991) Fig. 7	Post membrane	Damaged fibres	Met-One 210/211 (FALS, >2μm)	0.04	0.06	1.5	2	1000	500	333
Chipps *et al.* (1995) Table 3	Post RGF	Lower pre-ozone dose	Unspecified LO counter	0.04	0.05	1.3	400	4200	11	8
Hargesheimer *et al.* (1992) Fig. 8.15	Post RGF	Filter ripening	HRLD-150 sensor (LO, >1μm)	0.04	1.5	37.5	250	9,000	36	1.0
Hargesheimer & Lewis (1995) Fig. 6.1	Post RGF	Misc samples	PMS Liquilaz E20	0.05	0.15	3.0	12	490	41	14
Hargesheimer *et al.* (1992) Fig. 8.15	Post GAC	Filter ripening	HRLD-150 sensor (LO, >1μm)	0.07	1.3	18.6	750	12000	16	0.9
Johnson *et al.* (2000) Fig. 7	Post RGF	Unspecified event	Hach 1900 WPC	0.075	0.082	1.1	8	9	1.1	1.0
Hargesheimer *et al.* (1992) Fig. 8.11	Post RGF	Filter ripening	CMH-150 sensor (>2.5μm)	0.08	0.98	12.3	40	440	11	0.9
Goldgrabe *et al.* (1993) Table 3	Post filter	Filter acclimatisation	Hiac Royco 9064/HRLD-150 (LO, >1μm)	0.08	0.10	1.3	82	101	1.2	1.0
Hargesheimer *et al.* (1992) Fig. 3.10	Post RGF	Misc samples	Model 4100 / 346B (FALS, >0.7μm)	0.08	0.12	1.5	600	2100	3.5	2.3
Goldgrabe *et al.* (1993) Table 3	Post filter	Filter acclimatisation	Hiac Royco 9064/HRLD-150 (LO, >1μm)	0.09	0.11	1.2	172	514	3.0	2.4
Goldgrabe *et al.* (1993) Table 3	Post filter	Filter acclimatisation	Hiac Royco 9064/HRLD-150 (LO, >1μm)	0.09	0.10	1.1	174	413	2.4	2.1
Murray (1995) Fig. 3	Post RGF	Filter breakthrough	Not specified	0.09	0.21	2.3	3	350	117	50
Peters (1999)	Post RGF	Filter ripening	Not specified	0.10	0.16	1.6	140	250	1.8	1.1
Peters (1999)	Post RGF	Filter ripening	Not specified	0.10	0.16	1.6	150	200	1.3	0.8
Lewis and Manz Fig. 2	Post RGF	Filter breakthrough	Hiac Royco 4100/346-BCL (FALS)	0.10	0.30	3.0	100	3000	30	10
Lewis and Manz Fig. 2	Post RGF	Filter breakthrough	Hiac Royco 4100/346-BCL (FALS)	0.10	0.45	4.5	300	8000	27	5.9
Hall and Croll (1997) Fig. 1	Post RGF	Filter breakthrough	Hiac Versacount	0.1	0.5	5.0	100	2500	25	5.0
Keay (1995) Fig. 3	Post RGF	Filter breakthrough	Unspecified electrical resistance counter	0.10	0.25	2.5	50	550	11	4.4
Tate and Trussell (1978) Fig. 7	Post RGF	Poly dose change	Hiac Model 320	0.11	0.36	3.3	5	105	21	6.4
Beard and Tanaka (1977) Fig. 2	Post RGF	Filter ripening	Hiac PC-320 / Not specified (>2.5μm)	0.11	0.2	1.8	16	100	6.3	3.5
Hall and Croll (1997) Table 4	Post RGF	Filter ripening	Hiac Versacount	0.15	0.2	1.3	1500	4300	2.9	2.2
Kavanaugh *et al.* (1980) Fig. 10	Post RGF	Filter breakthrough	Hiac Model 320	0.18	0.36	2.0	20	1000	50	25
Hall and Croll (1997) Table 4	Post RGF	Filter ripening	Hiac Versacount	0.2	0.4	2.0	7100	15000	2.1	1.1
Wilson and Morse (1999) Fig. 5	Post RGF	Filter ripening	PMS Liquilaz E20	0.20	0.36	1.8	130	680	5.2	2.9
Tate and Trussell (1978) Fig. 8	Post RGF	Filt rate change	Hiac Model 320	0.20	0.25	1.3	10	40	4.0	3.2
Tate and Trussell (1978) Fig. 9	Post RGF	Coag dose change	Hiac Model 320	0.30	0.65	2.2	11	50	4.5	2.1
Bourgine *et al.* (1996) Fig. 3	Post RGF	Misc samples	PMS Liquilaz E20	0.3	1.2	4.0	600	5300	8.8	2.2
Hamilton *et al.* (2000) Fig. 8	Groundwater	Tidal influence	PMS Liquilaz E20	0.36	0.69	1.9	1385	3886	2.8	1.5
Hargesheimer & Lewis (1995) Fig. 6.1	Surface water	Misc samples	PMS Liquilaz E20	0.6	7.4	12.3	7800	30000	3.8	0.3

* Tables and figures in this column refer to the paper cited.
'RGF' = 'rapid gravity filter'; 'LO' = 'light obscuration; 'FALS' = 'forward angle light scatter'.

Table 5.1b *Literature data set (Particle index vs. turbidity).*

*Reference**	*Sample*	*Reason for change*	*Particle counter/sensor*	NTU_{low}	NTU_{high}	Δ_{ntu}	PSC_{low}*	PSC_{high}*	Δ_{psc}	S_{psc}
Adham *et al.* (1995) Fig. 10-11	Post membrane	Damaged fibres	Chemtrac PM3500	0.02	1.00	50.0	5	10000	2000	40
Adham *et al.* (1995) Fig. 10-11	Post membrane	Damaged fibres	Chemtrac PM3500	0.03	0.50	16.7	1	9000	9000	540
Adham *et al.* (1995) Fig. 10-11	Post membrane	Damaged fibres	Chemtrac PM3500	0.03	0.50	16.7	10	1000	100	6.0
Peters (1999)	Post RGF	Filter ripening	Diverse FPM	0.10	0.16	1.6	70	160	2.3	1.4
Peters (1999)	Post RGF	Filter ripening	Diverse FPM	0.10	0.16	1.6	70	140	2.0	1.3
Peters (1999)	Groundwater	Borehole pump start	Diverse FPM	0.12	0.27	2.3	75	300	4.0	1.8
Peters (1999)	Groundwater	Borehole pump start	Diverse FPM	0.12	0.32	2.7	75	350	4.7	1.8

* Tables and figures in this column refer to the paper cited.

Table 5.2 *Experimental data set.*

Works	*Sample*	*Reason for change*	*Particle Counter*	NTU_{low}	NTU_{high}	Δ_{ntu}	PC_{low}*	PC_{high}*	Δ_{pc}	S_{pc}	α**	*Diff***	β**	*Diff***
Newmarket 1C	Groundwater	Rain influence	Met-One PCX	0.05	0.08	1.6	9.3	54.1	5.8	3.7	0.0	±0.4	4.0	±0.6
Arundel	Groundwater	Increased flow	Met-One PCX	0.20	0.23	1.2	1417	1938	1.4	1.2	0.4	±0.0	3.0	±0.1
Burpham	Groundwater - Pre MF	Tidal influence	Met-One PCX	0.42	0.49	1.2	1253	2905	2.3	2.0	0.0	±0.1	3.6	±0.1
	Groundwater - Pre MF	Tidal influence	Met-One PCX	0.59	1.35	2.3	2047	5972	2.9	1.3	-0.1	±0.0	3.7	±0.0
	Groundwater - Pre MF	Tidal influence	Met-One PCX	0.83	1.72	2.1	2890	6557	2.3	1.1	-0.2	±0.1	3.8	±0.1
	Groundwater - Pre MF	Tidal influence	Met-One PCX	1.29	2.57	2.0	2871	6078	2.1	1.1	-0.2	±0.0	3.9	±0.0
	Groundwater - Post MF	Filter ripening	Met-One PCX	0.04	0.05	1.3	228	741	3.3	2.6	-0.9	±0.1	4.8	±0.2
	Groundwater - Post MF	Filter ripening	Met-One PCX	0.04	0.05	1.3	286	1247	4.4	3.5	-0.8	±0.4	4.6	±0.6
	Groundwater - Post MF	Tidal Influence	Met-One PCX	0.06	0.10	1.7	689	1159	1.7	1.0	-1.1	±0.1	5.1	±0.1
	Groundwater - Post MF	Tidal Influence	Met-One PCX	0.05	0.10	2.0	386	1085	2.8	1.4	-1.4	±0.1	5.4	±0.1
Burham***	Settled sludge - Pre MF	Increased flow	PMS Liquilaz E20	2	13	6.5	3865	9447	2.4	0.4	1.2	±0.1	1.9	±0.2
	Settled sludge - Pre MF	Increased flow	PMS Liquilaz E20	6	18	3.0	5334	9122	1.7	0.6	1.2	±0.2	2.0	±0.3
	Settled sludge - Post MF	Breakthrough	PMS Liquilaz E20	0.25	0.30	1.2	321	1573	4.9	4.1	1.0	±0.0	2.3	±0.0
	Settled sludge - Post MF	Breakthrough	PMS Liquilaz E20	0.25	0.27	1.1	371	1131	3.0	2.8	1.0	±0.1	2.2	±0.1
	Settled sludge - Post MF	Breakthrough	PMS Liquilaz E20	0.23	0.29	1.3	327	1448	4.4	3.5	1.1	±0.0	2.2	±0.1
	Settled sludge - Post MF	Breakthrough	PMS Liquilaz E20	0.22	0.41	1.9	387	6568	17.0	9.1	1.2	±0.1	1.8	±0.2
Testwood	Post RGF	Ripening	Met-One PCX	0.11	0.14	1.3	208	452	2.2	1.7	0.6	±0.1	2.7	±0.1
	Post RGF	Ripening	Met-One PCX	0.21	0.23	1.1	247	468	1.9	1.7	0.5	±0.0	2.9	±0.1
	Post RGF	Ripening	Met-One PCX	0.21	0.35	1.7	273	1435	5.3	3.2	0.5	±0.0	2.9	±0.0
	Post RGF	Ripening	Met-One PCX	0.47	0.65	1.4	570	2617	4.6	3.3	0.4	±0.1	2.9	±0.2

* >2μm counts per ml

** α and β values have been calculated for both PC_{low} and PC_{high} and the mean values shown. In each case, the difference between the two calculated values is shown in the 'Diff' columns.

*** A description of this works is included in Section 5.4.2.

Chapter 6: SURFACE WATER TREATMENT STUDIES

6.1 INTRODUCTION

Southern Water has eight surface water supply works (WSW), which supply around a third of all drinking water to around a million properties in Hampshire, Sussex, Kent and the Isle of Wight. This chapter summarises particle counting trials conducted at two of these works: Hardham and Testwood WSWs. Both these works comprise conventional coagulation-clarification-rapid gravity filtration processes.

Numerous studies have shown that minimising the number of particles in treated waters can reduce the risk of *Cryptosporidium* on a site-specific basis (Section 2.4). Although turbidimeters remain the first choice particle monitor, particle counters appear to have three potential benefits (Section 2.6): (a) they can be more sensitive than turbidimeters at lower turbidities; (b) they can be more sensitive to changes associated with larger particle sizes e.g. filter breakthrough; (c) they relate information on the particle size distribution of a sample. Each of these benefits may or may not be useful at different works depending on the type of water being treated and the treatment process used.

Following on from the previous study of monitor sensitivity (Chapter 5), it is now possible to see how those models relate to individual works and to consider practical issues such as where to install particle counters, how to use results (i.e. in process control or in one-off optimisation trials), what parameters to use, how often to measure etc.

6.1.1 Where to install particle counters

In general, particle counters appear to be best used on high quality filtered water and groundwater samples although the exact level of sensitivity gained at lower turbidities will vary depend upon the particle size distribution of the sample. This can be assessed on a site-specific basis using the sensitivity models derived in Section 5.3.

In terms of raw, coagulant-dosed, clarified, and some higher turbidity treated waters, indications are that any successful applications, if they exist at all will be limited to particle sizing as suggested by studies as Lartiges *et al.* (1995), Reed and Mery (1986), Hutchinson (1985) and Kavanaugh *et al.* (1980) (Section 2.6.3).

Particle counters are therefore most likely to be used on primary filtered water samples. Several authors such as Ginn *et al.* (1997), and Lewis *et al.* (1999) have argued that fitting particle counters to individual filter outlets can give significant benefits. For example, Ginn *et al.* showed how particle counters installed on all filters at three treatment works helped identify leaks in three filters. However, particle counters do have limitations, not least their cost, reported inaccuracy, difficulties in calibrating and calibration checking, and most significantly perhaps, their similarity with turbidity readings (Section 2.6). One could also perhaps question the long-term value of installing these monitors. Recognising these shortcomings, the regulators have so far fallen short of recommending the permanent installation of particle counters at treatment works. Particle counter use is merely encouraged as an additional optimisation tool (Bouchier 1998), which is largely achievable using portable instruments.

One compromise scenario would to be to install monitors on combined filter outlets. Bridgeman (2000) observed that particle counters installed on combined and individual filtrate sample lines gave similar information apart from peaks associated with backwashes, which showed up as much smaller peaks on the combined sample line. However, Hargesheimer and Lewis (1995) argued that individual filter outlets are the best location for particle counters, arguing that particle counters installed on combined samples respond more slowly to changes in water quality. Also one process (such as a filter) could be performing poorly and its performance could go undetected due to dilution by the other processes.

Particle counters can also be used on other samples such as groundwater and secondary filtered water. Adham *et al.* (1995) recognised that *'monitoring of large-scale membrane systems by particle monitoring devices is going to increase the capital cost of the system by a considerable margin'.* He therefore advised developing techniques for membrane testing that combine advantages of indirect methods (e.g. using portable particle counters and turbidimeters) and direct methods (e.g. air–pressure-hold tests).

6.1.2 How to use particle counters

Particle counter use at surface water works can work on four different levels.

(a) Permanently installed counters – used in process control;
(b) Permanently installed counters – used in process optimisation and research only;
(c) Portable counters – used in optimisation and research only;
(d) Particle counters not used.

The first of these is exemplified by Lewis *et al.* (1999): particle counters were installed upon raw and filtered (individual and combined) samples at a treatment works implicated in the Milwaukee cryptosporidiosis outbreak and the following control procedure implemented.

'Except for the half hour following filter ripening, any time that total particle counts exceed 100 per ml in an individual filter for four hours, a filter must be removed from service and investigated. For multiple filters..., any time that total particle counts exceed 50 per ml for four hours and continued to increase, corrective action is required.'

Because particle counters can offer a higher sensitivity at low turbidities the Lewis *et al.* approach is initially attractive. However, particle counter use is not without its problems (Section 6.1.1). In light of sensor inaccuracies, the appropriateness of applying a single particle count standard to all monitors could be questioned. Another criticism, which could be levelled at the Lewis *et al.* paper is that it does not detail what precisely is gained by using particle counters alongside turbidity. Perhaps filter breakthrough was a concern at this particular works. One example is given of how particle counters much clearly identified an improvement in particle numbers caused by preozonating filters. However, whether this fully justifies the installation of particle counters on every filter is questionable. Ultimately, this will depend on site-specific factors such as filtered water turbidity and particle size distribution (Section 5.3), the prevalence of filter breakthrough etc. It is also noticeable that the Lewis *et al.* control procedures contains a number of in-built features that lessens their severity. For example, they will not apply to breaches that last less than four hours. Secondly, no details are given as to what 'corrective action' should be taken. It is not always desirable or indeed possible to remove filters from service as this may have a negative impact on other filter performance (Ginn *et al.* 1997, Saunders *et al.* 1999). This is especially true if breaches occur across several filters as might occur were the deterioration to be caused by suboptimal coagulant dosing (Bellamy *et al.* 1993, Consonery *et al.* 1997).

A more flexible approach was shown by Ginn *et al.* (1997). Here particle counters were fitted to all filters, but were not used as control parameters. No level of particle count was considered 'satisfactory' or 'unsatisfactory'. Instead, the counters were used purely as a troubleshooting and optimisation parameter.

In most cases, water companies are perhaps best directed toward process control regimes based on turbidity as recommended in Bouchier. Edwards *et al.* (2000), for example, detailed a turbidity improvement programme initiated in October, 1999 by Thames Water. As part of this programme, statistical summaries of individual filter outlet turbidities were to be examined on a weekly basis, to detect anomalies in (a) mean turbidity, (b) 97.5th percentile turbidity and (c) the number of hours per week that each filter's turbidity exceeded 0.2 NTU. Filters would be investigated if their 97.5th percentile turbidity exceeded 0.2 NTU. These parameters would also be assessed during each filter run and used as on-line process check parameters. A traffic light system was described whereby individual filter alarm status would be designated either as green (no problem), amber (warning) or red (requires action). The study concluded that *'this demonstrable, increased vigilance adds to the Company's "due diligence" defence'*. This scheme was scheduled to be implemented at an initial works in August, 2000.

Finally, as mentioned in Section 6.1.1, if a water company does not consider permanently installed particle counters to be cost-effective, it can instead use portable instruments in one-off optimisation trials. Such trials might include targeted monitoring to optimise coagulant dose, test of filter pretreatments, investigate suspect filters for leaks and breakthrough etc.

6.1.2.1 Optimising filter start-up strategy

One way in which portable particle counters can be used is to test various filter ripening and start-up strategies. This subject is of particular relevance to this study and is now reviewed in some detail.

When a filter is returned to service after a backwash it undergoes a period of ripening. During this time particles gradually accumulate on media grains thereby improving the filter particle removal efficiency until the pre-wash efficiency is reached. The filter ripening period is thought to be a relatively strong source of *Cryptosporidium* risk (assuming that oocysts are present in the raw water). In seeded oocyst trials, Hall and Croll (1995) showed that more oocysts passed through their filter in the first hour of operation than during the rest of the filter run. In order to minimise the number of particles passing into supply, water companies have tried using different ways of ripening filters such as slow start or delayed start strategies. These have been detailed elsewhere (Colton 1996, Colton *et al.* 1996, Baird and Hillis 1998). Essentially, in a slow start, the filter outlet valve is opened incrementally over an extended period (typically around 30 minutes to 1 hour). The purpose of this is to reduce the shear forces on the media surface, thus allowing particles to retained by the filter (Baird and Hillis 1998) and so improve filter ripening.

In a delayed start, a washed filter is allowed to stand before being returned to service. This allows the settlement of particles contained within the remnant of the backwash water within the interstices of the media grains, and is intended to promote their reattachment onto the media surface. Advantages of delayed start include the fact that less water is lost from the system compared with some 'filter to waste' strategies, for example, and that it is a relatively cheap strategy to implement. Slow and delayed starts were extensively trialled by Colton (1996). His work showed that these strategies could lead to a reduction in particulate passage through a filter during ripening (Table 6.1). In the case of delayed start strategies, the evidence was less significant, apart from trials using dirtier raw water conditions (>1 NTU, >3,000 counts per ml) where improved ripening was more strongly observed. Delayed start also seemed to be more beneficial in filters with smaller media (0.5mm – 1.0mm diameter), presumably because the interstices between the media were smaller.

Table 6.1 *Review of filter start-up strategy tests.*

Ref	*Plant Scale*	*Start-up*	*Particle count spike height*	*Total no. of particles in filtrate during ripening (T)*	*% Reduction in T*	*Comments*
Baird and Hillis (1998)	Full	Control	800[a]	5.37 x 10^{10}[b]	-	Works A
		30 min delayed start	250[a]	3.49 x 10^{10}[b]	35.0 [n/r]	
		Control	3,700[a]	2.57 x 10^{11}[b]	-	Works B
		15 min delayed start	2,200[a]	1.59 x 10^{11}[b]	39.2 [n/r]	
		30 min delayed start	1,800[a]	1.51 x 10^{11}[b]	41.3 [n/r]	
		Control (13 min ss)	1,200[a]	5.76 x 10^{11}[b]	-	Works C
		30 min slow start	500[a]	4.35 x 10^{11}[b]	24.5 [n/r]	
		30 min delayed start	500[a]	3.31 x 10^{11}[b]	42.6 [n/r[	
Colton *et al.* (1996)	Pilot	Control	1,900[a]	0.87 x 10^{8}[c]	-	Media 1 (fine)
		30 min slow start	1,800[a]	0.82 x 10^{8}[c]	5.7	
		60 min slow start	1,300[a]	0.41 x 10^{8}[c]	52.9	
		Control	1,600[a]	1.40 x 10^{8}[c]	-	Media 2 (coarse)
		30 min slow start	1,500[a]	0.71 x 10^{8}[c]	49.3	
		60 min slow start	600[a]	0.61 x 10^{8}[c]	56.4	
Colton (1996)	Pilot	Control	2300 [4]	n/r[a]	-	Media 1 (fine)
		30 min slow start	1800 [2]		22.3 [8]	
		60 min slow start	600 [2]		42.1 [6]	
		30 min delayed start	1200 [2]		29.5 [6]	
		60 min delayed start	1600 [2]		34.7 [8]	
		Control	2100 [4]		-	Media 2 (coarse)
		30 min slow start	2000 [2]		24.2 [8]	
		60 min slow start	1400 [2]		21.0 [7]	
		30 min delayed start	2600 [2]		-62.8 [7]	
		60 min delayed start	1000 [2]		39.0 [8]	
Hall and Croll (1997)	Pilot	Control	n/r	6.2 x 10^{8}	-	
		15 min slow start		4.3 x 10^{8}	30.5 [3]	
Pizzi and Rodgers (1998)	Full	Control	527 [1]	1486[d] [1]	-	
		4 hours delay	425 [1]	933[d] [1]	37.2 [1]	
Saunders *et al.* (1999)	Full	Control	50	n/r	n/r	20 min slow start
		10 min slow start	70			
		30 min slow start	90			
		Control	90			20 min slow start
		40 min delayed start	80			20 min slow start

Unless otherwise stated, all particle counts are measured in the >2μm size range.

a	2-5μm per ml
b	The total number of 2-5um particles in the first 50,000 litres passed by the filter.
c	The total number of 2-5um particles passed by the filter in the first hour of operation
d	Sum of eight particle counts (>2μm per ml) taken during first 18 minutes of filter ripening
[n]	Where a number in square brackets is shown, the value shown is the mean taken from n runs.

6.1.3 What size ranges to use

6.1.3.1 Cumulative vs. differential counts

One of the biggest dividing issues in particle counting is how best to record counts, as differential particle counts (i.e. discrete size ranges such as 2-5µm, 5-10µm etc.) or cumulative counts (e.g. >2µm, >5µm, >10µm). Some different approaches are shown in Table 6.2.

On balance, cumulative counts appeared to be favoured by most scientists. Cumulative counts can be converted to differential counts whereas the reverse is not always true unless the counts are contiguous. Hargesheimer and Lewis (1995) suggested that total count (>2µm) is often the most useful parameter as it is the simplest, but that if the particle counter is required to monitor specific sizes of particle, then selected differential counts may be of interest.

As far as differential counts are concerned, the most commonly used is the 2-5µm count. This is especially common in the UK where is regularly used in preference to the total count. For example, Baird and Hillis (1998) two different size bands, 2-5µm and >5µm to compare filter start-up strategies. The 2-5µm size band was used as this *'corresponds closely to the size of Cryptosporidium oocysts'*. [In fact, oocysts are 4-6µm in diameter, although, in defence of Baird and Hillis, the Versacount particle counter used counts particles in fixed size ranges 2-5µm, 5-10µm. Moreover, the 2-5µm size range should also give a more conservative estimate of oocyst removal, as shown in Section 2.4]. Hall and Croll (1997) also favoured using the number of 2-5µm particles. They noted particles in this range were more numerous (compared to other differential bands) and so *'would give the most sensitive indication of risk'*.

Ultimately, the arguments for and against cumulative and differential particle counts are largely cosmetic since as noted in the previous two chapters, particle counts tend to vary in similar proportions across all size bands, with most particle counts following a standard inverse power size distribution. An interesting exception to this was described by Bridgeman (2000), who while monitoring a combined filtrate sample at one works, observed a high degree of correlation between >2µm counts and turbidity (R^2 = 0.85), but not between 2-5μm counts and turbidity (R^2 = 0.30) turbidity. This is counter-intuitive as one would expect turbidity, which is strongly influenced by submicron particles (Section 2.2.1.2), to correlate more closely with the number of smaller sized particles. The reason for this discrepancy was that the sample underwent a large diurnal variation in particle counts, probably caused by algae or some other micro-organism. This organism had a large impact on turbidity and >5μm counts but not on 2-5μm counts. Arguably, this is perhaps the only example described thus far where the using 2-5μm differential particle count has been truly advantageous. I.e. it is more representative of real plant performance in terms of removing 'naturally occurring', i.e. non-cultivated, particles such as *Cryptosporidium* oocysts.

6.1.3.2 Particle sizing parameters

One of the main criticisms levelled at particle counters is they can generate too much data. This can lead to a 'data overload' situation where valuable information can be overlooked. It is prudent therefore to use only a minimal number of key parameters.

Pryor and Ceronio (2000) recommended monitoring at 2, 3, 7, 10 and 15μm from which three 'critical sizes' should be picked:

(a) >2μm - This would indicate "the total number of particles measurable in the final water and the clarity of the water".

(b) >5μm – This would indicate "the particle contamination in the size in which *Cryptosporidium* and *Giardia* are expected to occur".

(c) >15μm – High counts in this range would indicate "significant filter failures and a higher risk of the presence of organisms in the lower sizes".

Although the reduction in the number of particle sizes studied is a welcome step, one could argue that this choice is rather subjective and would still lead to much redundant information being produced.

Rather than looking obliquely across a range of different particle sizes, an alternative approach would be to use particle size statistics such as particle ratio or the inverse power coefficient β. Some examples where these have been used are also shown in Table 6.2. Initial assessments of β have not been promising. Hargesheimer *et al.* (1992) observed not only that the value of β could vary significantly depending on which parameters were used to calculate it (Section 5.2.3), but also that the β trends contained a high degree of noise. This noise was attributed to using particle count data sets with few counts in many of the size ranges, with the 'most reliable' β values obtained if more than 10 particles per ml were present in each size channel. Goldgrabe *et al.* (1993) also noted a degree of noise, which made it difficult to discern any true changes in trend. This was attributed to the fact that the measured total particle count was low (less than 100 per ml, >2μm). Nevertheless both studies did show some significant deviations in particle size during their filter runs. The Goldgrabe *et al.* study used grab sampling, which, from experience, is not as precise a method as continuous on-line analysis and may have contributed to the noise seen in the data.

6.1.3.3 Particle count differentials

In addition to monitoring particle counts and particle size, another potentially useful statistic proposed in Bridgeman (2000), is the use of particle count differentials to monitor the rate of change in successive particle counts. For example, the differential defined in Equation 6.1 is a simple measure of the difference in successive 15-minute total counts.

$$Differential = (>2\mu m Particle\ count)_{t=0} - (>2\mu m Particle\ count)_{t=-15} \qquad (6.1)$$

Count differentials should not be confused with differential counts i.e. those measured over discrete size ranges, 2-3μm, 5-10μm etc. This statistic is fairly resistant to calibration differences between individual sensors and is in keeping with the idea that particle counters should be used as a 'trend parameter'. Bridgeman suggested that the potential exists for incorporating this within an alarm-based monitoring system to identify sudden increases in the rate of change in particle counts.

Table 6.2 *Applications using different particle count parameters.*

(i) Cumulative particle counts

Ref	*Particle counter*	*How used*	*Particle counts used*
Baird and Hillis (1998)	Hiac Versacount	Comparing filter start-up strategy	2-5um, >5um
Hall and Croll (1997)	Hiac Versacount	Monitoring filter ripening and breakthrough	Mostly uses 2-5um, 5-10um. Also quotes 10-15um, 15-20um, 20-25um, 25-50um, 50-100um, >100um
Colton *et al.* (1996)	Hiac Versacount	Comparing filter start-up strategy	2-5um, >5um

(ii) Differential particle counts

Ref	*Particle counter*	*How used*	*Particle counts used*
Englehardt *et al.* (2000)	Met-One PCX and PCX-10	General optimisation tool	>1µm or >2µm
Hargesheimer *et al.* (1998)	Met-One PCX.	Optimising coagulant dose using filtered water counts	>2µm
Huck *et al.* (1999)	Not specified	Testing filter performance	>2µm
Lewis *et al.* (1999)	Not specified	Control parameter used on individual filter outlets.	>2µm
Morse *et al.* (1999)	Met-One WGS-267	Optimising backwash and filter run-times	>2µm, >3µm, >5µm
Pryor and Ceronio (2000)	Not specified	General optimisation tool	>2µm, >5µm, >15µm recommended as three most 'critical sizes'

(iii) Particle size statistics

Ref	*Particle counter*	*How used*	*Parameters used*
Hargesheimer *et al.* (1992)	Unspecified FALS sensor (>0.7µm)	Showed particle size increasing during filter run	β, Particle ratios (% of total)
Goldgrabe *et al.* (1993)	Hiac Royco 9064/HRLD-150	Looking at the effect of chlorination on biological filter performance	β, least significant particle size detected (LSPSD), mean particle diameter
Kavanaugh *et al.* (1980)	Hiac Model 320	Looking at effect of flocculation on filter performance	β

6.1.4 How often to measure particle counts

Hargesheimer and Lewis (1995) analysed sampling intervals by comparing trends taken at 10, 20, 40 and 60-minute intervals. They found that overall, the resulting graphs were similar although more trend definition was seen with the smaller intervals. These results were corroborated both by LeChevallier *et al.* (1999) and Bridgeman (2000). LeChevallier found that a logging frequency of 40-60 minutes did not result in the loss of operational trends in the data. Similarly, Bridgeman concluded that all major events which were detected using a 5-minute sampling frequency were also detected by a 45-minute collection regime. Southern Water has the facility to store particle count data on an existing remote archive (referred to as PI). This records on-line data every 15 minutes. There is an obvious need to examine what information is retained or lost using this logging interval.

6.2 OBJECTIVES

6.2.1 Assessing the future use of particle counters

The main aim of the work presented in this chapter is to assess the benefits of on-line particle counters at surface water treatment works and to determine the best use of these monitors to optimise the treatment process. Practical aspects of monitoring are examined such as what the monitors say about the process, how this data can be used, which parameters to use, how often to measure etc.

6.2.2 Delayed start trial (Hardham only)

A delayed start was also implemented at Hardham to see if particle counters could be used to improve filter ripening performance.

6.3 HARDHAM – MATERIALS AND METHODS

6.3.1 Works description

Between Hardham's High and Low Works, Southern Water is licensed to abstract a total of 75 Ml/d of water from the River Rother and/or several local boreholes. A process flow diagram (PFD) of the works is shown in Figure 6.1. At the time of the study, the High Works was designed treat up to 52 Ml/D (Megalitres per day). Because the Low Works was due to be decommissioned as part of a works upgrade, it was not included in the study.

Within the High Works, the river water undergoes primary coagulation and clarification treatment. At the time of the trial, aluminium sulphate was used to achieve this together with a non-ionic polyelectrolyte (CIBA LT20). No pH correction is required. The coagulant dose was automatically controlled dependent on set-levels of incoming raw turbidity. Below 10 NTU, alum is dosed at 6ppm aluminium. For every increment of 5 NTU above this level, the dose was raised by 1ppm to a maximum of 16ppm aluminium at 60 NTU. This water was then settled in one of two flat-bottomed clarifiers.

Any borehole water that is abstracted is first aerated in two aeration towers to oxidise manganese and iron. Both this and the clarified water passes into the filter inlet channel, which, at the time of the trial, fed four RGF filters (each with surface area 37.3m^2). The filter media comprised different layers of anthracite (1.18-2.36mm), polarite (0.42-0.85mm) and sand (0.5-1.0mm), coarse sand (1.18-4.75mm) and a base layer of pebbles (6.7-13.2mm). Chlorine is dosed into the filter inlet channel at around 2.0 – 2.5 mg/l Cl mainly to prevent microbiological growth on the filter media.

The borehole and clarified water enter the filter inlet channel at different ends as shown in Figure 6.1. Spot samples were taken at the inlet of each filter and analysed for turbidity to determine the degree of mixing between the clarified and borehole water in the filter inlet channel (Figures 6.2a and 6.2b). A clear step-change was seen in the readings suggesting that little mixing was occurring between the two waters. As a result, filters will predominantly receive either clarified or borehole water depending on the abstraction rates adopted at the time. Because of the ordering of the filters, Filter 4 will always receive the highest proportion of clarified water, then Filter 3 and Filter 2, whilst Filter 1 will receive the highest amount of borehole water. Unfortunately, there are no flow meters on each filter outlet at Hardham - only a combined filtered inlet and outlet reading. For the purpose of estimating filter surface loading rates, it is assumed that the flow through each filter is approximately equal.

The filter outlet water is further treated by ozonation and GAC filtration. This is used primarily for pesticide removal but it also forms an additional barrier against *Cryptosporidium* oocysts. Finally, the water is chlorinated at around 1.7 mg/l Cl. After around 12 hours contact time (depending upon works flow), it undergoes final pH correction (with caustic soda) and sulphonation (with sulphur dioxide).

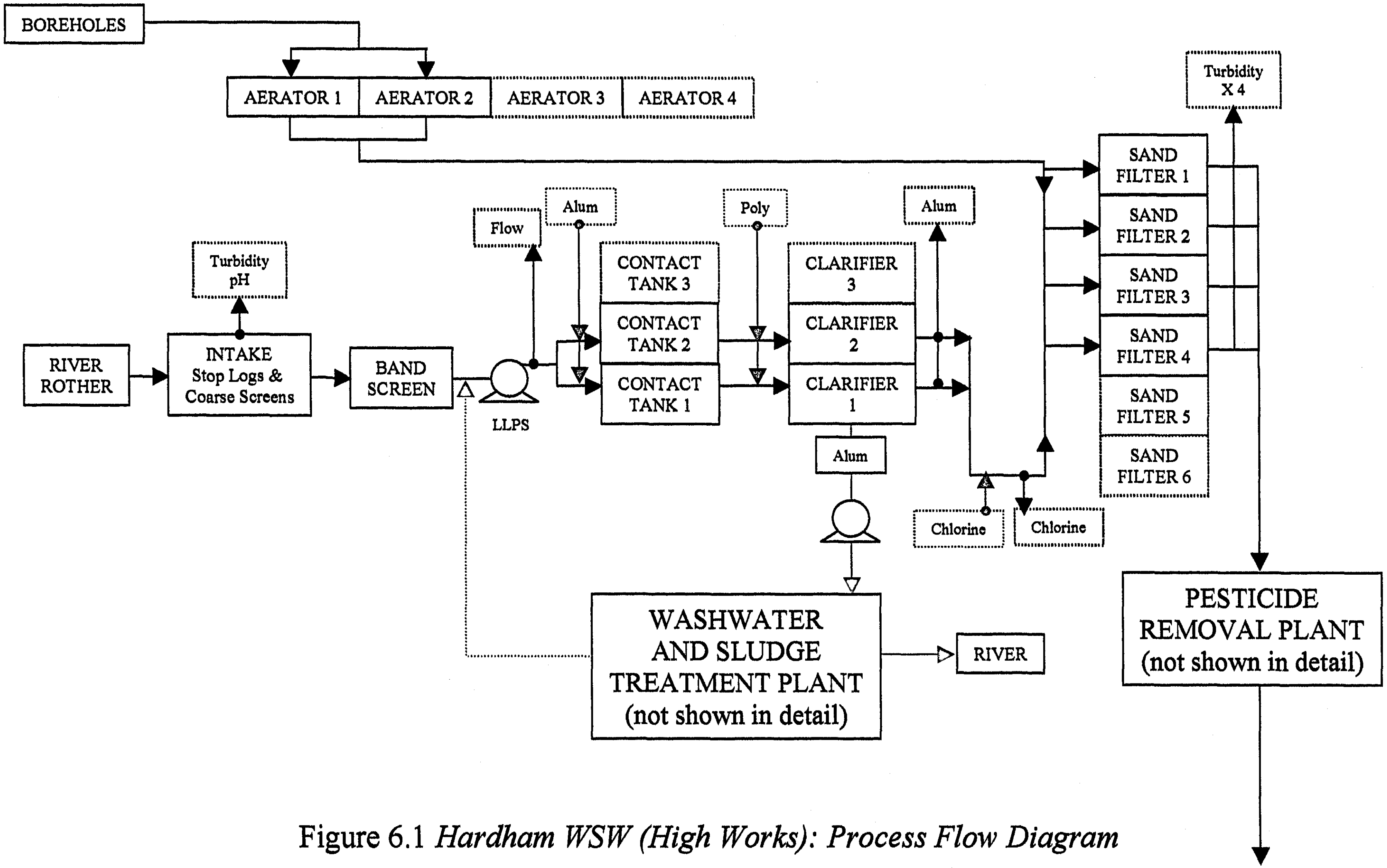


Figure 6.1 *Hardham WSW (High Works): Process Flow Diagram*

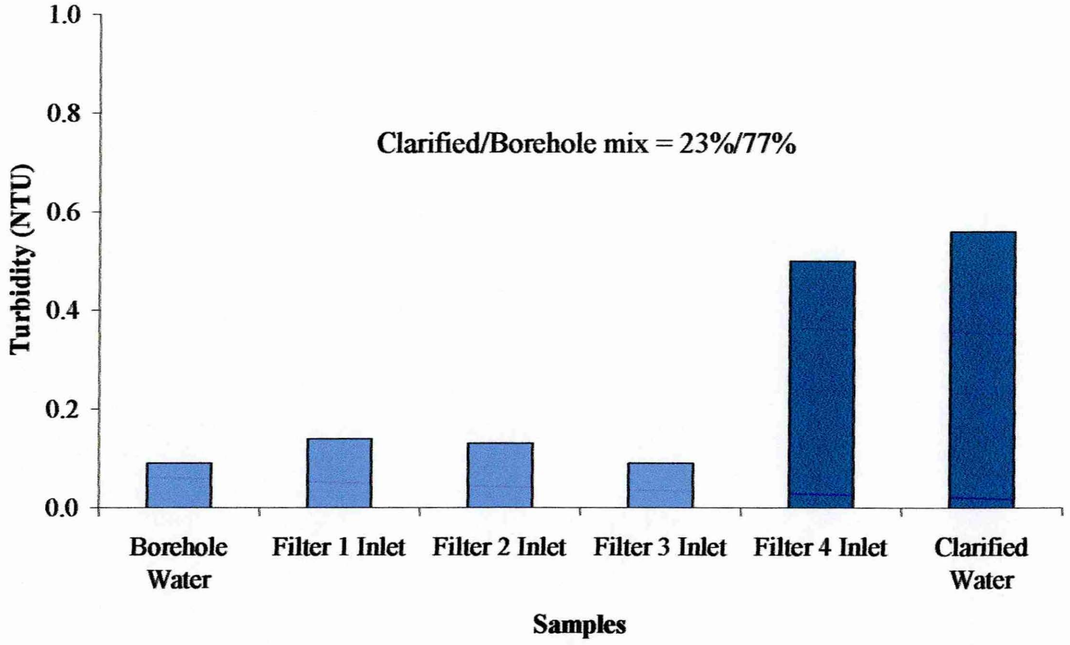


Figure 6.2a *Hardham WSW: Filter inlet channel dip samples taken 15:00, 5th March, 1999.*

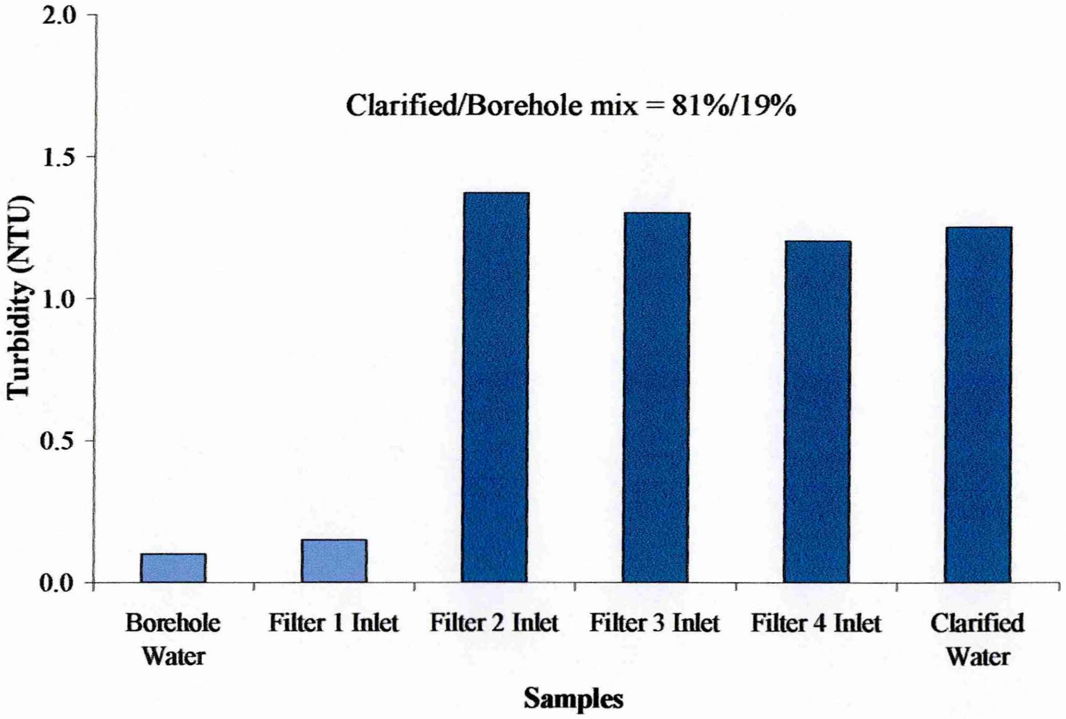


Figure 6.2b *Hardham WSW: Filter inlet channel dip samples taken 12:30, 12th March, 1999.*

6.3.2 Unusual aspects of works operation during the trial

6.3.2.1 Filter 4 media replacement

Between the 13th and 25th January, Filter 4 was taken out of service while its media was replaced. During this time the other three filters were subjected to higher surface loading.

6.3.2.2 Clarifier refurbishments

At the start of the trial, the accumulation of sludge at the bottom of both clarifiers had significantly restricted their inlet flows. In the case of Clarifier no.1, it was being run throughout at a very low flow rate (8 Ml/d output) and was refurbished at a later date. Clarifier 2 was being to be refurbished when the trial started. It was returned to service on 8th March after which the combined clarified flow was increased from 8 Ml/d to around 35 Ml/d. Correspondingly, the borehole flow was reduced from around 25 Ml/d to around 10 Ml/d. This increased the surface loading rates onto the filters, as well as the number of filters that were receiving predominantly clarified water (Section 6.3.1). It is thought that after filters 5 and 6 have been commissioned as part of the works' upgrade, the clarifiers can be run at higher flow rates thereby reducing the likelihood of the sludge accumulation problems reoccurring.

6.3.2.3 Washwater recycling

Used washwater is usually treated by Densadeg clarification and 2 Atkins-Fulford 'Filtomat' microfilters and then returned to the high works inlet. However, this recycling option was not being exercised during this trial.

6.3.3 Particle monitoring

Two Liquilaz E20 (PMS) particle counters were set up in the filter gallery at Hardham high works on the two filter outlets that were receiving the highest proportion of clarified water. This was, for the most part, Filters 3 and 4 although they were initially set up on Filters 2 and 3 while Filter 4 was out of service. The monitoring of individual filter samples (as opposed to a combined sample, for example) was done in order to assess the value of using a delayed start. In addition, the trends were examined to see if could they showed any weakness in filter treatment. The instruments were set up to count particles in the following size ranges: >2μm, >5μm and >10μm. The accompanying Aquaview software was configured so that a reading was taken every minute with a mean value recorded every five minutes.

Particle counter calibration and maintenance details have already been provided (Section 4.2). Problems were encountered when trying to obtain a continuous sample from the filters as described in Section 4.2.1. For this reason peristaltic pumps were used upstream of the constant head weirs.

6.3.4. Other data

The times of backwash events were obtained from the works event log. These were accurate to the nearest minute. All other data was retrieved from the works computer archive, which records hourly readings. Unfortunately, parameters that were not available for the study included individual filter flow rates (since no such meters are installed) and individual filter turbidity readings (since this data was not being archived at the time of study).

6.3.5 Implementing the delayed start

The current backwash procedure at Hardham is as follows: (a) Drain down, (b) Air scour for 5 minutes, (c) Upwash for 5 minutes, (d) Refill. The delayed start had to be manually controlled within the filter wash programme. The following procedure was used: after a works operator had initiated a backwash, the inlet penstock closed automatically and the filter started to drain down. During this time, automatic control of the inlet penstock was turned off to inhibit a filter refill. The wash sequence then proceeded automatically with an air scour and upwash stage but halted before the refill stage. The delay period was then timed from the moment when the upwash pumps stopped. After the required delay period, the inlet penstock control was opened manually. To simulate a 'normal' refill, the inlet penstock was firstly raised to 23% of its full opening position. (This took around 15 seconds to open). After 10 more minutes, it was then opened fully (taking around another 45 seconds). The filter outlet valve opened when a level-detecting float in the filter reached a 'high' position. With the wash now completed, the inlet penstock control was returned to 'automatic'.

6.4 TESTWOOD - MATERIALS AND METHODS

6.4.1 Works description

Testwood Water Supply Works, located in Totton, near Southampton, is licensed to abstract 136Ml d^{-1} from the River Test. Under normal operating conditions, water is abstracted from the river, screened and pumped to the Little Testwood Lake. The lake provides a nominal two days bankside storage at maximum throughput for the works.

The works is divided into three stages (Figure 6.3). Stage 1, which was installed first, consists of four Accentrifloc clarifiers, numbered 1 to 4, which can treat a maximum of 42 Ml d^{-1}. Stage 2, installed next, has one flat-bottomed clarifier (number 5), which can handle a maximum of 32 Ml d^{-1}. Stages 1 and 2 feed into twelve rapid gravity filters (RGF). These are conventional dual media (sand and anthracite) filters (each with surface area 56m^2. Stage 3, installed last, consists of two identical flat-bottomed clarifiers, numbered 6 and 7, which can treat a maximum throughput of 42 Ml d^{-1}. Stage 3 clarifiers feed into Enelco RGFs Nos 13 and 14, each of which is divided into 88 x 0.305m wide cells. Each filter is serviced by an automated, travelling, backwash assembly, which backwashes the cells consecutively.

Raw water is dosed with ferric chloride and polyelectrolyte (CIBA LT20) prior to the various clarifiers. Bentonite or powdered activated carbon (PAC) can also be dosed at this point. PAC is used for pesticide removal purposes when the works is running on the River. Bentonite is also used sometimes to increase the solids content of the lake water in order to maintain the stability of the floc blanket in the clarifiers. Provision has also made for the dosing of caustic soda prior to the clarifiers at such times when there is a requirement to raise the pH of the water for improving flocculation.

The works' operators maintain the optimum dose of coagulant using a series of look-up tables that link measured parameters such as raw water turbidity and pH. These tables were established in 1995, following extensive coagulation trials using a pilot scale clarifier test-rig.

Filters 1-12 are usually backwashed about every 72 hours, on a rotational basis. The stop regime is a slow stop, determined by the time the valve takes to close. This takes around two minutes. The start regime is a slow start, during which the flow gradually ramps up, over a 20 minute period. The backwash regime consists of an initial drain down period, followed by an air scour of the flooded bed, followed by a backwash that is divided into 4 minutes of slow backwash followed by 3 minutes of full backwash. Backwashing of the Enelco filters (Filter 13 and 14) normally occurs 4 to 5 times daily. The backwash carriage dwells over each cell for between 15 to 30 seconds. A longer period is provided over the central cells to allow the washed half of the bed to "mature", prior to washing the second half of the bed. The two filter beds are interlocked, so that only one filter cell is undergoing a backwash at any time. The washwater flow rate is typically 1.5 to 2.0% of the inflow.

6.4.2 Unusual aspects of works operation

6.4.2.1 *Lake/river abstraction*

Between 30th March and 20th April, 2000, raw water was abstracted directly from the River Test to permit the installation of a flow meter. Direct abstraction had been standard practice until the commissioning of the bankside storage lake in late 1997.

6.4.3 Particle monitoring

The monitoring rig with the Met-One PCX particle counter installed was used at Testwood as described in Section 4.1.2. Here only data from Filter 14 is presented.

This filter was chosen because, there was a convenient nearby power source and pumped sample. Attempts were also made to monitor effluent from Filter 4, a stage 1/2 filter. However, several problems were encountered, not least the critically low pressure in the sample lines. This was discussed in Section 4.2.1. Filter 14 was monitored for 1 month from 4th April, 2000. At the time of the survey, the telemetry to record individual and treated water turbidities were in progress but not completed. Instead 8 hourly readings were readings were taken from operator logbooks.

^ Figure 6.3 Testwood Pfd

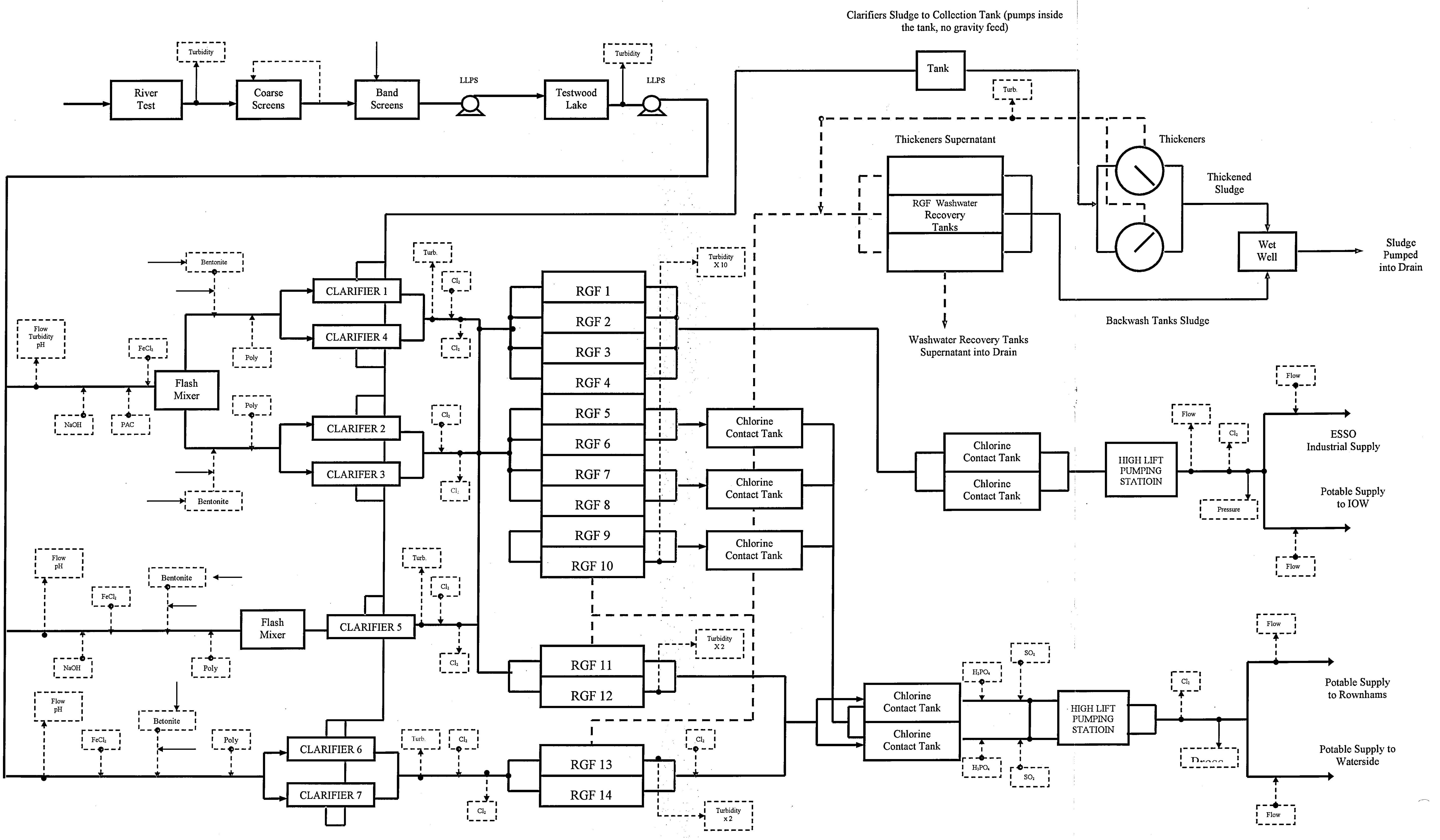


Figure 6.3 *Testwood WSW: Process Flow Diagram.*

Keys:

⟶	Main Process Stream
→	Mixed/Sludge Stream
- - ->	RGF, Dirty Backwash water Streams
- - ->	Sludge Supernatant
- - - ->	Recycled Washwater
⬚	Chemical Injection Point
⬚	Sampling or Monitoring Point
☐	Other Processes

Comments

- Static Mixer after each injection point
- Thickeners are not really needed as sludge is discharged into drain. No polymer is added.
- The reason for operating the thickeners is that the clarifiers sludge discharge into drains is not gravitational, therefore the sludge has to pass through the thickeners in order to reach the wet well from where it can be pumped into drain.
- Submersible pumps are provided in the clarifiers sludge collection tank and the wet well.
- Thickened sludge can be tankered to a nearby WTW where it can be used as thickener aid.
- RGF are backwashed with RGF filtrate. The washwater tanks are not shown in the above PFD.

6.4 HARDHAM - RESULTS

6.4.1 What the particle counters show

At Hardham, the particle counters were trialled as an optimisation and process research tool. The main objective was to assess the delayed start strategy, the results of which are detailed later. The particle count trends were also useful in revealing several potential weaknesses in treatment (relative to the high standard of treatment usually seen at the works).

It has previously been shown that particle counters can be more sensitive to changes in particle numbers than turbidity (Section 5.3). Unfortunately, because individual filter turbidities were not logged during the Hardham trial, it has not been possible, at this works, to assess fully what particle counters offer in addition to turbidimeters. Indeed, it is possible that turbidimeters may have detected most, if not all, of the changes seen by the particle counters. However, considering the very low turbidity of RGF effluent (typically around 0.05 NTU), it is likely that the particle counters were appreciably more sensitive to these changes than turbidimeters and therefore more suited to this .one-off process investigation. By applying the sensitivity model, described in Section 5.3.2, with typical baseline filtered water turbidity of 0.05 and a β value of around 3, it is predicted that particle counts would be roughly 5-6 times more sensitive than turbidity in detecting changes in particle numbers.

6.4.1.1 *Data overview*

Throughout the study, monitored filtered water particle counts were generally very low. In the case of Filter 4, for example, which received the highest proportion of clarified water, most (85%) readings were below 10 counts per ml (Figure 6.4). In the case of Filter 2, which receives predominantly borehole water, 87% of readings were below 1.0 count per ml, a level of water quality normally associated with membrane filtration (Adham *et al.* 1995).

This high level of water quality was maintained despite large variations in river water quality, from 3 to around 200 NTU (not shown), indicating that the coagulation regime employed during the trial is effective in terms of particle removal.

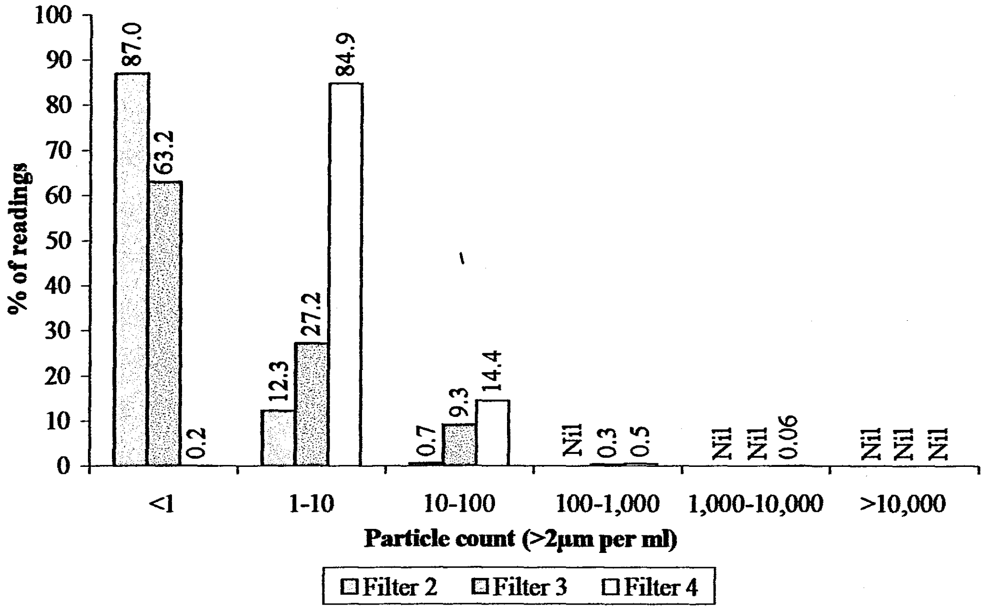


Figure 6.4 *Breakdown of particle count data measured in filter effluents at Hardham WSW (18 Jan – 14 Mar 99).*

6.4.1.2 Effect of increasing filter surface loading rate

One of the more interesting results shown by the monitoring was the occasional increases in filtered water particle counts seen during periods of increased surface loading (SL). The SL rates onto the filters varied substantially during the trial owing to (a) different raw water abstraction rates, (b) the temporary removal from service of Filter 4 for refurbishment and (c) the frequent occurrence of filter backwashing, during which time the flow to the filter was distributed between the other filters (Section 6.3.1).

In most cases, the increase in SL appeared to have a negligible impact on filter quality. However, it was noticeable that when filters were under some 'challenge' such as they were ripening or were receiving higher turbidity water from the clarifiers, then such an increase could have a significant affect on particle numbers. For example, if two separate filters were washed in quick succession, then the effect of taking the second filter off-line impacted significantly upon the quality of the ripening filter (Figure 6.5). This deterioration took the form of a step-increase, which suggests that the particle counts increased in response to the higher SL rate (from 8.7 to 11.7 mhr^{-1}) rather than to the initial change in SL. (In the latter case, one would expect to see a sudden increase followed by a steady decay). The clarified water turbidity remained constant at 1.0 NTU during this period. In addition, since Filter 4 is 'first in order' to receive clarified water, the composition of its inlet water should not be affected by Filter 3's washing.

Another feature of the increased particle counts seen during the increased SL rate is an intermittent 'spiking' in particle counts (also seen in later examples). The exact cause of these spikes is unknown. One possible explanation is that they may represent particle 'avalanching' or 'cascading' within the filter media as described by (Ives and Clough 1985; cited in Ginn *et al.* 1992).

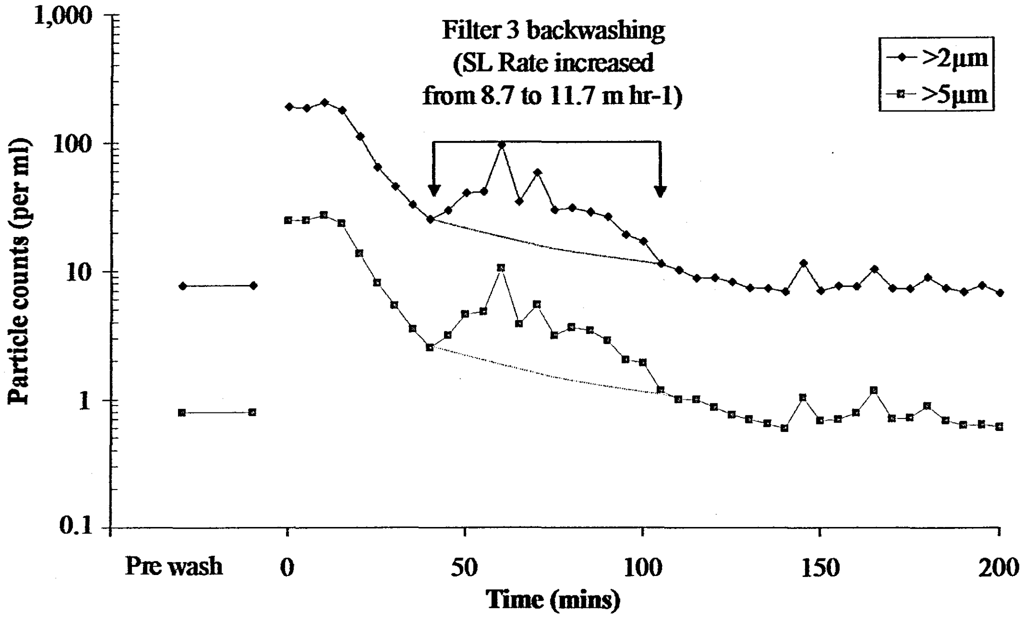


Figure 6.5 *Hardham WSW: Filter 4 ripening curve, 1st Feb 1999.*

Although this deterioration is relatively small, a more significant excursion was seen on the 9th March, when there was a larger increase in measured filtered water counts (Figure 6.6). The reason for this increase is unknown but an increase in Clarifier 2 outlet turbidity (from around 1.0 NTU to around 3.5 NTU) suggests that the clarifier sludge blanket may have become unstable; the clarifier had just been returned to service some 24 hours earlier. The filters seemed to be coping adequately with the increased challenge, until Filter 2 started to backwash (on run-time). The extra surface loading onto Filter 4 seemed to effect a large increase in particle counts from around 300 up to 2,000 per ml. The backwashing also affected Filter 3 particle counts although to a lesser extent. As with the previous example it is not anticipated that the quality of Filter 4's influent water will have improved significantly by taking Filter 2 offline.

It is noticeable that despite these problems, no specific problem was detected immediately after Clarifier 2 was returned to service on the 8th March, 1999 (Figure 6.6), despite the SL rate on each of the four filters increasing from 9.2 to 13.3 m hr^{-1}. This shows that the relationship between particle counts and surface loading is complex.

High SL rates also appeared to have a detrimental effect on filter ripening. Early on in the trial, Filter 4 was taken out for refurbishment. During this period, it was noticeable that Filter 3's ripening period was protracted by several hours. An example, presented in Figure 6.7, shows how under a higher SL rate, Filter 3 took more than 5 hours to fully ripen whereas normally it is fully ripened within a hour. This is concerning, especially considering the low particle counts produced by the filter before the backwash was instigated. These ripening problems persisted until 25th January, 1999 when Filter 4 was brought back into service whereupon, Filter 3's ripening improved.

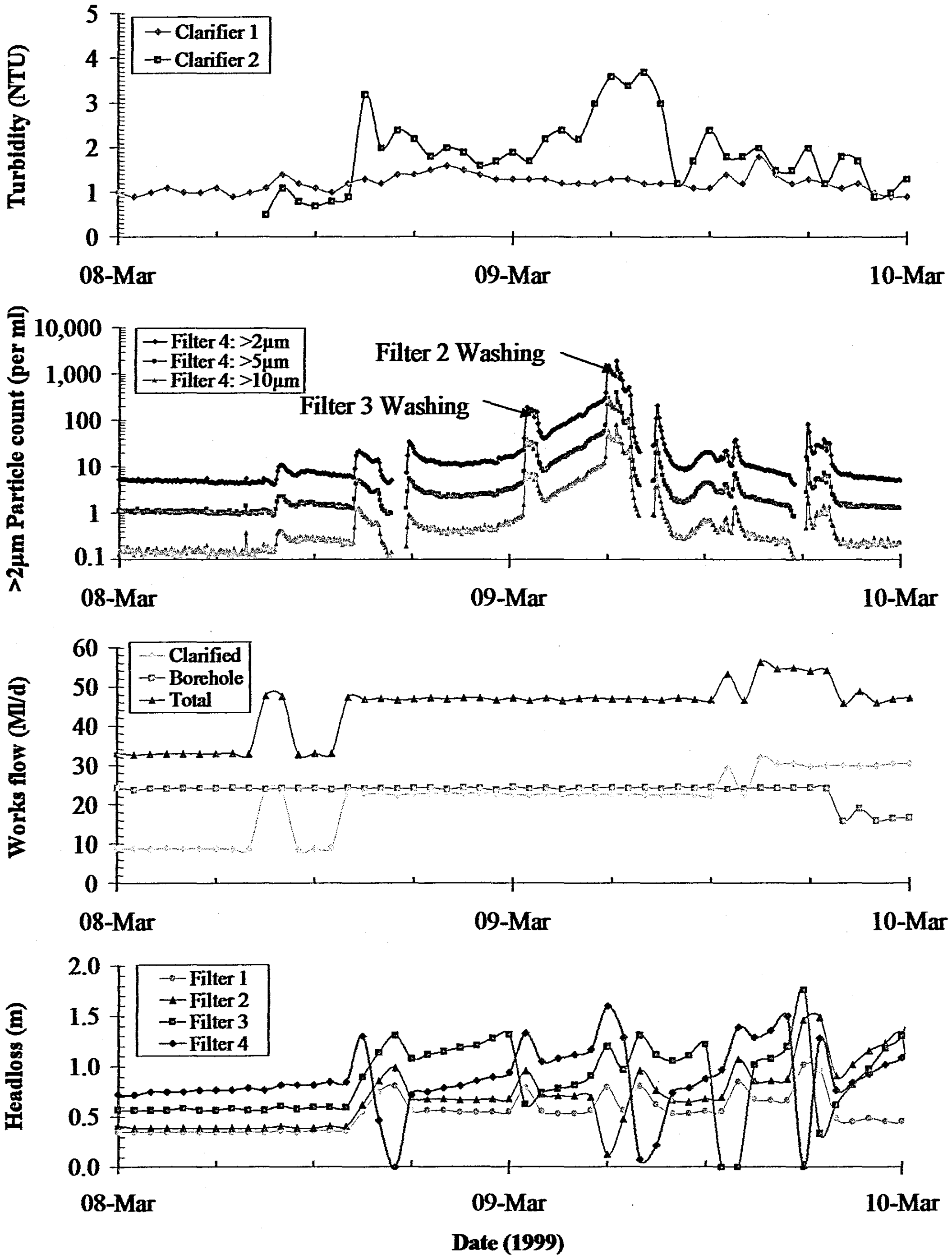


Figure 6.6 *Large excursion in Filter 4 particle counts, 9th March 99.*

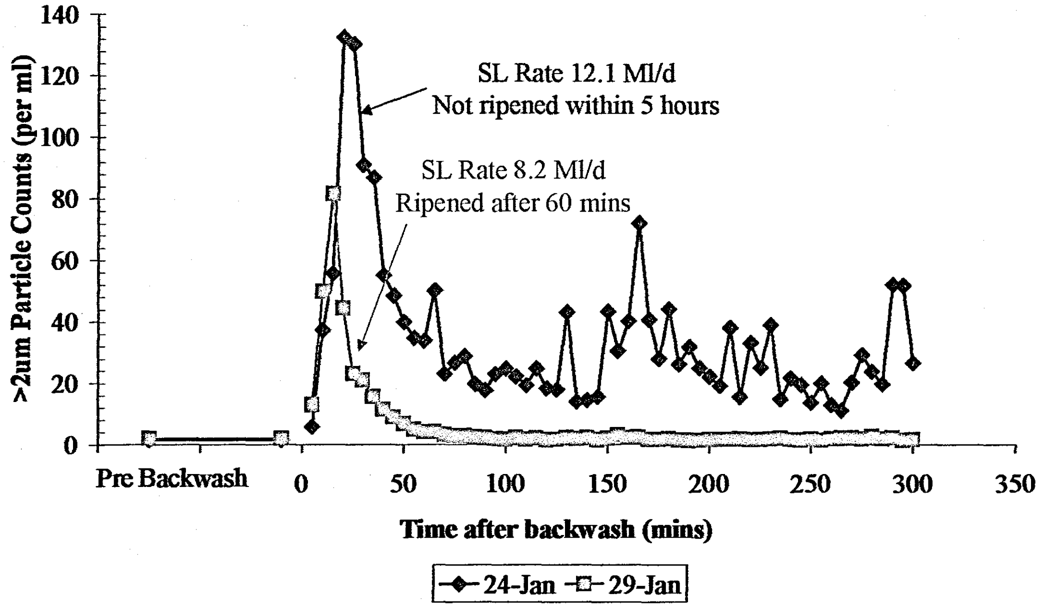


Figure 6.7 *Two Filter 3 ripening curves (no delay).*

6.4.1.3 *Result of using a delayed start*

The results from the delayed start trial were analysed in detail. In this study, there was no evidence that the inclusion of a delay period whether it was 30, 45 or 60 minutes, led to any significant improvement or deterioration in filter ripening. This can be seen from a visual comparison of some delay and no-delay curves (Figure 6.8).

A feature of all the curves is that the number of particles passed by the filter during ripening performance depended strongly upon the number of particles in the filter influent water. This was apparent both in terms of ripening 'spike' height (Figure 6.9) and the total number of particles passed by the filter in the first hour of operation (Figure 6.10). Both these relationships were proven statistically ($p<0.001$). The delayed start data has also been shown in these figures. It can be seen that outside of this effect, the delay had no positive or negative impact on filter ripening. This was confirmed by statistical analysis: no further improvement could be made to the models shown in Figures 6.9 and 6.10 by adding a 'delayed start' dummy variable ($p=0.71$ and $p=0.98$ respectively).

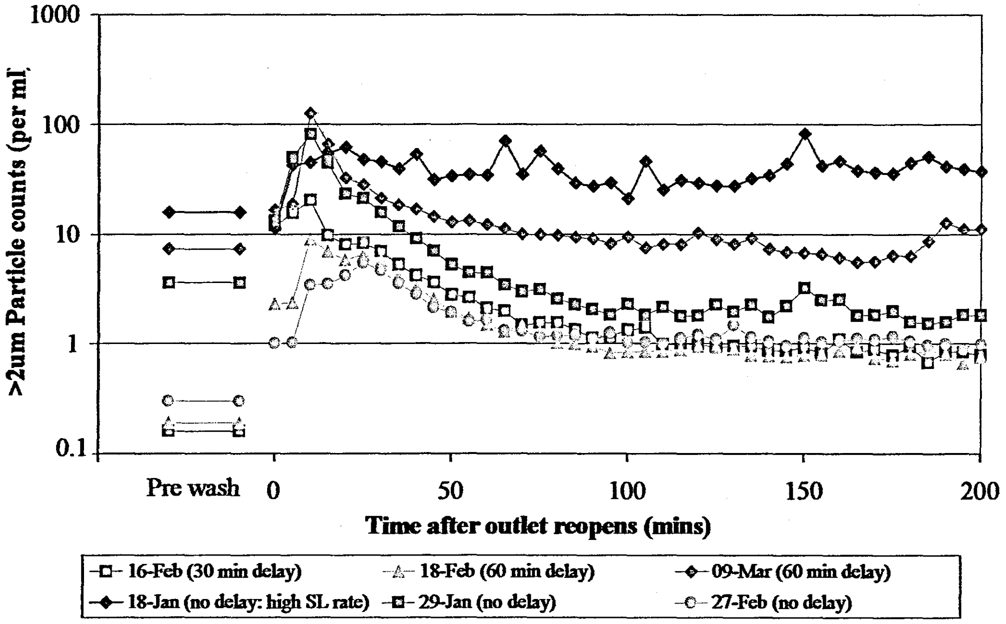


Figure 6.8 *Visual comparison of 'delay' (red) and 'no-delay' (blue) ripening curves.*

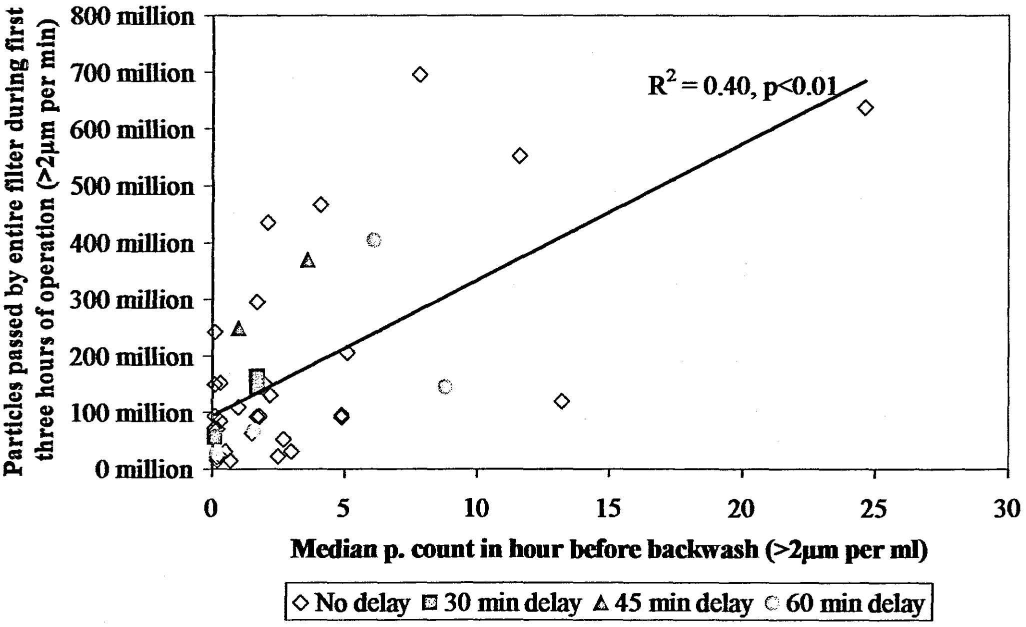


Figure 6.9 *Number of particles passed by filter during ripening under 'delay' and 'no delay' start-up conditions compared with pre-wash filter particle counts.*

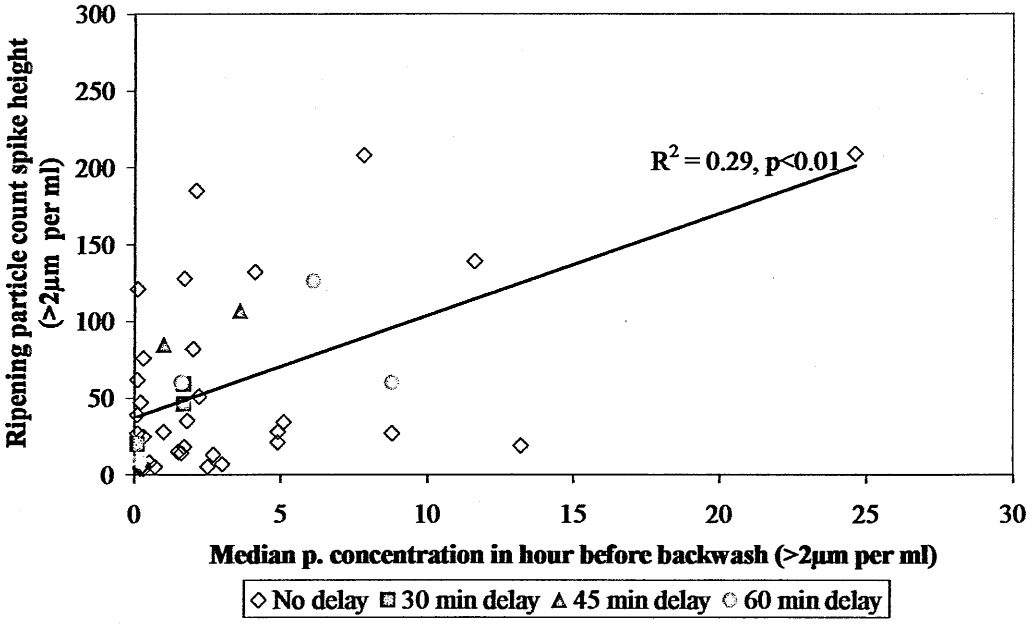


Figure 6.10 *Ripening spike heights under 'delay' and 'no delay' start-up conditions compared with pre-wash filter particle counts.*

6.4.2 What parameters to use

The Hardham work also gave an opportunity to investigate practical considerations such as what particle count parameters to use.

6.4.2.1 Particle size ratios and beta

A representative sample of data is shown in Figures 6.11 and 6.12. The particle counts have been shown on a $\log_{10}$-scale as this provides a convenient way of showing detail in the data, especially in the low particle counts. On this scale, a relatively high degree of noise was seen in the >10µm data when total particle count was very low (below 1 per ml). This, for example, can be seen in Filter 3's data prior to the 9th March when the filter was receiving predominantly borehole water (Figure 6.11).

There is a very high degree of correlation between the different particle counts with the three trends varying in roughly equal proportion (Figures 6.11 and 6.12). This shows the heterogeneous nature of the particles passed by the filter (in terms of their detection by the particle counter).

Several points were chosen arbitrarily from the available data and their size distribution analysed more rigorously (Figures 6.13-6.14). All sample points analysed (including others not shown) were found to adhere to the inverse power distribution as described in Section 5.1. This is demonstrated by the fact that the particle count data appears as a straight line on the log-log scale (Figure 6.14). This shows two things:

(a) The debate over which size ranges to use is mostly superfluous since most particle counts measured over different size ranges vary in similar proportion.

(b) Trending particle counts over different size ranges produces a lot of redundant information. Particle size distribution is therefore best observed using a size distribution statistic such as β (Section 5.1) or a particle ratio (Section 5.2.4).

As theorised in Kavanaugh *et al.* (1980), a point of equilibrium exists at $\beta=3$, either side of which a sample can be classified as having a size distribution biased towards smaller particles (higher β) or larger particles (lower β). Beta values of 3 therefore represent a 'typically balanced' particle size distribution.

Note that in this study, β has been estimated from size ranges whose mid-points do not exceed 20μm (Section 5.2.3). In the case of the Hardham data, in order to derive a third point, the >10μm size range has been treated as if it were 10-20μm. Although this is not ideal, the approximation does not destroy linearity (Figure 6.14) and is adequate for this site-specific investigation.

Subsequently, the inverse power coefficient, β was calculated for all the data using

$$\beta = \frac{\sum_{1}^{n} (y_i - \bar{y})(x_i - \bar{x})}{\sum_{1}^{n} (x_i - \bar{x})^2} \qquad (6.2)$$

where x_i = the mid point of size channel i (μm),

and $y_i = \dfrac{\text{particle count in size channel i (per ml)}}{\text{channel width } (\mu m)}$.

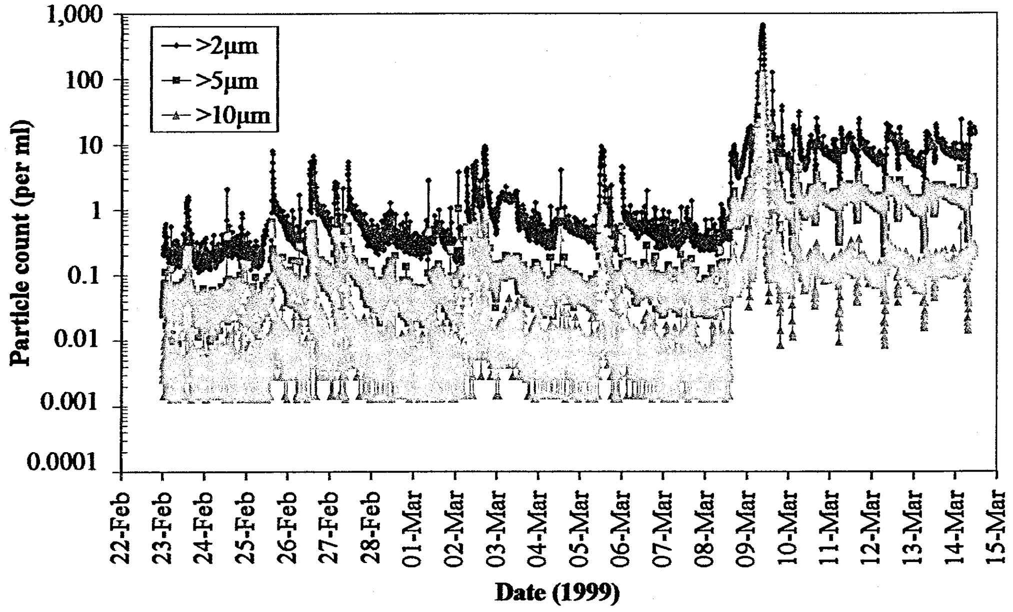


Figure 6.11 *Filter 3: Comparison of >2µm, >5µm and >10µm particle count trends.*

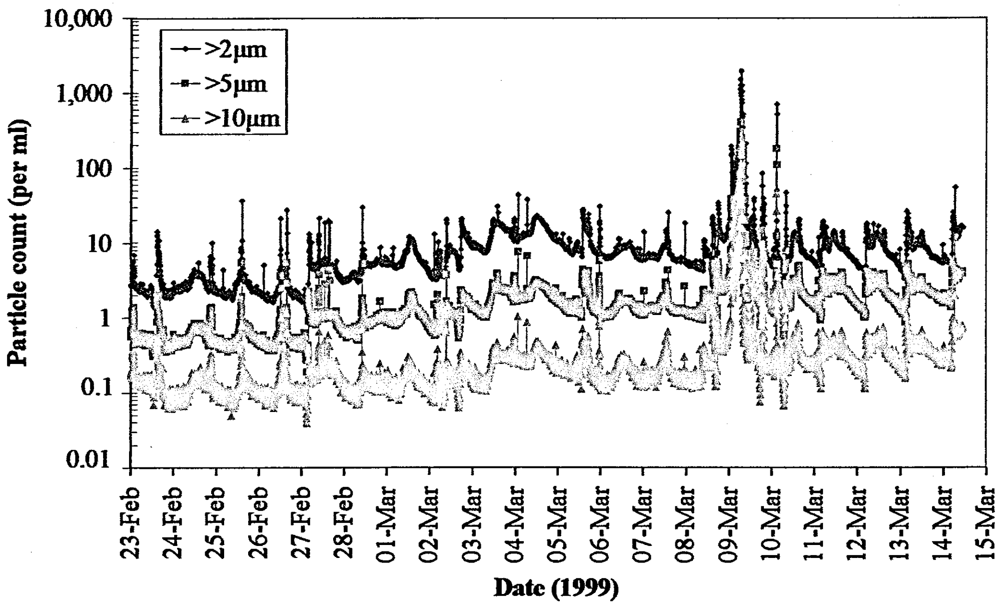


Figure 6.12 *Filter 4: Comparison of >2µm, >5µm and >10µm particle count trends.*

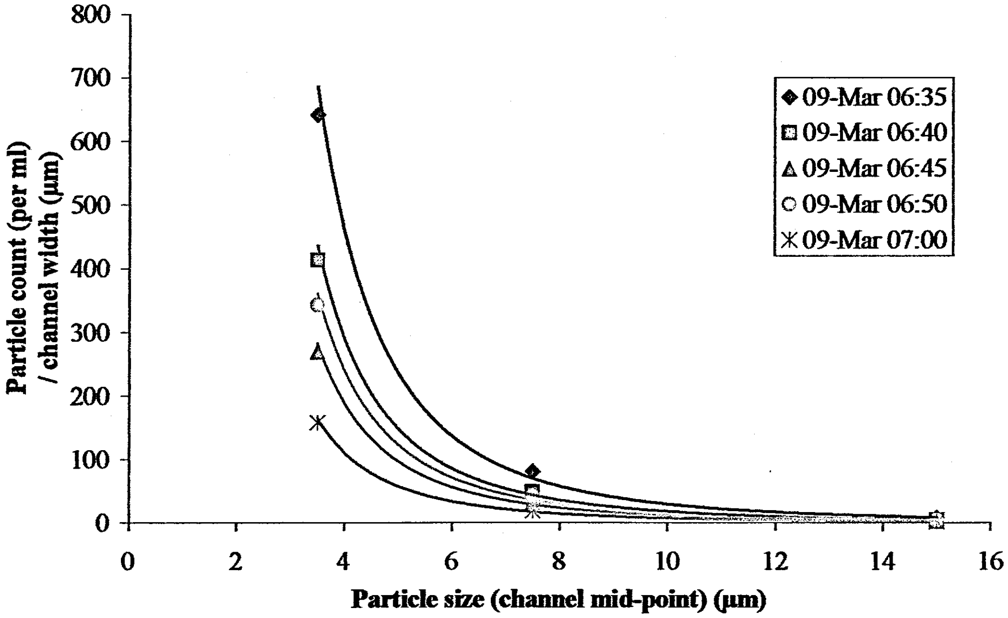


Figure 6.13 *Particle size distributions of 5 data points (Filter 4 - Linear scale).*

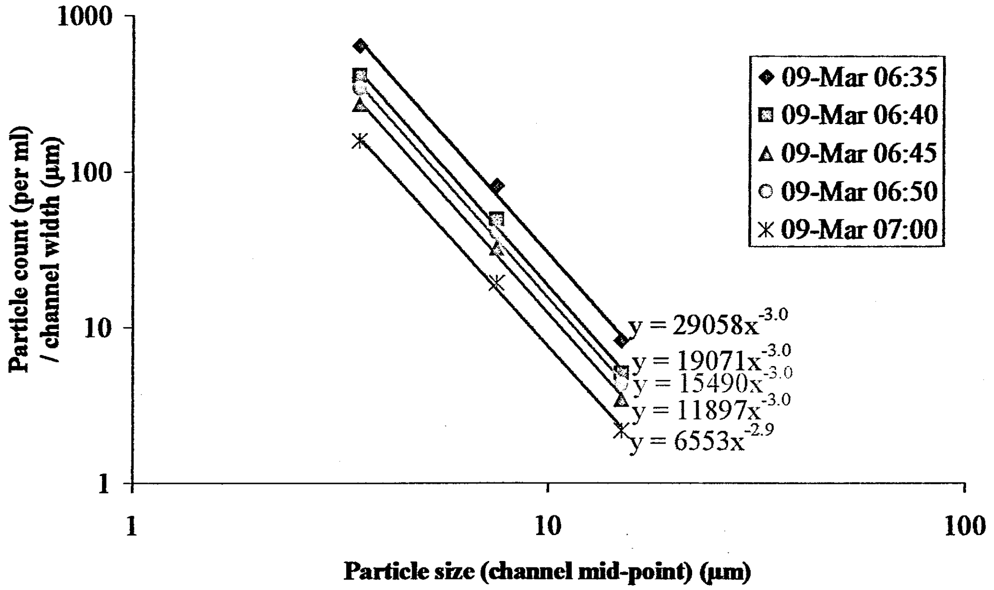


Figure 6.14 *Particle size distributions of 5 data points (Filter 4 – Log_{10} scale).*

Two different particle ratios were also examined (Figures 6.15-6.19), namely the proportion of 2-5µm and 2-10µm particles expressed as a percentage of the total count. The 2-10µm particle ratio is the converse of the >10µm particle ratio used in Section 5.2.4. Although the >10µm ratio has previously been preferred, the 2-10µm ratio has been used here because it is synchronous with β (i.e. both parameters decrease when there is an increase in particle size) and therefore is more easily compared.

The most distinguishing feature is the amount of noise seen in both β and the particle size ratios when the number of counted particles is low (total count less than 1) i.e. when Filter 3 was receiving predominantly aerated borehole water. This reflects the degree of noise seen previously in the >5µm and >10µm trends (Figures 6.15-6.16). Apart from the noise, the data shows that the size distribution of particles as measured by the particle counters remains fairly constant (β typically is around 3.5). There is a strong level of correspondence between the beta and particle size ratios trends, which suggests that particle size ratios are a sound alternative to β. However, different aspects of the data are emphasised by the different ratios. There are, for example, subtle differences between the 2-5µm and 2-10µm size ratio trends with the latter showing more clearly the increase in particle size 17th- 24th February (Figure 6.19). Unfortunately, the cause of these changes in particle size is currently unknown.

Finally, a shift decrease in filtered water particle size could be seen apparent immediately following certain filter backwashes. This was most obvious on the 21st February, for example, where a backwash coincided in a jump from around 86% to 96% of particles being measured in the 2-10µm size range (Figure 6.19).

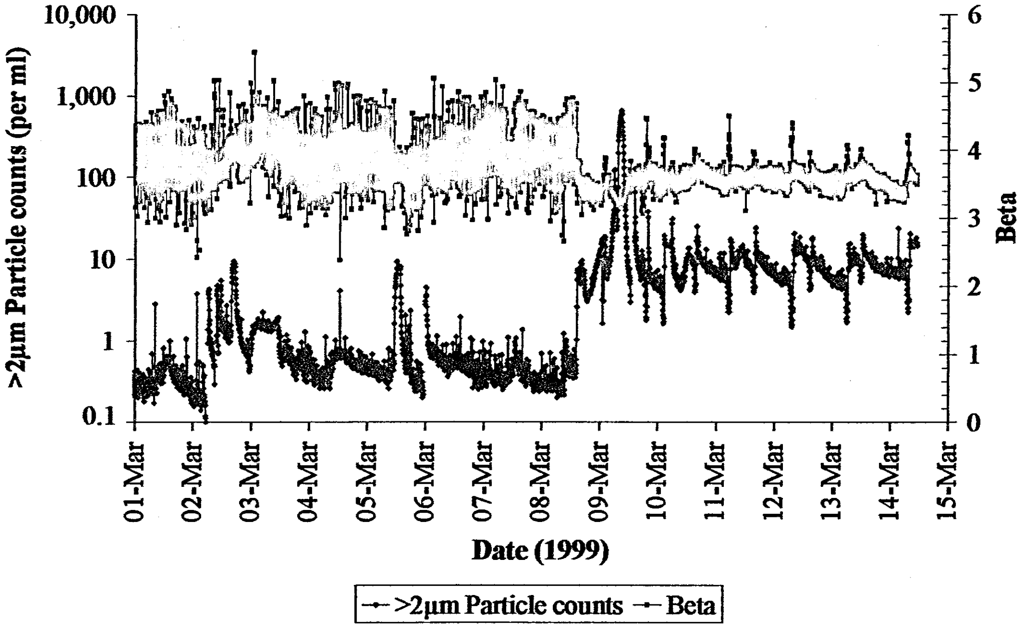


Figure 6.15 *Hardham WSW Filter 3: total particle count and β.*

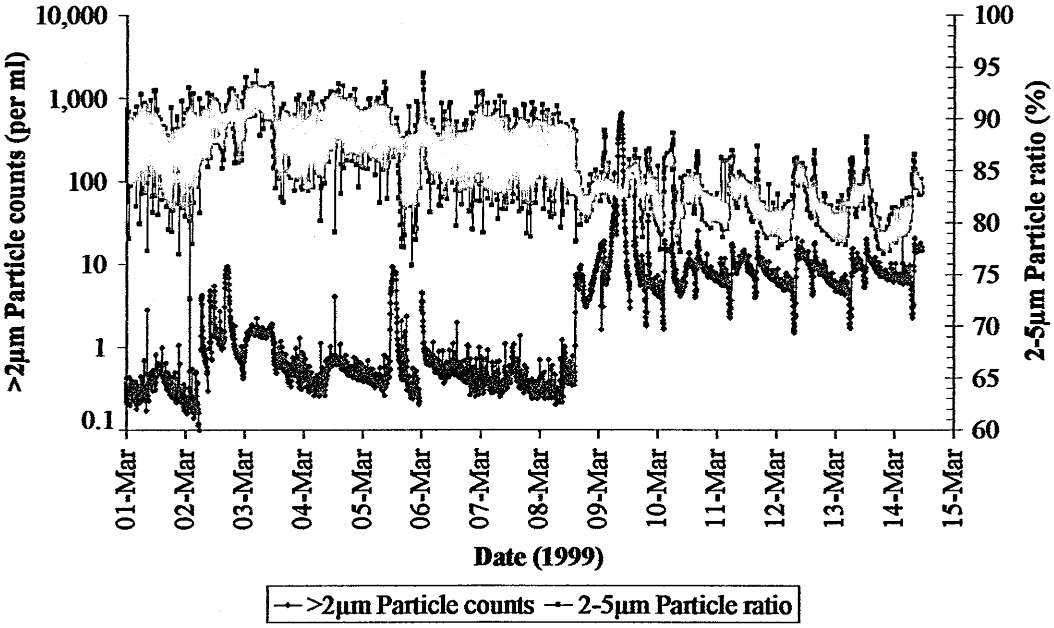


Figure 6.16 *Hardham WSW Filter 3: total particle count and 2-5μm particle ratio.*

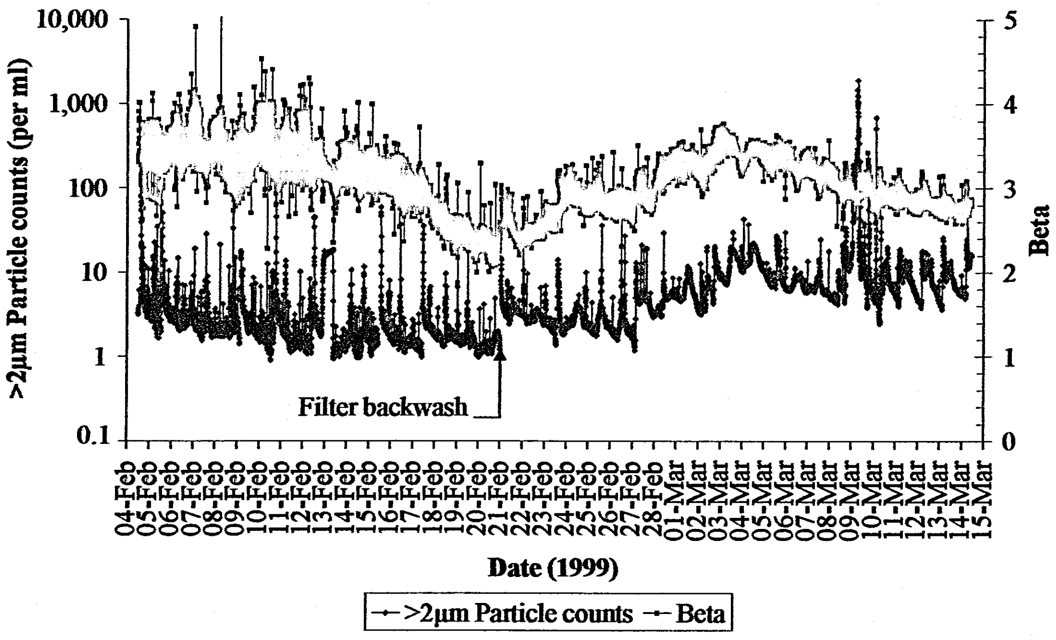


Figure 6.17 *Hardham WSW Filter 4: total particle count and β.*

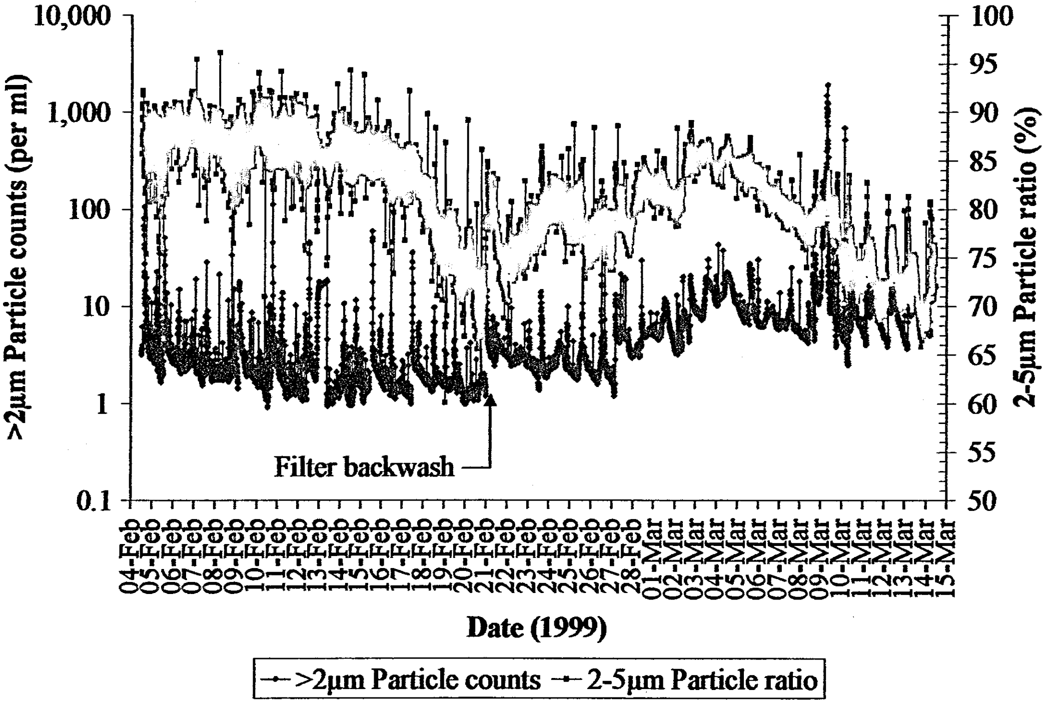


Figure 6.18 *Hardham WSW Filter 4. Total particle count and 2-5µm particle ratio.*

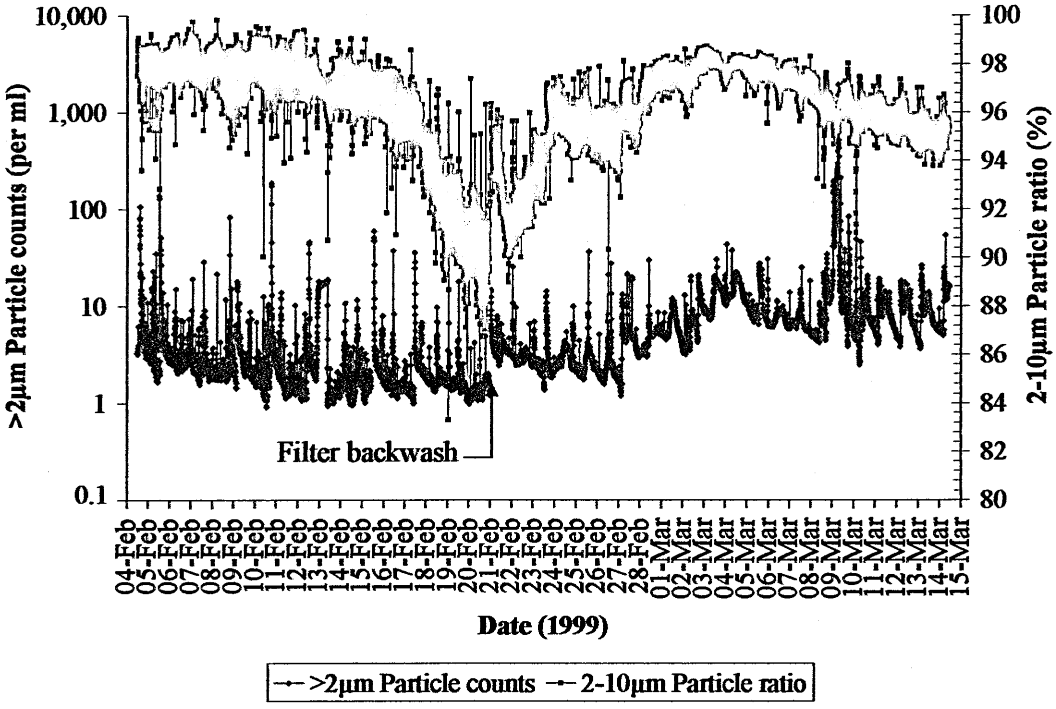


Figure 6.19 *Hardham WSW Filter 4: total particle count and 2-10µm particle ratio.*

6.4.2.2 Particle count differentials

Particle count differentials (Section 6.1.3.3) were calculated for the period 8th-11th March, 1999 (Figure 6.20). This period was chosen, because the data contained a large amount of fluctuations, including the large excursion early on the 9th March (Section 6.1.4.2). A 'cut-off' line is shown at the 10 counts per ml mark. An alarm trigger set at this value would successfully pick out the anomaly seen on the 9th as well as most filter ripening curves.

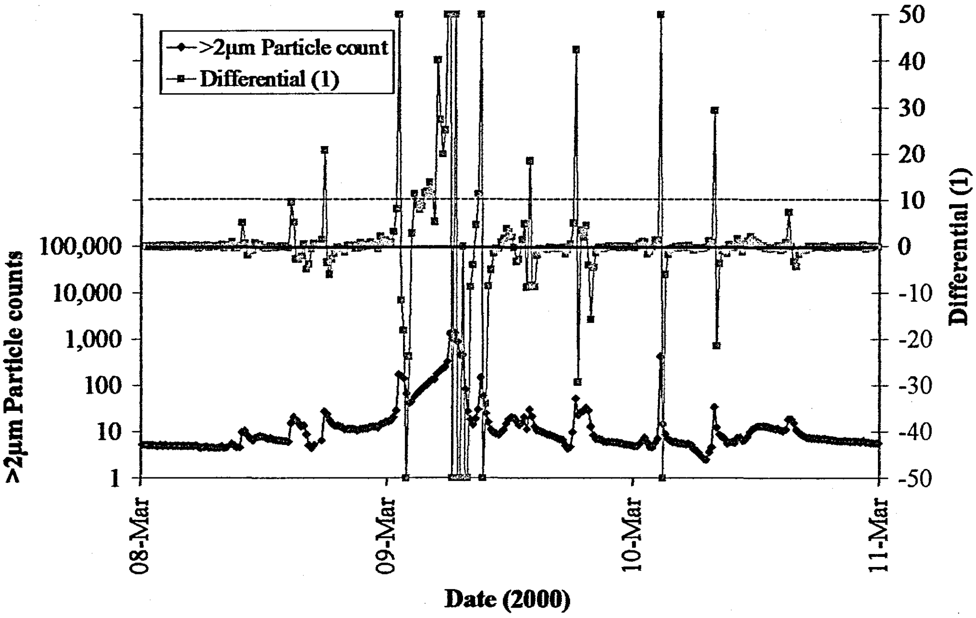


Figure 6.20 *Hardham Filter 4: Fifteen minute count differential.*

6.4.3 How often to sample

The Liquilaz E20 particle counters take a reading every minute. The Aquaview software used to log the data stores a mean average of 5 readings every 5 minutes. To determine an ideal data-logging interval, a section of the data was analysed (Figure 6.21) to see if reducing sampling intervals led to a significant loss in trend definition. The analysis method used is similar to one described in Hargesheimer *et al.* (1992). Visually, very little definition was lost when moving between a 5 and 20 minute mean reading. However, a significant amount was lost when the interval is increased to an 80 minutes.

The optimum sample interval will ultimately depend upon the duration of the anomalies seen in the particle counts. Most of the deteriorations seen in Figure 20 are caused by filter ripening, which typically lasts for around 60-80 minutes. This is why the event is sometimes missed when using a sample interval of 80 minutes. Although, a sample interval of around 20 minutes is adequate to detect most process events, a smaller interval (e.g. 5 minutes) is preferable as this provides (a) a shorter reaction time, (b) greater trend definition, and (c) the potential to identify very short process events. A five-minute interval also allowed the detection of noise (Section 6.1.4.2), which may be of significant interest.

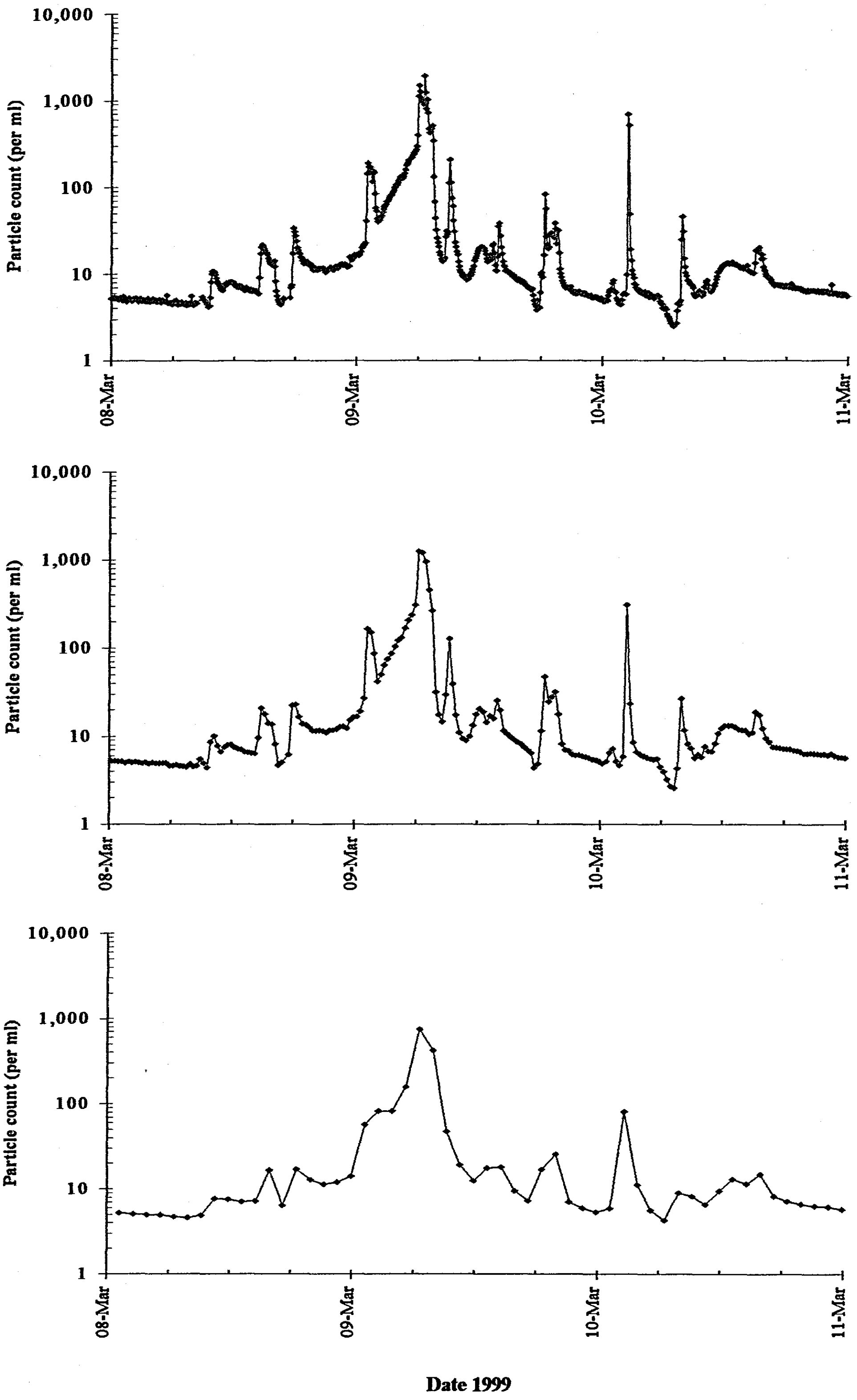


Figure 6.21 *Hardham WSW Filter 4: mean particle counts calculated every (i) 5 minutes (ii) 20 minutes and (iii) 80 minutes.*

6.5 TESTWOOD - RESULTS

6.5.1 What the particle counter shows

6.5.1.1 Data overview

On a quick inspection of the data, it is clear that many more particles were found in the Filter 14's effluent data in corresponding samples analysed at Hardham. Whereas, particle counts (>2μm) from filters receiving clarified water typically lay between 1 and 10. Particle counts from the Testwood filter were some two orders of magnitude higher (Figure 6.22). As discussed in Section 2.4, this does not necessarily guarantee higher *Cryptosporidium* risk as this will ultimately depend upon the concentration of oocysts in the plant's raw water.

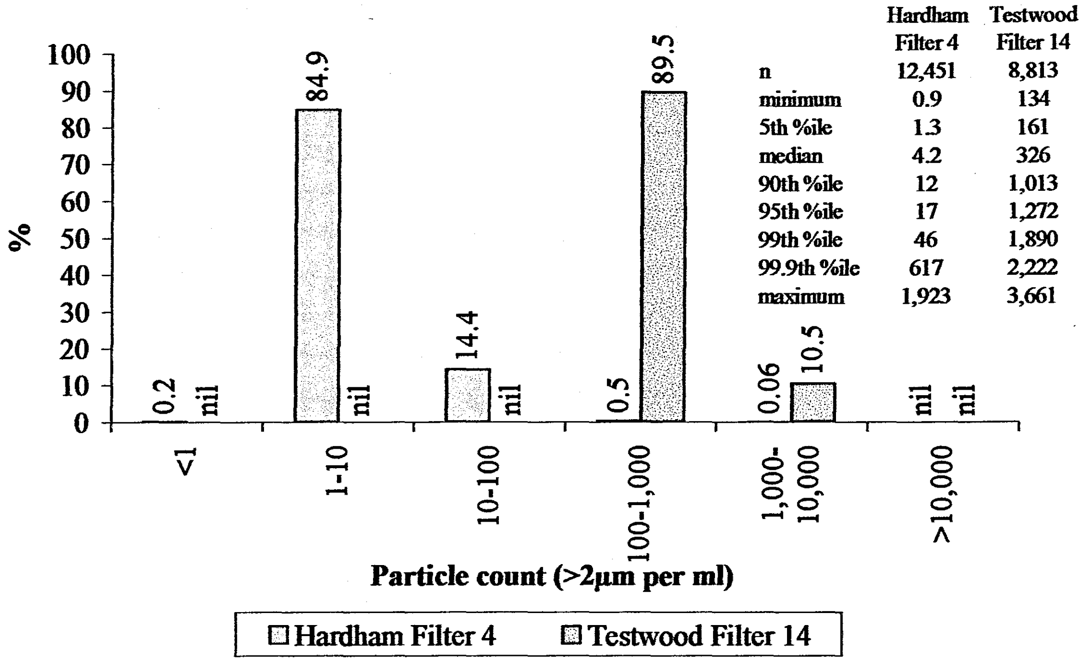
There are four main reasons for this disparity:

(a) The low solids content of the lake can adversely affect floc blanket stability with the result that higher loadings are passed onto the filters.

(b) The lake supports a high algal population, which can add significantly to filter loading. The problem is exacerbated by further algal growth in the works clarifiers. As highlighted in Section 6.1.3.1 algae can contribute significantly to treated water particle counts without necessarily adding to *Cryptosporidium* risk.

(c) The Enelco filters have an unusual design whereby each of their cells is washed in sequence whilst still in service. This whole process lasts around 100 minutes and currently runs every 10 hours. A relatively high number of particles are passed by the filters during these washes and in the subsequent ripening periods (Figure 6.23). The particle count data also shows that the ripening process is very slow, it sometimes taking a full 10 hours for the filter's particle counts to return to the pre-wash reading. This information also is shown, to a lesser extent by the turbidity trends.

(d) Whilst abstracting directly from the River Test, there were four separate occasions where filtered water turbidities rose sharply during river spate conditions, labelled A-C (Figure 6.24). It is believed that these arose because of the difficulty in maintaining optimised coagulation conditions under rapidly changing raw water conditions. Coagulation is currently controlled manually, with dose chosen according to look-up tables. Event D also took place during river spate conditions but occurred just after the abstraction was switched back to lake water.



	Hardham Filter 4	Testwood Filter 14
n	12,451	8,813
minimum	0.9	134
5th %ile	1.3	161
median	4.2	326
90th %ile	12	1,013
95th %ile	17	1,272
99th %ile	46	1,890
99.9th %ile	617	2,222
maximum	1,923	3,661

Figure 6.22 *Comparison between Hardham and Testwood WSW's filtered water particle counts.*

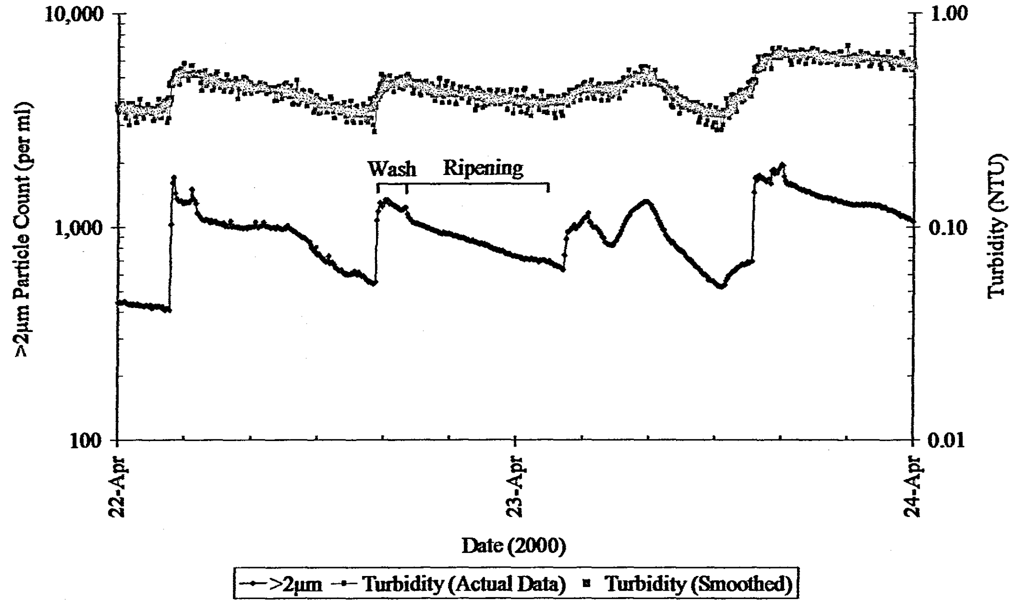


Figure 6.23 *Testwood WSW: Filter 14 particle counts and turbidity trend (22^{nd}-24^{th} April, 2000).*

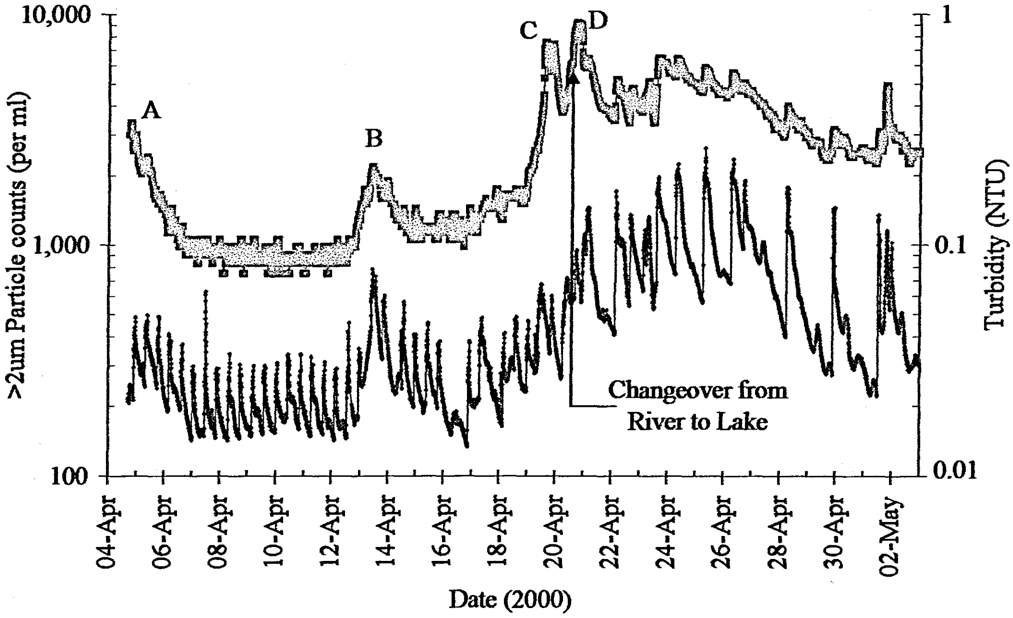


Figure 6.24 *Testwood Filter 14: Particle count and turbidity trends.*

6.5.1.2 *Sensitivity modelling*

Interestingly, although one would expect filter turbidity and particle counts to be comparable in their response to the large changes seen during events A, B and C, in fact, the increases seen in the turbidity trend were surprisingly large relative to particle counts. This was further analysed using the sensitivity model (Table 6.3, Figures 6.25 and 6.26).

By comparing these against the models derived in Section 5.3, it is evident that as far as the filter backwash and ripening spikes, turbidity and particle counts respond in a reasonably predictable manner in light of the sample turbidity and particle size distribution. Particle counters are around 2 to 4 times more sensitive in detecting these spikes. However, as far as the increases associated with river water turbidity increases, turbidity appears to provide a more sensitive response than predicted by the model. This shows that the sensitivity model is fallible. The discrepancy in the model implies that there has either been an increase in the number of particles too small to be detected by the 2μm sensor by the particle counter, or that there is a predominance of particles which preferentially scatter more light then they block. Although the model is fallible, the method at least provides an in-depth way of highlighting and comparing differences in the data.

Point D differed significantly from the rest. This corresponded to a change in abstraction, from river to lake, and coincided with a large increase in particle size in the filter outlet sample. On this occasion, the particle counter was around 2-3 times more sensitive than turbidity, a good fit with the model.

A similar analysis was given by both sensitivity models, once more justifying the use of β. In future, unless the β model demonstrates something different, only the model derived from the particle ratio, a will be shown.

Table 6.3 *Testwood WSW Filter 14: Data used in sensitivity analysis.**

Deterioration cause	*Date*	*NTU*	Δ_{ntu}	*>2μm*	*>3μm*	*>5μm*	*>10μm*	Δ_{pc}	S_{pc}	*>10μm (%)*	*a*	*Mean a*	*Diff a*	*β*	*Mean β*	*Diff*
Raw NTU Change (A)	07-Apr-00 10:37	0.09	2.3	146	68	28	7	1.7	0.7	4.8	0.7	0.6	±0.2	2.6	2.8	±0.3
	05-Apr-00 07:47	0.21		247	112	35	7			2.8	0.5			3.0		
Raw NTU Change (B)	12-Apr-00 20:51	0.09	1.9	171	80	30	8	1.9	1.0	4.7	0.7	0.6	±0.1	2.6	2.7	±0.1
	13-Apr-00 19:35	0.17		325	154	53	13			4.0	0.6			2.7		
Raw NTU Change (C)	16-Apr-00 20:50	0.12	3.4	134	67	21	7	2.0	0.6	5.2	0.7	0.7	±0.1	2.6	2.7	±0.1
	20-Apr-00 06:02	0.41		270	141	45	11			4.1	0.6			2.7		
Raw NTU Change (D)	21-Apr-00 06:02	0.41	2.2	270	141	45	11	5.3	2.4	4.1	0.6	1.0	±0.8	2.7	2.1	±1.3
	21-Apr-00 04:06	0.90		1439	1036	614	378			26.3	1.4			1.4		
Backwash	15-Apr-00 09:05	0.11	1.3	208	107	39	10	2.2	1.7	4.8	0.7	0.6	±0.2	2.6	2.7	±0.2
	15-Apr-00 10:25	0.14		452	219	73	15			3.3	0.5			2.8		
Backwash	05-Apr-00 07:57	0.21	1.1	247	112	35	7	1.9	1.7	2.8	0.5	0.5	±0.1	3.0	2.9	±0.1
	05-Apr-00 09:52	0.23		468	231	77	15			3.2	0.5			2.8		
Backwash	29-Apr-00 21:30	0.21	1.7	273	125	36	9	5.3	3.2	3.3	0.5	0.5	±0.1	2.9	2.9	±0.0
	29-Apr-00 23:00	0.35		1435	774	252	41			2.9	0.5			2.9		
Backwash	25-Apr-00 06:26	0.47	1.4	570	295	71	13	4.6	3.3	2.3	0.4	0.4	±0.2	3.1	2.9	±0.3
	25-Apr-00 07:46	0.65		2617	1577	446	86			3.3	0.5			2.8		

*Refer back to Section 5.2.1 for notation and analysis method

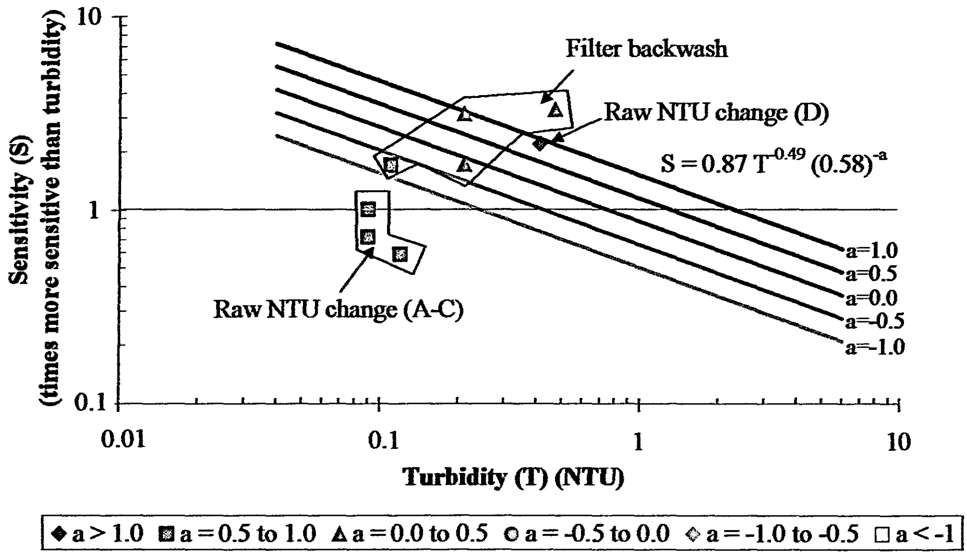


Figure 6.25 *Testwood WSW Filter 14: Data analysed using sensitivity model (with a).*

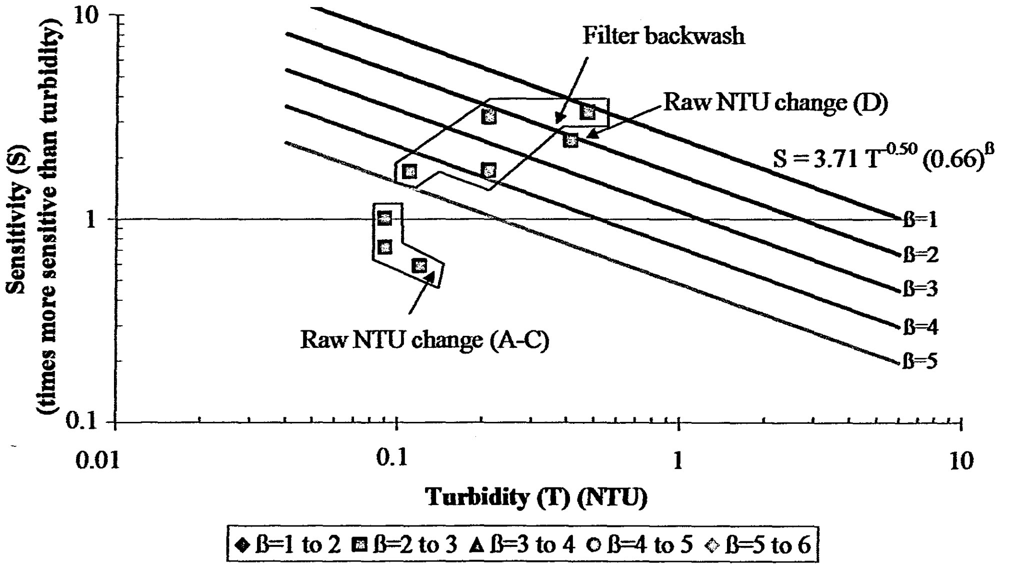


Figure 6.26 *Testwood WSW Filter 14: Data analysed using sensitivity model (with β).*

6.5.2 What parameters to use

6.5.2.1 Particle size ratios and beta

As with the Hardham study (Section 6.4.2.1), particles in the filtered water (as detected by the particle counter) adhered to the inverse power particle size distribution (Figure 6.27). This again questions the value of monitoring over many different size ranges. The beta coefficient and 2-5µm and 2-10µm particle ratio were calculated to see if provided any interesting information on particle size distribution. As can be seen in Figures 6.27-6.29, all sizing parameters more or less related the same information. Several observations can be made from these trends.

(a) All parameters reveal diurnal variations in particle size with peaks occurring mid afternoon. These variations appear to be independent of backwash events. The likeliest explanation is that they are related to light-sensitive algal growth in the raw water.

(b) A very increase change in mean particle size was seen on the 20th – 21st May. This coincided with a changeover in abstraction from the river back to the bankside storage lake (Event D). The change in size distribution is important as it reflects a large increase in particle volume. The exact cause of the increase is unclear at this time of writing although is possibly due to algae or some unspecified organism which may have accumulated in the lake.

(c) There is no evidence that any of the coagulation problems experienced resulted in a change in filtered water particle size distribution (above 2µm).

As with the Hardham study, it is evident that these different size parameters highlight different aspects of the data. Although they can be made to appear more or less sensitive depending upon which scaling is used, it is clear that the 2-10µm ratio (Figure 6.29) is most responsive to the aforementioned change seen on the 20th – 21st May. This is important considering impact that larger particles have on particle volume. The 2-5μm ratio trend (Figure 6.28) and, in particular, the β trend (Figure 6.27) are less sensitive to this event.

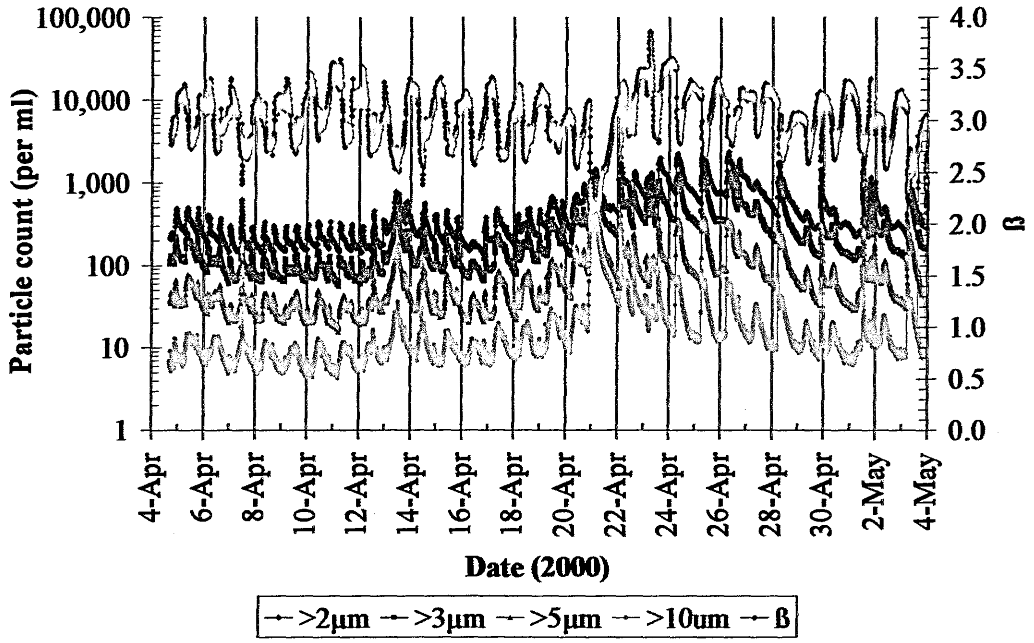


Figure 6.27 *Testwood WSW: Filter 14 particle counts and β trends.*

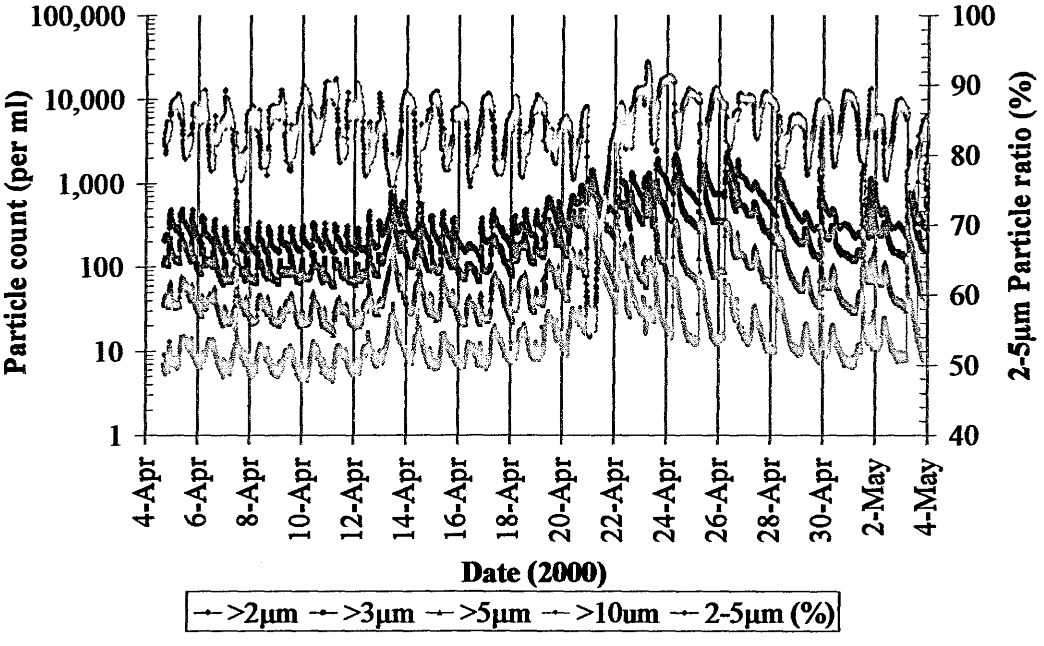


Figure 6.28 *Testwood WSW: Filter 14 particle counts and 2-5µm particle ratio trends.*

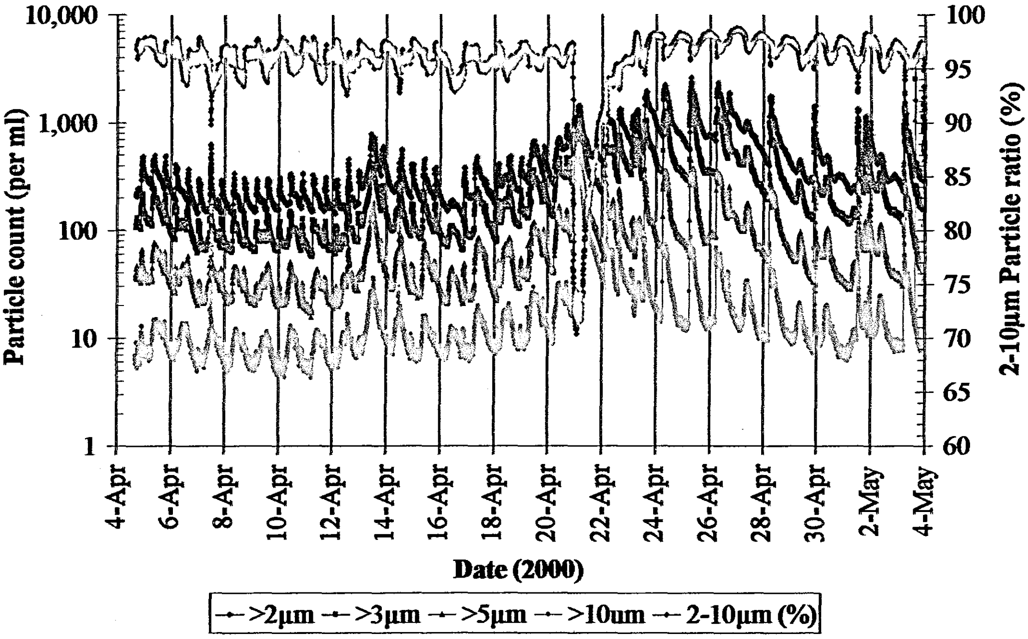


Figure 6.30 *Testwood WSW: Filter 14 particle counts and 2-10µm particle ratio trends.*

6.5.2.2 Count differentials

The >2µm count differential (described in Section 6.1.3.3) was also calculated for the Testwood data. In order to show detail in the data, only a small representative sample is presented here (Figure 6.31). As with the Hardham data, a differential of 10 counts per ml (between 15 minute readings) appears to be a suitable alarm threshold, if one is required. In addition to filter backwash events, this also picks up the highlighted increases in particle counts, which coincided with increases in raw water turbidity.

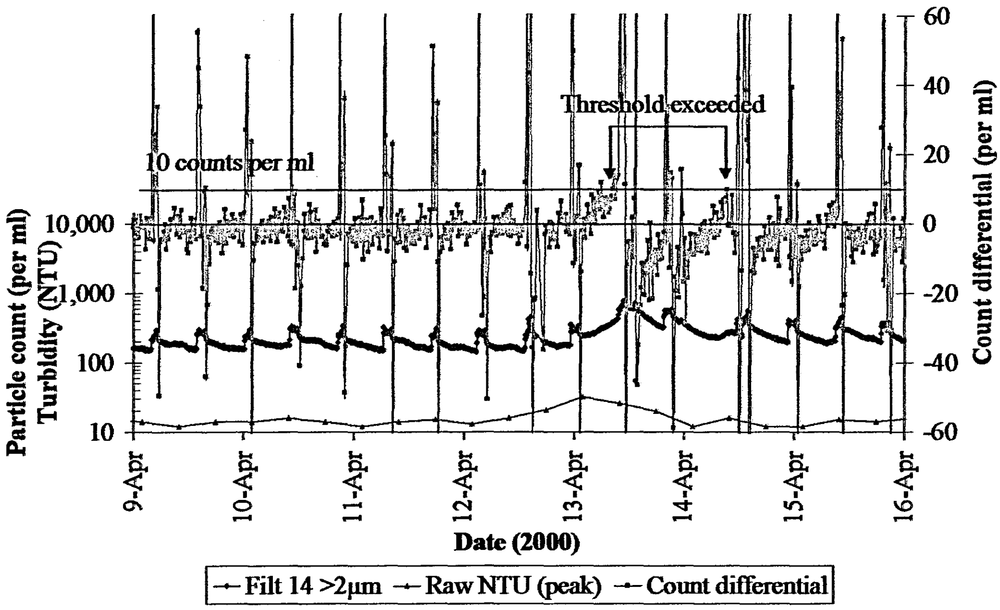


Figure 6.31 *Testwood WSW Filter 14: Fifteen minute count differential trend (9^{th} – 16^{th} April).*

6.5.3 How often to sample

A representative fraction of the Testwood data was analysed to investigate the suitability of different logging intervals. Although some definition was lost, the 80-minute readings picked up all the main changes seen with the 5-minute interval. This result differs from the Hardham study, where significant information was lost at this larger interval. The reason for this discrepancy is that at Testwood Filter 14's ripening is much more protracted than those monitored at Hardham (12 hours compared to 30 minutes), and so is still detected by an 80-minute interval.

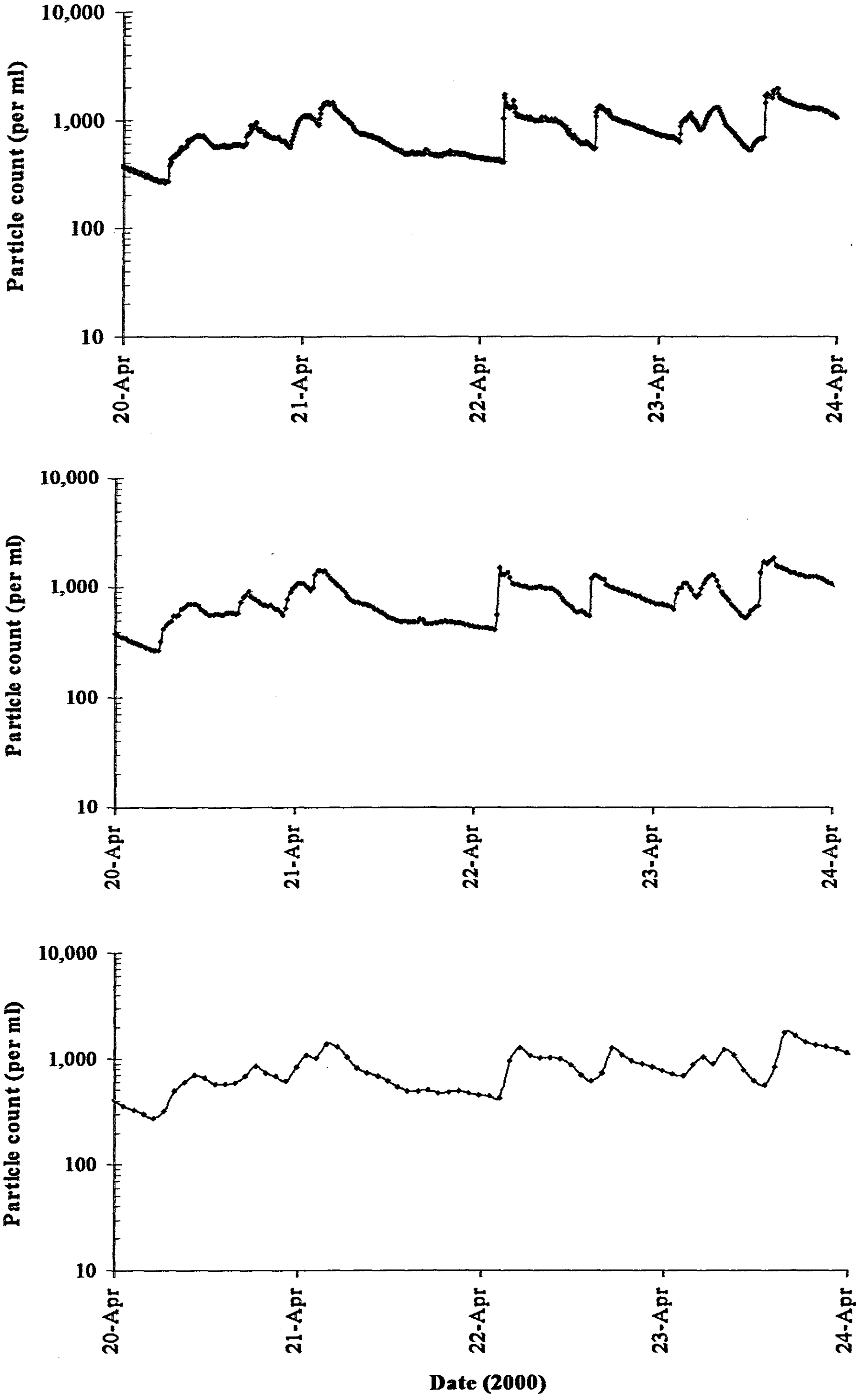


Figure 6.32 *Testwood WSW Filter 14: mean particle counts calculated every (i) 5 minutes (ii) 20 minutes and (iii) 80 minutes.*

6.6 DISCUSSION

6.6.1 What the particle counters show

In the Hardham and Testwood WSW studies, particle counters were shown to be useful in several ways. For example, at Hardham, they were useful in testing filter start-up strategy and in identifying weaknesses under increased surface loading. At Testwood, they more sensitively identified increases in particle counts during the backwash of the Enelco filters and the protracted ripening periods. These benefits all derive from the particle counters' higher sensitivity at lower turbidities.

In terms of their sensitivity to larger sized particles, their value was less apparent. No evidence of filter breakthrough could be found, for example, at either works. On one occasion at Testwood (Section 6.5.2.2) a high number of larger particles (>10μm) passed through the filter; these were believed to be algae. Although the particle counter (total count) responded more to this increase than did the turbidimeter, the increase was still apparent in turbidity readings. Referring back to the sensitivity models (Figures 6.25 and 6.26), it is apparent that particle counters were only 2.4 times more sensitive in detecting this event (D). This was very close to the value of 2.3 times more sensitive as predicted by the model.

One way in which this study differed significantly from previous work (Hargesheimer *et al.* 1992, Goldgrabe *et al.* 1993) was that particle size statistics such as β and the particle size ratios used were found to be reasonably reliable. Some noise was seen in these trends although only where the total count was less than 1 per ml. This study finds that where particle counters are being used, attention should be given to particle size distribution and changes therein. If this information is not used then arguably there is no real reason for buying a multi-channel particle counter. A simple single-channel particle counter or a particle index meter would suffice.

In Section 2.6.3 it was questioned whether the monitoring of particle size distribution is really useful in routine works monitoring. Here it was useful in a few instances: for example, the size information permitted a more meaningful comparison between total particle count and turbidity using the sensitivity model. At Hardham, an immediate shift-decrease in filtered water particle size was sometimes seen following a backwash. Some longer-term variations were also seen although the cause of these is currently unknown. At Testwood, in addition to Event D described previously, small diurnal variations in particle size were also observed and attributed to algae growing in the bankside storage lake and/or work's clarifiers. Although all this information is interesting from a process optimisation/research point of view, it is arguably of little operational value. This suggests that whereas particle sizing may be useful in one-off optimisation or process evaluation trials, it is probably not a long-term requirement in potable water treatment.

With this in mind, it is important to recognise the importance of existing turbidimeter technology. The Testwood study corroborates the findings of Morse *et al.* (2000) that much of the information given by particle counters is also provided by turbidimeters. In addition, as discussed in Section 2.3.5 and 6.1.2, turbidimeters are much easier to calibrate than particle counters and therefore should remain the mainstay of plant particle monitoring. Although particle counters are shown to be useful optimisation tools, their role is secondary to turbidimeters. Although not extensively tested here, particle index monitors may have some value used as a cheap alternative to particle counting. It is recommended that further trials be conducted to assess their reliability/value.

6.6.2 Where to install particle counters

This work confirms previous work (Section 5.3) that particle counters are generally best used on very low turbidity samples. In this study, particle counters were used on individual filter outlets. This was done in order to observe processes linked to filter run-time. Although some useful information was revealed, this study falls short of recommending the installing particle counters on every filter. There are several reasons against this:

(a) Particle counters, for the most part, duplicate turbidity information and may not be cost-effective additions to a plant.

(b) Although particle sizing can occasionally provide some useful information, this is primarily of process optimisation/evaluation interest only. Arguably it offers little in terms of routine works monitoring.

(c) As argued previously (Section 2.3), particle counters are not ‘operator friendly’ in terms of their accuracy or their ease of calibration. Calibration is labour intensive and usually requires the sensors to be sent back to the manufacturers, which adds significantly to instrument running costs.

(d) At present, it could be argued that not enough is currently made of turbidity readings especially with regard to statistical quality control. The generation of additional particle count data on top of this might further add to the ‘data rich, information poor’ monitoring environment.

(e) Since particle counters are only fine-tuning instruments, other initiatives may be more significant in minimising *Cryptosporidium* risk. These might include (i) a programme to reduce treated water turbidities, (ii) better on-line coagulation control, (iii) improvements to plant design and operations etc.

Lewis *et al.* (Section 6.1.2) reported upon a works where particle counters have been installed on every rapid gravity filter outlet. Although, this might yield some occasional benefit at a small number of works e.g. where filter breakthrough is especially prevalent, it could be argued that, such an approach would not generally be cost-effective.

One compromise solution would be to install particle counters on combined filter outlets, an option favoured by Southern Water. This is obviously a much cheaper option although the information provided by these would be less specific (Section 6.1.1). However, the same five arguments could also be made regarding the permanent installation of particle counters on combined filtered water samples. Currently, particle counters have only proved themselves to be useful as an occasional research and optimisation tool. This study therefore concludes that currently the safest course of action for a company wishing to invest in particle counter technology would be to buy several portable instruments and to promote the use of these in commissioning and optimisation work (discussed later). It is believed that the Badenoch/Bouchier Recommendations are therefore well balanced encouraging the use of particle counters without specific instructions over their installation.

In previous work with South-West Water, the author of this study used a portable 'grab sampler' in various continuous particle counting trials. The instrument used (Met-One WGS) is a particle counter into which a sample is pumped using an in-built vacuum pump. This was run for periods of up to a month without encountering any significant sampling problems. According to Engelhardt (2001), however, such instruments are designed primarily for laboratory use and so a set-up such as the mobile rig used in this study may be preferable for extended trials.

6.6.2.1 *Further monitoring trials at Southern Water*

As the next part of its research, Southern Water is installing Met-One PCX (>2μm) particle counters on combined filter effluents at all its surface water sites. This work is being undertaken in conjunction with the installation of automatic coagulation control systems (AZTEC). The particle counters will initially be used for process optimisation and research purposes only.

The case for permanent installation on combined filtered water has not yet been strictly proven. The work here shows that, apart from at very low turbidities, most of process monitoring will be ably performed by turbidimeters. However, although it is easy to be critical of the decision to install particle counters, it is possible that, because of the high sensitivity of these monitors, they might yet reveal some hitherto unknown information at least at some of these works.

The installation on combined filter samples contravenes advice given by Hargesheimer and Lewis (1995) who suggested that particle counters are best used on individual filter outlets because the monitoring of combined samples would be slow to respond to improvements and decreases in water quality. They also argued that an individual filter could be performing poorly and its performance could go undetected due to 'dilution' by other filters. However, as indicated by Bridgeman (2000), some information relating to individual filters e.g. ripening/breakthrough events can sometimes be seen in the combined sample. In addition, Bridgeman found that other respects, readings taken from combined and individual filter outlets were virtually identical. The main function therefore of installing particle counters on combined filters sample would be to troubleshoot problems, which affect all filters simultaneously e.g. those caused by changes in raw water quality, coagulation problems, poor clarification, etc.

At 4 of its 8 surface water treatment works, Southern Water is installing the particle counters downstream of secondary GAC filters. This is perhaps a more contentious decision and has perhaps been taken because the company obviously wishes to present its works in the best light. However, the information provided by these monitors may be so unspecific that information on the primary treatment stages (coagulation/clarification/primary filtration) may therefore be clouded. These treatment stages form the main defence against *Cryptosporidium* oocysts and arguably require most attention in terms of process optimisation. Tobiason and O'Melia (1988) predicted that a 3-log removal (99.9%) of oocysts should be attained in typical rapid sand filters. In contrast, the main function of GAC filters is to remove organic contaminants such as pesticides.

Whether there are significant benefits in permanently installing particle counters to monitor treated water quality is something that will hopefully become clearer in the next few years of their use within the company. Currently, however, this study would favour promoting a greater use of portable instruments as now discussed. Whatever the type of investment, it is important to recognise that particle counters do not by themselves minimise *Cryptosporidium* risk and water companies should ensure that they provide sufficient manpower to pursue relevant optimisation projects e.g. fine-tuning coagulant dosage, filter start-up strategies etc. Ultimately the success of such a venture may depend upon promoting their use as optimisation tools to company staff.

6.6.3 How to use particle counters

6.6.3.1 Specific process optimisation/evaluation studies

This study has found that particle counters can be useful aid to process optimisation and research tool. A list of ways in which they can be used is provided below (Table 6.4). As discussed in Section 6.1.1 and 6.6.2, a sensible step forward therefore would be to promote the use of portable particle counters in these targeted areas.

Table 6.4 Some recommended uses of particle counters on filtered water samples.

Application	*Reference*
Fine-tuning coagulant dose by comparing filtered water particle counts during stable raw water conditions.	Hargesheimer *et al.* 1999
Evaluating the effect of different filter pretreatments e.g. flocculation, preozonation on filtered water counts.	Bourgine *et al.* (1998), Chipps *et al.* (1995), Hall *et al.* (1999), Wilczak *et al.* (1992)
Optimising filter backwash procedure and filter start-up strategies.	Colton *et al.* (1996), Saunders *et al.*, (1999), Morse *et al.* (1999)
Investigating suspected filter breakthrough.	Kavanaugh *et al.* (1980), Keay (1995), Murray (1995), Saunders *et al.* (1999)
Identifying structural defects in filters	Ginn *et al.* (1997)
Testing membrane filter integrity	Adham *et al.* (1995)
General trouble shooting and performance evaluation	-

6.6.3.2 *Long-term troubleshooting tool*

If a company decides to go one step further and permanently install particle counters at a works then this provides the opportunity of using them as a longer-term troubleshooting tool. As discussed in Section 6.1.2, rather than attach too much significance to specific readings, this is achieved by looking for changes in particle count (or size) trends, an approach best illustrated by Ginn *et al.* (1997).

One problem with this approach is that once any initial problems have been identified, the long-term value of permanently installing particle counters is uncertain. Another danger is that particle counters might become viewed only as a reactive rather than a proactive tool, i.e. particle counters would only consulted whenever a positive *Cryptosporidium* detection is made, in the hope that they would give some indication of the contamination source. As mentioned in Section 6.6.2.1, it is clear that particle counters do not by themselves minimise *Cryptosporidium* risk, but that in order to maximise their use, proactive steps must be made to interpret data and where possible to reduce the number of particles in drinking water.

For Southern Water, having installed particle counters on a combined filtered sample, an obvious use for these monitors would to be try to improve coagulation treatment regime. Data taken from Testwood WSW (Section 6.5.1.2) indicates that particle counters appear to be of little value (beyond turbidimeters) in monitoring the loss of coagulation control dosing during rapidly changing raw water conditions. However, Hargesheimer *et al.* (1998) showed how particle counters can be used to fine-tune coagulant dosing during stable conditions, leading to possible financial savings. One obvious way forward for the Company would be to try this in conjunction with the on-going AZTEC automatic coagulation control trials.

6.6.3.3 <u>Process control parameter</u>

Using permanently installed particle counters to control treatment processes is the most advanced level of use for these monitors. In the opinion of the author, this will only be merited at very low turbidity works (as discussed in Chapter 5). This can be directly assessed using the sensitivity model. For example, it could be deemed that particle counters should only be used in preference to turbidimeters where they regularly detect changes in particle numbers around 10 or more times more sensitively. Works that might fall into this category would include some high performance filtration plants such as membrane or other microfiltration plants.

One might also consider using particle counters to detect filter breakthrough (or any other significant particle size anomaly). However, no instance was found of filter breakthrough was found at Hardham or Testwood. At Southern Water most filters are run with shallow media penetration such that filters are more likely to backwash on excessive headloss rather than turbidity. For treatment processes that encourage deeper bed penetration, there may be a greater role for permanently installed particle counters to detect filter breakthrough, although, even in this instance, the best approach might be to first try using portable particle counters to optimise filter run-times.

Where companies are seeking to employ a particle standard for treated water, one could obviously prescribe a total count standard e.g. 100 counts per ml (Lewis *et al.* 1999). However, this author believes there could be some value in the count differential (Section 6.1.3.3, 6.4.2.3 and 6.5.2.3). This is because it is relatively unaffected by calibration error between different sensors, and also is in keeping with the idea that particle counters should be used as (a) a fine-tuning tool and (b) a trend parameter. Operators could therefore be alerted to changes in water quality even at very low turbidity. Such a system would obviously have to be tested before being implemented fully and some compensation would have to made for 'noise' in the particles count trend. Where particle counters are not being used, a similar system based on turbidity readings could be beneficial.

On balance, however, most process control is probably best conducted through turbidimetry. Particle counters will probably be suitable on exceptionally high performance works only.

6.6.4 What parameters to use

In terms of which particle count parameters should be logged, this will ultimately depend on the available archive space. In this trial the following size ranges were preferred: >2µm, >3µm, >5µm, >10µm and >20µm. The use of additional or alternate size ranges such as >7µm and >15µm, would seem to be equally valid as long as they provide a reasonable spread of particle sizes. If the inverse power coefficient is of interest, then at least four or more different size ranges are desirable (Section 5.2.3). Particle counts could also be logged as a set of contiguous, differential counts (2-3µm, 3-5µm, 5-10µm-20µm, >20µm etc.), depending on personal preference although this study favours cumulative counts (Section 6.1.3.1).

These particle counts should be logged for 'research' purposes so that unexpected anomalies can be investigated in depth. However, in terms of which parameters are trended (on chart recorders or works operating systems) and looked at as part of 'routine' monitoring, there is a more obvious need to focus on those parameters that relate the most important information. The Hardham and Testwood results corroborate work done by Hargesheimer *et al.* 1992, Hargesheimer and Lewis 1995, Casale *et al.* 1999, Morse *et al.* 1999, Hamilton *et al.* 2000 which show a high degree of similarity between different sizes. This can lead to a 'data overload' situation where valuable information can be overlooked. To minimise the number of particle trends, this study suggests that it would seem prudent to focus attention on three key parameters.

(a) *A single particle count statistic.*

Although this could feasibly be any particle count, the total count (>2μm) or a suitable alternative is advised. This can be used as a general parameter to identify changes in particle number.

The choice of particle count statistic is largely of personal preference although the total count has been chosen because of its simplicity (as argued by Hargesheimer and Lewis 1995). It also provides a conservative estimate of *Cryptosporidium* risk (Section 2.4). The one instance where differential count could be considered e.g. 2-3μm as an alternative would be if one wanted to discount the effect of algal growth (Section 6.1.3.1) which can dominate larger particle size counts.

(b) *A particle size distribution statistic.*

Rather than looking obliquely across two or more differently sized particle count trends, changes in particle size were best detected using parameters such as particle ratios or β. On current knowledge, the >10μm particle ratio has been preferred as (a) it is more sensitive to larger particle sizes, (b) unlike β, it can used for any particle distribution shape, and (c) it also avoids the complications over which size ranges are needed to calculate β.

Southern Water's particle counts are intended to be stored on an existing remote archive. This receives only 4-20mA analogue input signals, which correspond to a preselected range of particle counts. This range is divided into 4096 increments. Higher resolution will only be achievable for smaller measurement ranges. For example, if particle counters are set up to measure between 0 and 4095 counts per ml, then stored readings will have an interval of 1 count per ml. To reduce noise in counts measured at larger size ranges (>10μm) and subsequent particle ratios, it may be necessary to choose upper count limits carefully. The optimum limits will depend between different sites. If noise is still problematic using the >10μm ratio then, then a different size ratio (e.g. >5μm) may be preferable.

(c) *Turbidity*

Particle counts are best viewed alongside existing turbidity or other particle monitor information. This is because each monitor reflects a different aspect of the data and so a more detailed picture is given when the data is put together. For a deeper analysis of the data, the sensitivity model can be used to compare the data.

These three parameters are recommended as they summarise the key information. This approach is very much trend-based: a particle 'counting' parameter for changes in particle number and a particle 'sizing' parameter for changes in particle size. It does not attach special significance to absolute particle figures or indeed to counts in any specific discrete size range (e.g. 2-5μm, 4-6μm, 5-10μm etc.). An advantage of this approach is that it does not rely too heavily on the resolution and accuracy of the particle counter (Section 2.3.5).

6.6.5 How often to monitor

The results here corroborate findings of Hargesheimer and Lewis (1995), LeChevallier *et al.* (1999) and Bridgeman (2000) that an interval of up to 40 minutes appears adequate for identifying major deteriorations in water quality. Although particle counter software typically permit readings to be taken at intervals of less than a minute, Southern Water archives will record a reading every 15 minutes. It is reassuring to note that this sample interval should not incur significant loss of trend definition. It is noted, however, that in general sampling/logging intervals should be kept as short as possible since this would provide maximum trend definition and shorter reaction times. At Hardham, for example, For example, a five-minute interval allowed the detection of different levels of noise (Section 6.4.1.2), which may be related to particle detachment within the filters.

6.6.6 Other discussion points

6.6.6.1 Delayed start trial (Hardham only)

At Hardham, the use of a delayed start led to no significant improvement on filter ripening (Section 6.4.1.3). This contrasts directly with observations made by Colton (1996) and Baird and Hillis (1998) who showed that the implementation of a delayed start could reduce particulate passage through the filter during its ripening phase (Table 6.1). One interesting observation is that in the Colton, and Baird and Hillis studies the ripening spikes produced in the control trials (the 'no start-up strategy') were considerably taller than in the Hardham results: up to 800-3,700 counts per ml (2-5μm) compared with 4-209 (median 28) counts per ml (>2μm) at Hardham.

Therefore a delayed start strategy may only be valuable where existing filter ripening performance is relatively poor. One study, which supports this theory, is Saunders *et al.* (1999). There pre-optimisation ripening spikes also peaked below 100 counts per ml (>2μm). Saunders *et al.* mention the fact that their existing start-up strategy already contained a 20-minute slow start. At Hardham, a filter's outlet value opened incrementally when the filter water had refilled up to a 'high-level' sensor.

Both the Hardham and Saunders *et al.* study also observed that the implementation of a delayed start led to increase in surface loading onto and particle counts produced by the other filters, and a net deterioration in combined filter effluent quality. The detrimental impact of filter backwashing on 'other filters' was also seen by Quirke (1996) and Ginn *et al.* (1997).

Finally, the dependency of ripening and pre-backwash quality seen at Hardham was also discussed in Colton (1996). This implies that improvements in prefilter treatment will have a secondary effect on filter ripening. This would also give credence to work described by Bucklin *et al.* 1988 and Yapijakis 1982 (both cited in Hall and Croll 1997) that the addition of polyelectrolyte or coagulant to filter inlet water immediately prior to the filter refilling may lead to an improvement in filter ripening. Confirmation of this would obviously need to look at the size as well as the number of particles entering leaving the filter.

6.6.6.2 Coagulation

Another interesting observation was that, at Testwood, particle counters were noticeably less sensitive than turbidity to deteriorations in filtered water quality caused by sub-optimum coagulation (Section 6.5.1.2). The exact cause of this is unknown although one possibility is that the filtered water contained an abnormally large number of submicron particles. On a similar theme, Ginn *et al.* (1997) detailed an instance where a failure in coagulant dosing pump was picked up by turbidity, but not by particle counts. Although there is no direct evidence linking the two events, it is possible that investigating the effects of sub-optimal coagulation using a sensor measuring down to 1µm or small sizes may yield interesting results.

On a similar theme, several examples are presented in Hargesheimer *et al.* (1992) of unusual size distributions in particle count data measured down to 1µm and below. Although this study has exclusively looked at >2µm sensors, it is worth noting that monitoring below 1µm might yield some more interesting results in terms of irregular particle size distributions. However, submicron sensors are expensive and due to increased risk of coincidence error are suitable for only very low turbidity water samples.

6.7 CONCLUSIONS

6.7.1 Particle monitoring

Particle counters provided some interesting information on filter performance utilising (a) their high sensitivity to changes in particle number below 0.1 NTU and (b) their particle sizing ability. However this information was mostly useful from a process optimisation/evaluation point of view and not a primary operational concern.

Apart from processes that consistently produce very low turbidity water, most routine particle monitoring needs are catered for by turbidimeters. At most treatment works, therefore the permanent installation of particle counters is not likely to be a cost-effective exercise, especially in the long-term. Instead, water companies should promote the use of portable particle counters in targeted plant optimisation/evaluation studies.

Turbidity will remain the most important particle measurement especially with regards to routine process monitoring and control. To minimise *Cryptosporidium* risk, water companies should first look at reducing treated water turbidity at high-risk works. The implementation of a statistical quality control system based on turbidity such as that described by Bouchier (1998) or Edwards *et al.* (2000) is arguably more desirable than the permanent installation of particle counters or similar instruments.

No evidence of filter breakthrough (which might be best monitored using particle counters) could be found during the study. For treatment processes that encourage deep bed penetration, there may be a greater role for permanently installed particle counters. to detect filter breakthrough. However, it would probably be more cost-effective to first try to use portable particle counters to optimise filter run-times.

A high degree of similarity was seen in particle trends measured across different sizes. This can lead to a 'data overload' situation where valuable information can be overlooked. To minimise the number of trends, this study suggests that where particle counters are used it would seem prudent to focus attention on two key parameters: (a) a total count (>2μm) to monitor changes in particle count, and (b) a particle size statistic such as the >10μm particle ratio (%) to monitor changes in particle size.

Contrary to other published work, this study found particle size statistics such as β and particle size ratios to be reasonably reliable. Some noise was seen in these trends although only where the total count was less than 1 per ml. If these statistics are not used then arguably there is no real reason for buying a multi-channel particle counter. A simple single-channel particle counter or a particle index meter would suffice.

A sample interval of 15 minutes was sufficient to pick out all the major changes seen in water quality. A shorter interval (e.g. 5 minutes or lower) is preferable, however, as it provides greater trend definition.

If a water company wishes to use a particle count standard for controlling processes (e.g. for works that consistently produce treated water with a very low turbidity), it might be worth implementing a local alarm system based on the particle count differential parameter to flag up significant changes in water quality. Where particle counters are not being used, a similar system based on turbidity readings could be beneficial.

It is recommended that unusual particle count and/or turbidity readings be compared using the sensitivity model. Turbidimeters appeared to respond especially sensitively to increases in particle number associated with coagulation control problems at Testwood. Its response was much higher than that predicted by the particle monitor sensitivity model, which may indicate an abnormally high number of submicron particles in the sample. Not all particle monitor data therefore is effectively modelled by the sensitivity model. Such anomalies, however, may be of special interest and are well highlighted by the model.

Although this study has exclusively looked at >2μm sensors, monitoring below 1μm might yield some more unusual particle size distribution shapes especially during periods of sub-optimal coagulant dosing.

Whatever the investment in particle counters (permanently installed or portable), it is important to realise that particle counters do not minimise *Cryptosporidium* risk by themselves. Water companies should ensure that they provide sufficient manpower to pursue specific optimisation projects e.g. fine-tuning coagulant dosage, filter start-up strategies etc. Ultimately the success of such an investment may depend upon promoting their use as optimisation tools to company staff.

6.7.2 Other related issues

The implementation of a delayed filter start-up strategy at Hardham led to no improvement in ripening. It actually led to a net deterioration in filter performance because the addition surface loading placed upon the other filters created problems in treatment.

Care should be given to filtered water turbidity/particle counts when increasing surface loading rates onto filters especially during filter ripening.

Chapter 7 GROUNDWATER SUPPLY WORKS

A preliminary study of particle counter applications at groundwater supply works was published in Hamilton *et al.* (2000) and has been reproduced in Appendix A.

7.1 INTRODUCTION

Groundwater is found in permeable rocks called 'aquifers', which are at least partly saturated as a result of the infiltration of rainfall. The water is filtered during its slow passage through the ground, flowing between the small grains that make up an aquifer or the many fine fissures that intersect it. Although most groundwater supplies in the UK are free from significant oocyst contamination, those, which are strongly influenced by surface waters, carry more of a risk. Contaminated groundwater was suspected to be the cause of the first documented waterborne outbreak of cryptosporidiosis at Braun Station, Texas in 1984 (Badenoch, 1990). Similar outbreaks in the UK have included the 1997 Three Valleys outbreak, which affected 345 people in North London and Hertfordshire (Bouchier, 1998, DWI, 1998). Following this outbreak, the Bouchier Report made several recommendations. In particular, it stressed that '*careful attention should be given to the operational aspects of groundwater abstraction*'. It also recommended the development of operational monitoring tools to improve the detection of rapid influence of surface water sources on the quality of groundwater.

Around two-thirds of Southern Water's drinking water supplies come from boreholes situated at around a hundred water supply works (WSW). It therefore has a special interest in exploring the potential role of particle counters at those sites considered to be of relatively high *Cryptosporidium* risk.

7.1.1 Particle counting at groundwater sites

Relatively few particle count studies of groundwater supply works have been published. Englehardt (2000) observed that particle counters were more sensitive than turbidimeters in detecting surface water influence at one borehole studied (a low turbidity water source). Two previous studies conducted in collaboration with Southern Water have been written. Evans (1997) used particle counters to optimise a microfiltration plant installed to reduce groundwater turbidity at Burpham WSW. That study noted that the level of particle removal (%) measured across the microfilters deteriorated over time. Filter run-times were therefore shortened to ensure higher levels of particle removal. (This work was summarised in Hamilton *et al.* 2000). The study also highlighted cyclical variations in groundwater particle counts caused by tidal influence.

These observations were confirmed in a follow-up study conducted by Doyle (1998). Both Evans and Doyle noted that changes in particle numbers occurred roughly proportionately across all sizes, although Doyle, using a particle size ratio (the ratio of >2μm to >5μm particles) did identify some subtle changes in particle size distribution. This ratio varied according to which combination of boreholes were being pumped. Other small variations occurred that could not be attributed to known process events. It is not currently known whether these anomalies have any real significance in terms of routine monitoring. In fact, in both these studies, because of the close correlation between particle counts and turbidity, it could be questioned whether particle counters really added anything substantial in addition to the information provided by turbidity.

7.2 OBJECTIVES

Particle counters were installed (mostly on a temporary basis) at five groundwater treatment works. Data from three of these: Arundel, Burpham, and Newmarket are discussed in detail as they provide an interesting comparison. These works were selected as they were given 'high risk' status in a 1998 *Cryptosporidium* risk assessment, conducted by Southern Water's Technology Group.

This study sought to determine whether particle counters added any new information on groundwater quality beyond that imparted by turbidimeters. This focused specifically upon the three areas of beneficial particle counter use outlined previously (Chapter 2.6). Practical aspects of particle counting have also been studied such as what parameters to use, where to use particle counters etc. Work looking at the associations been particle monitor and *Cryptosporidium* oocyst data has been reported separately (Chapter 9).

7.3 ARUNDEL – MATERIAL AND METHODS

7.3.1 Works description

Arundel is one of a number of Southern Water groundwater supply works sunk into the chalk of the South Downs, which form a water distribution network serving approximately 120,000 customers in West Sussex. Water is abstracted from a single borehole at Arundel, is chlorinated and is then pumped to one of three storage reservoirs. The site is licensed to abstract 4.5 Ml/d, but in recent years has abstracted only around 2.5-3.5 Ml/D. The pumps are controlled remotely according to demand with additional restrictions imposed during the four winter months to avoid higher electricity tariff charges. Like most groundwater supply works, the site is unmanned but is monitored by the RICAS telemetry system whereby all site alarms are received and managed off-site. Since the time of study, an ultra-violet light irradiation plant has also been installed to provide additional protection against *Cryptosporidium*.

7.3.2 Particle monitoring

Particle monitor data was gathered using the mobile particle monitor rig described in Section 4.1.2. This was installed for a period of 3 weeks, from 20th October to 8th November, 1999 although the works was run only for 9 days during this period (as shown). The unchlorinated sample was used located within the site building. Rainfall data was supplied by the Environment Agency and was taken from the 'Arundel 3' rain gauge (Gauge Ref. 264122003), located less than 1 kilometre from the pumping station.

7.4 BURPHAM – MATERIALS AND METHODS

7.4.1 Works description

Burpham WSW, also located in West Sussex, receives water from up to four boreholes sunk into the chalk of the South Downs. Southern Water is licensed to abstract up to 25 megalitres per day (Ml/d) from these boreholes, but typically takes only around 15 Ml/d because of deteriorating water quality at higher rates. The groundwater in this area has historically been high in turbidity, aluminium and iron. This is thought to be due to fissure connections at depth drawing water from the tidally influenced River Arun, which flows over 1km distant from the boreholes.

In 1995, the Company installed an Atkins Fulford 'Filtomat' MT38P microfiltration plant at the works to reduce turbidity and to provide additional protection against *C. parvum*. A Filtomat unit is a depth filter with a nominal pore size of 5μm. The plant at Burpham operates as a two-stage process with up to five units used in the first stage and four in the second, on a rotating basis. Each unit processes up to 300m^3/hr of water and is automatically configured to run in either stage following a backwash. A schematic diagram of the works is provided (Figure 7.1). Optimum performance is maintained through backwashing filters either (a) when filter run time exceeds 24 hours, (b) when combined filtrate water turbidity exceeds 0.6 NTU or, as more commonly occurs, (c) when differential pressure (d.p.) across either stage exceeds 0.3 bar.

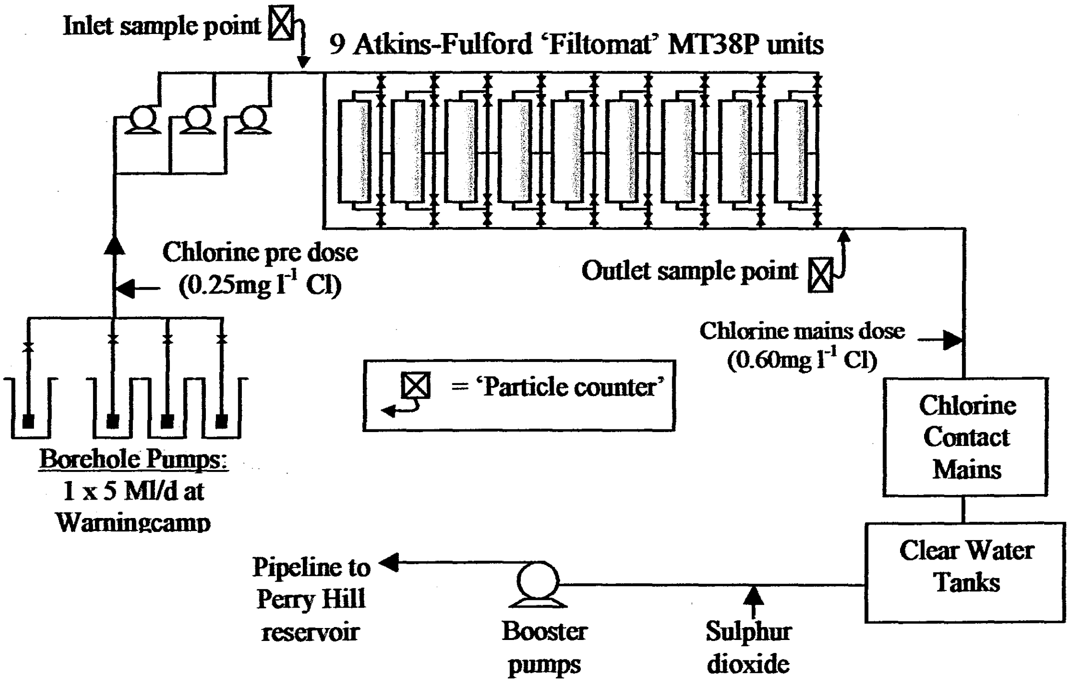


Figure 7.1 *Burpham water supply works - Process flow diagram (Particle size counter sampling locations shown).*

7.4.2 Particle monitoring

At Burpham WSW, two Met-One PCX particle counters were installed in 1997 for process optimisation and research purposes. The monitors were calibrated and routinely checked for the first two years of this study. Data was also taken from two Hach 1720C turbidimeters installed on a combined microfilter inlet and outlet sample line. At the time of the study, only the inlet meter was connected up to the company telemetry systems (providing 15-minute readings). Treated water turbidity measurements were taken manually from chart recordings (30-minute readings).

7.5 NEWMARKET 1C: MATERIALS AND METHODS

7.5.1 Works description

Newmarket WSW, located in East Sussex, treats water from four chalk boreholes. These boreholes are situated on three different sites, lying within two kilometres of each other, and historically referred to as '1B', '1C' and '1D' (Figure 7.2). Southern Water is licensed to abstract a total of 14.8 Ml/d from these four boreholes, each day of the year, but currently takes only around 10.8 Ml/d. The pump start/stop times are pre-programmed according to forecast demand. The plant is usually turned off between 16:00 and 19:00 during the months November to February to avoid high electricity tariff charges incurred.

Factors contributing to the high *Cryptosporidium* risk assessment given to the works include the following:

(a) The areas around Newmarket '1C' and '1D' are prone to flooding after heavy rainfall in the winter months.
(b) A substantial level of cattle grazing and fertiliser use is found in the surrounding area.
(c) There is a high likelihood of fissuring occurring in the chalk.

Treatment at the works has historically comprised chlorination, sulphur dioxide and phosphate dosing to reduce plumbosolvency, but in 2001 a ultra-violet light irradiation plant was installed to reduce *Cryptosporidium* risk.

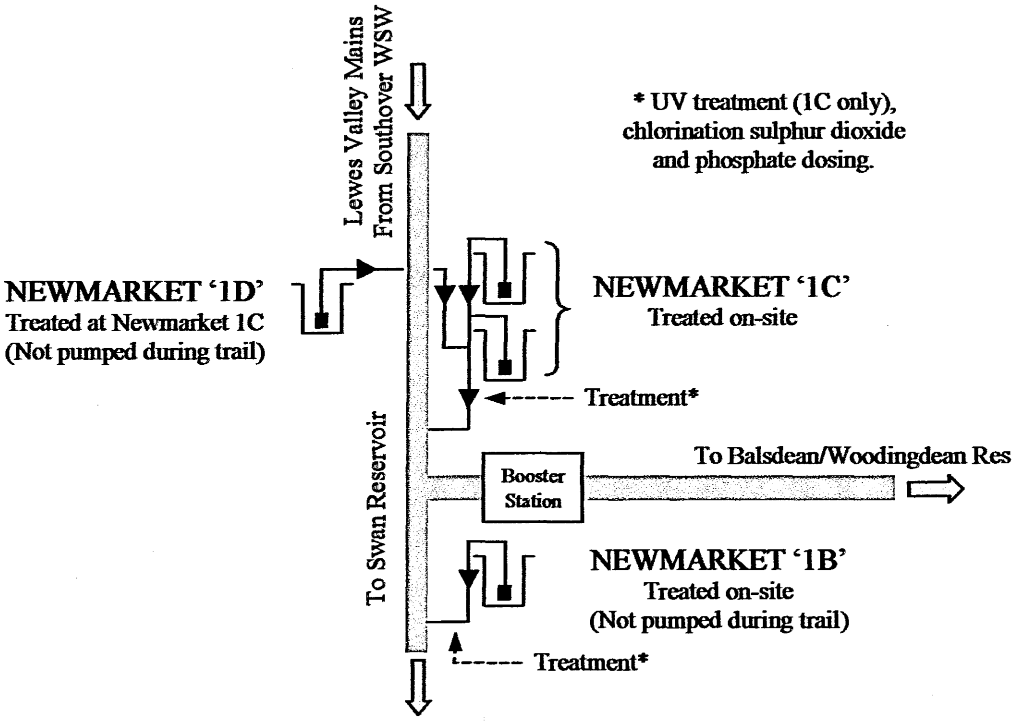


Figure 7.2 *Newmarket WSW schematic.*

7.5.2 Initial monitoring

A Liquilaz E20 (PMS) particle size analyser was set up at Newmarket '1C' in 1998 to monitor the site's treated water. The instrument was set up by Southern Water's Process Group to monitor particles in the following size ranges: 2-3μm, 3-4μm, 4-5μm, and >5μm. The accompanying Aquaview software was configured so that a reading was taken every minute and a mean value recorded every five minutes.

The approximate times of pump stops and restarts were obtained from works flow chart recorders. The Environmental Agency provided daily rainfall data from their site at Housdean Farm, within 2 kilometres of the works.

7.5.3 Follow-up monitoring

A number of anomalies were seen in the original monitoring (described later). These were further investigated in two short periods of monitoring, between 17th February and 14th March, 2000 and between 2nd and 13th August, 2001. The purpose of this additional monitoring was to identify the type of particles present during observed increases in particle counts. A number of grab samples were taken and submitted for microbiological and metals analysis at Southern Water's laboratory. Further details of this aspect of the study are provided in Chapter 9.

In both these follow-up surveys, the mobile particle monitor rig was used (described in Chapter 4.1.2). This comprised a Met-One PCX particle counter, an ABB 7997/202 turbidimeter and Diverse FPM particle index monitor. By this time, a standard set of size ranges in which to count particles had been formulised, namely >2μm, >3μm, >5μm, >10μm and >20μm.

7.6 ARUNDEL - RESULTS

7.6.1 What the particle counter shows

Particle count data obtained at Arundel and associated graphs are presented in Figures 7.3-7.5. It is apparent from the first of these, that drinking water produced by the plant contained a relatively high number of particles compared to Testwood and especially Hardham WSW (Chapter 5 – Surface). During the survey, turbidities at Arundel were measured between 0.10 – 1.00 NTU; total particle counts between 1,000 and 10,000). These particle counts were around an order of magnitude higher than Testwood WSW. The links between particle counts/turbidity and *Cryptosporidium* risk has been investigated in Chapter 9.

Large increases in particle numbers were seen each time a borehole pump was started. This is believed to be due to the stirring up of sediment within the borehole and connected mains although it is also possible that some surface water is sucked down into the borehole. Particle counts were also seen to undergo step-changes corresponding to changes in borehole abstraction rate (Figure 7.4). The changes occurred because the water was pumped sequentially to different treated water reservoirs. These are located at different heights above sea level and so pump speed varied according to head. Groundwater quality in this area appeared not to be directly influenced by rainfall. According to a local weather station data (Figure 7.5) around 8mm of rain fell on the 5th November. This appeared not have any impact on particle readings.

Disappointingly, the data provided by all three particle monitors was virtually identical in terms of trend. Particle counters (and index monitors) did not appear to add anything to the monitoring of this works in terms of monitor sensitivity. This has been shown graphically using the sensitivity model (Figure 7.6). The data set shown here is the subset of all groundwater data taken from the sensitivity model described previously (Section 5.3). The model contained a single point generated from the Arundel data, based upon the change seen in particle count linked to the change borehole abstraction rate. The response of the particle counter to the change was actually slightly below that predicted by the model (a=0.36). Caution must be taken when interpreting such data during a pump start-up because of the high probability of sampling error caused by (a) air bubbles in the sample and (b) the possibility of dislodging material previously settled in the sample lines. A decision was made to omit all similar spikes from the sensitivity analysis as the accuracy of these spikes could not be guaranteed.

Another disappointing feature was that, aside from sensitivity modelling, the particle counters also provided little information of real interest in terms of particle size distribution (Figure 7.7). Particle counts measured over different size ranges adhered universally to the inverse power size distribution described in Section 5.1. The >10μm ratio remained fairly constant at around 3% (a=0.4). A small increase in particle size was seen after the start-up of a borehole pump, which, as mentioned previously, may be due to stirring up of larger particles which have settled in the borehole and the connected mains. Other than this, the >10μm particle ratio trend showed little appreciable change in particle size.

On current evidence, particle counters appeared to add little to monitoring of this works and so a permanently installed instrument is not likely to be a worthwhile investment.

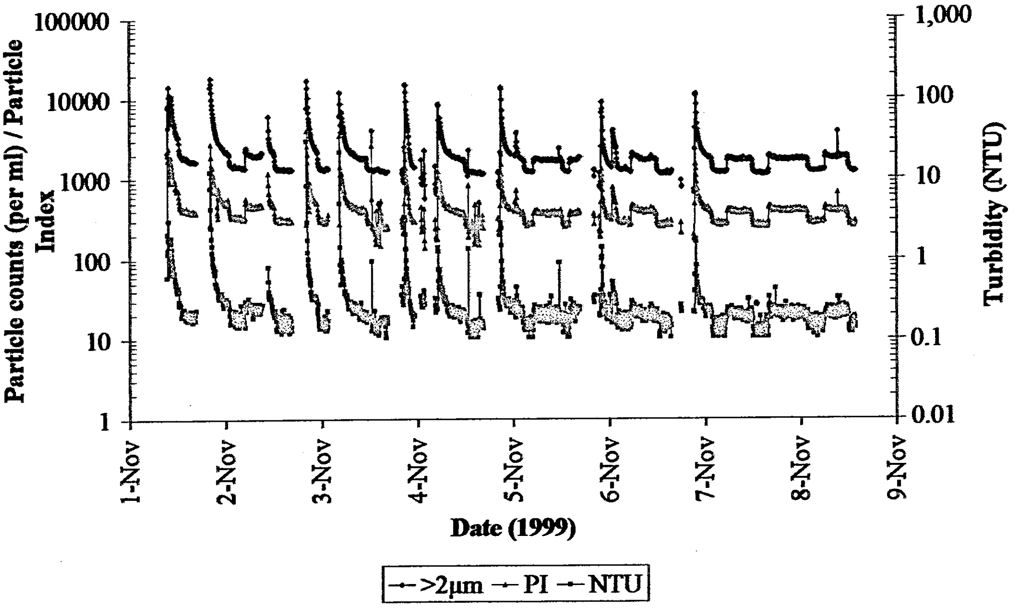


Figure 7.3 *Arundel WSW: treated water total particle count, turbidity and particle index.*

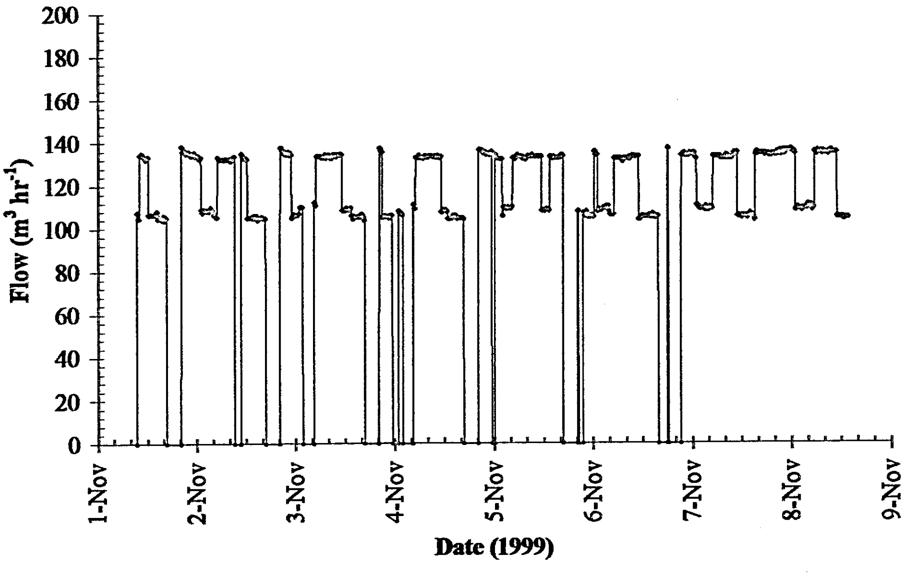


Figure 7.4 *Arundel WSW: borehole abstraction rates*

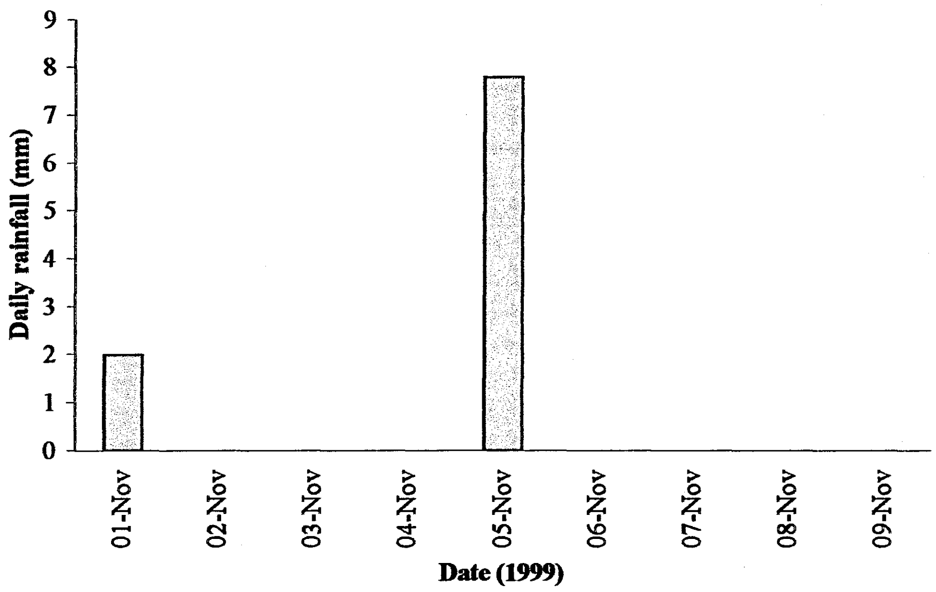


Figure 7.5 *Arundel WSW: daily rainfall*

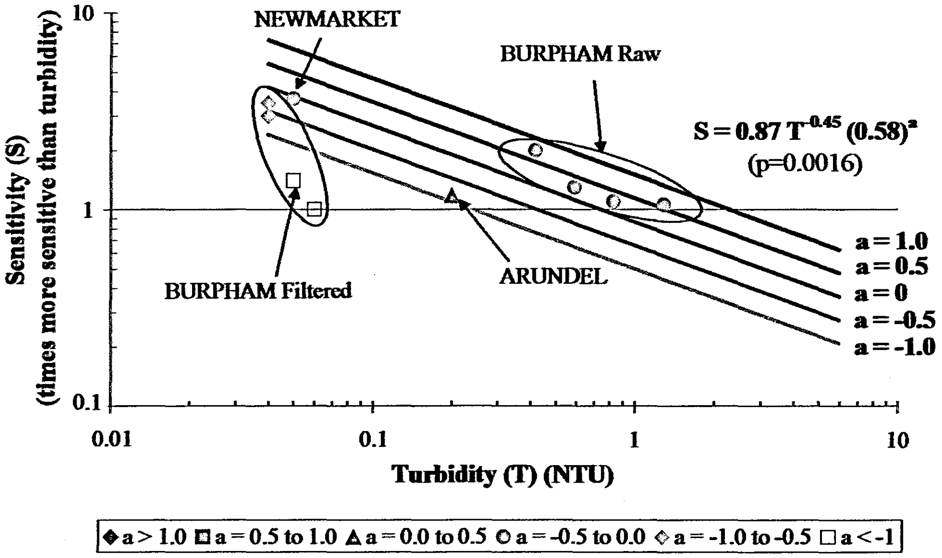


Figure 7.6 *Sensitivity model:groundwater data.*

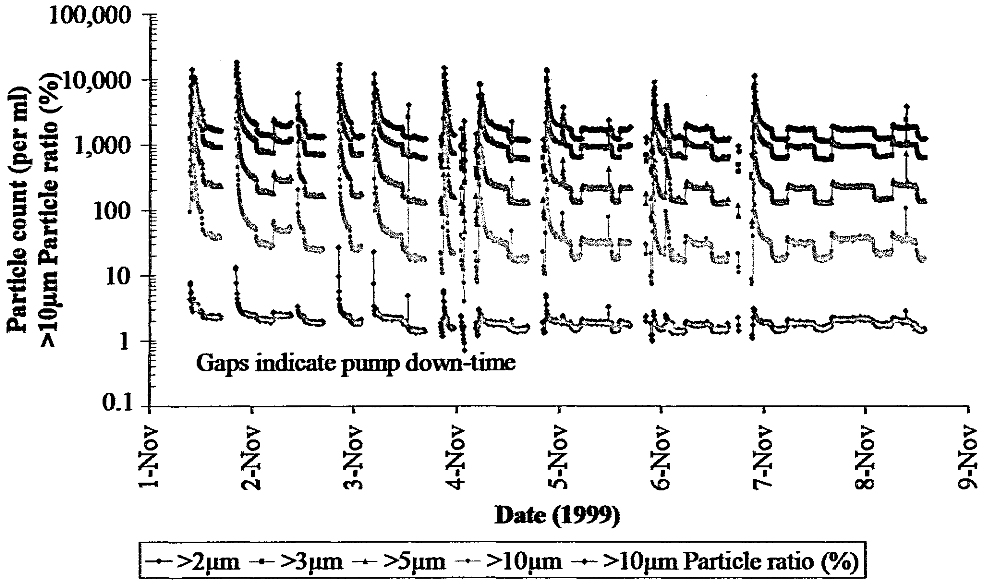


Figure 7.7 *Arundel WSW: treated water particle counts 1st-9th November, 2002.*

7.7 BURPHAM WSW - RESULTS

7.7.1 What the particle counters show

Representative samples of the data, taken from the period of monitoring July-November, 1999, are shown in Figures 7.8 and 7.9. The groundwater abstracted is of relatively high turbidity (>0.2 NTU) and particle counts (>1,000 counts per ml) compared to treated waters from surface and groundwater supply works studied). In addition, the following influences on particle numbers were noted.

(a) Groundwater particle count and turbidity readings are tidally influenced. This is especially noticeable during period of spring tides during the summer months where very large cyclical variations were seen peaking over 6,000 counts per ml (>2μm) (Figure 7.9).

(b) Particle counts and turbidity increased considerably during higher rates of abstraction. On the 30th July, 1999 when a third borehole pump was started to meet demand, monitors detected around a tenfold increase in particles from around a thousand to over ten thousand counts per ml (>2μm). Note that particle counts above 12,000 are subject to excessive coincidence error (Section 4.2.4). A comparative increase was also seen in raw and filtered water turbidities.

As with the Arundel study, it is apparent that much of the information shown by particle counters can also be seen in turbidity readings. Both instruments responded very similarly (in terms of trend) to the observed changes in water quality (Figure 7.9). According to data inputted into the sensitivity model (Figure 7.6), particle counters installed on the filter inlet sample at best were only twice as sensitive as turbidimeters. This was seen at when the inlet turbidity was at its lowest (around 0.4 NTU). The particle counter installed on the filter outlet showed a little more sensitivity, up to 4 times more sensitive at 0.04 NTU (Figure 7.6). Yet it is perhaps surprising that this particle counter did not show even more sensitivity. Data in the model shows that, on at least two occasions, the particle counter and turbidimeter were equally sensitive around 0.05 NTU, and yet the filter inlet particle counter was twice as sensitive around 0.4 NTU turbidity. This is explained by the model; in addition to the reduction in particle number across the microfilters, there is also a reduction in particle size distribution since the larger particles (>10μm) are preferentially removed. As indicated by the sensitivity model, this results in the filter outlet particle counter's being less sensitive than it would have been had no shift in particle size distribution occurred. This shows that particle counters may not always be suitable below 0.1 NTU.

A more detailed comparison between raw and filtered particle size distribution is shown in Figure 7.10. The >10μm particle ratio has been shown by its logarithmic equivalent a (Chapter 5.2.4). This shows more clearly the details in the filtered water trend, which would otherwise be lost close to 100%. The filtered water trend reveals that an increase in particle size occurred during each filter run when the filters were 'under challenge' from increasingly turbid inlet water.

Although all the previous observations are interesting from a research point of view, as with Arundel WSW, the real value of the particle count information in terms of routine monitoring, is questionable. This is especially true since the plant at Burpham is, for the most part, unmanned.

However, a more significant benefit came from a fairly unexpected source, namely from the use of particle removal trends. This followed on from a previous study reported in Evans (1997) and Hamilton *et al.* (2000) (Appendix A), which showed how particle removal information could be used to optimise microfilter run-times. A comparison between particle removal and turbidity removal trends is provided in Figures 7.11 and 7.12. These show that whereas particle counters clearly identify a drop in filter performance towards the end of certain filter runs, this information is not apparent from turbidity readings. This is probably due to two factors: (a) the relative insensitivity of turbidimeters to changes below 0.1 NTU, and (b) the preferential removal of larger particle sizes, which have a greater impact on particle counts.

In defence of the Atkins-Fulford microfilters, it is worth noticing that they cope well with the increases in particle loadings. Particle removal rates, typically between 80-90% across both stages of filtration, begin to deteriorate only after a period of twelve hours. It is not known why the 0.3 bar differential pressure backwash trigger did not activate filter backwashes on these occasions. It is presumed that the 'filter breakthrough' seen must have occurred without a significant increase in differential pressure.

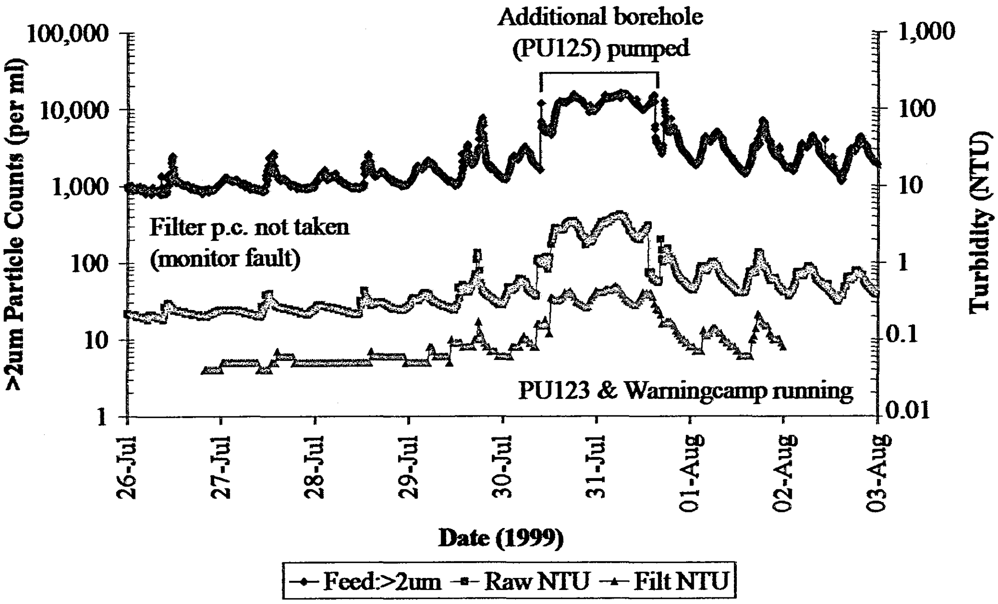


Figure 7.8 *Burpham WSW: Pre and post microfilter quality 26th July - 3rd August, 1999.*

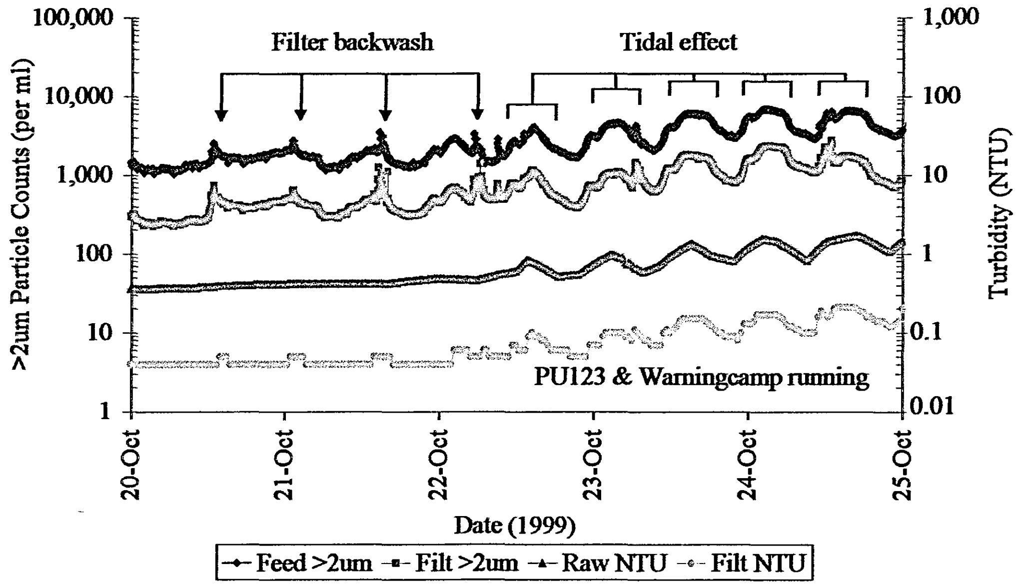


Figure 7.9 *Burpham WSW: Pre and post microfilter quality 20th - 25th October, 1999.*

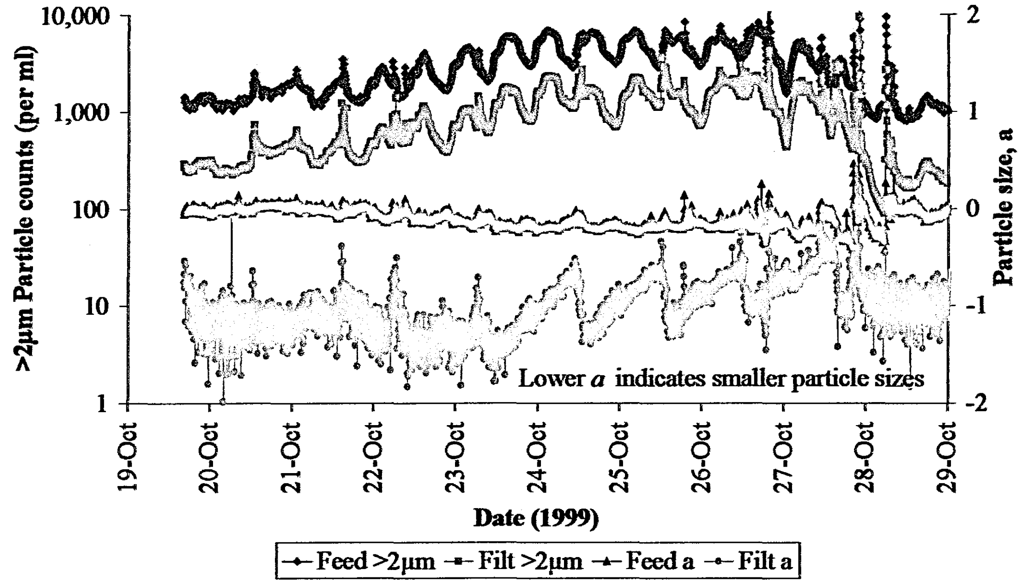


Figure 7.10 *Burpham WSW: Particle counts and particle size distribution*

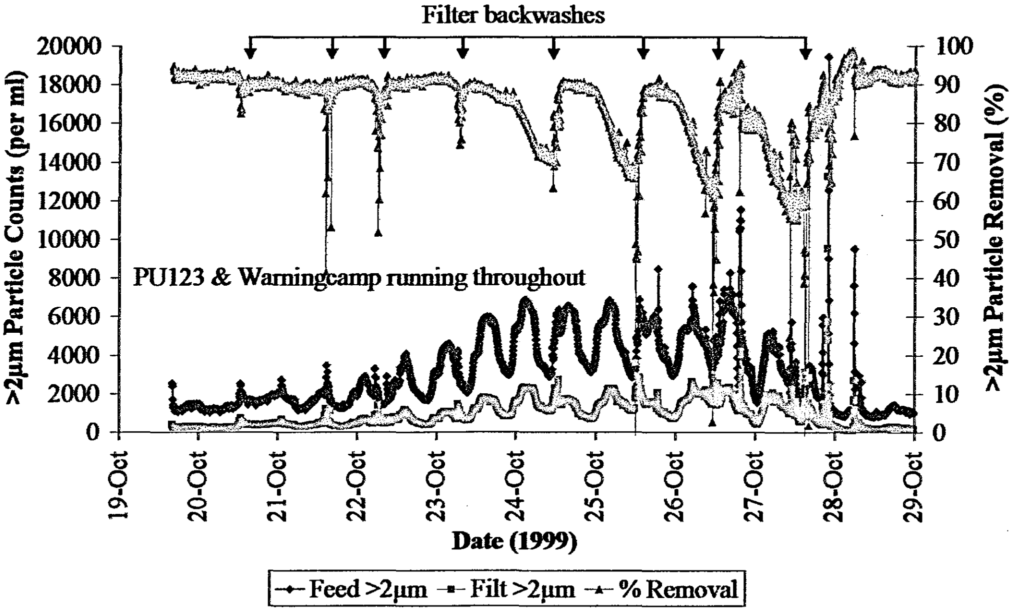


Figure 7.11 *Burpham WSW: Particle counts and particle removal*

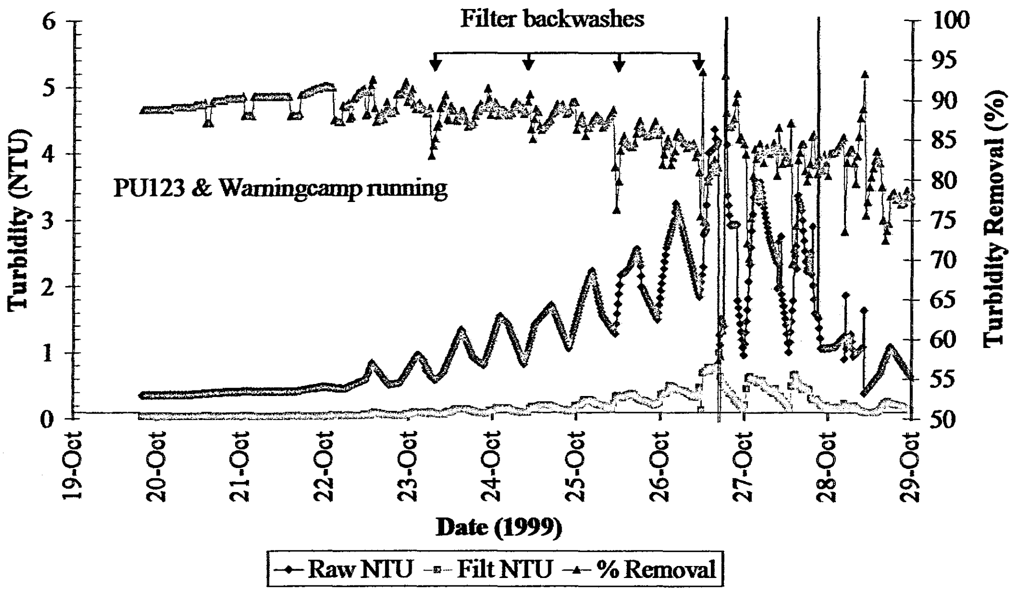


Figure 7.12 *Burpham WSW turbidities and turbidity removal.*

7.8 NEWMARKET 1C - RESULTS

7.8.1 What the particle counters show

7.8.1.1 *Initial monitoring*

As can be seen in Figure 7.13, Newmarket WSW typically produces drinking water with a very low particle count, typically around 20-30 per ml). Only two deviations from this norm were observed during the three-month monitoring period. These occurred (a) immediately after the borehole pump was started and (b) several hours after a heavy rainfall.

As far as particle size distribution is concerned, particle size remained fairly constant with around 10% of particle being counted above 5µm (Figure 7.13), although some small fluctuations were seen in particle size; for example, the spikes seen after borehole pump start-ups comprised a higher proportion of larger (>5µm) sized particles. This was also seen in the Arundel monitoring (Section 7.6.1). In contrast, a particle count spike induced by heavy rainfall appeared to contain an abnormally low proportion of larger particles. It is questionable whether this information has any real practical value. (The >5µm particle ratio was used here instead of the >10µm ratio used previously because of the narrow selection of particle size channels settings in this early study – Section 7.5.2.)

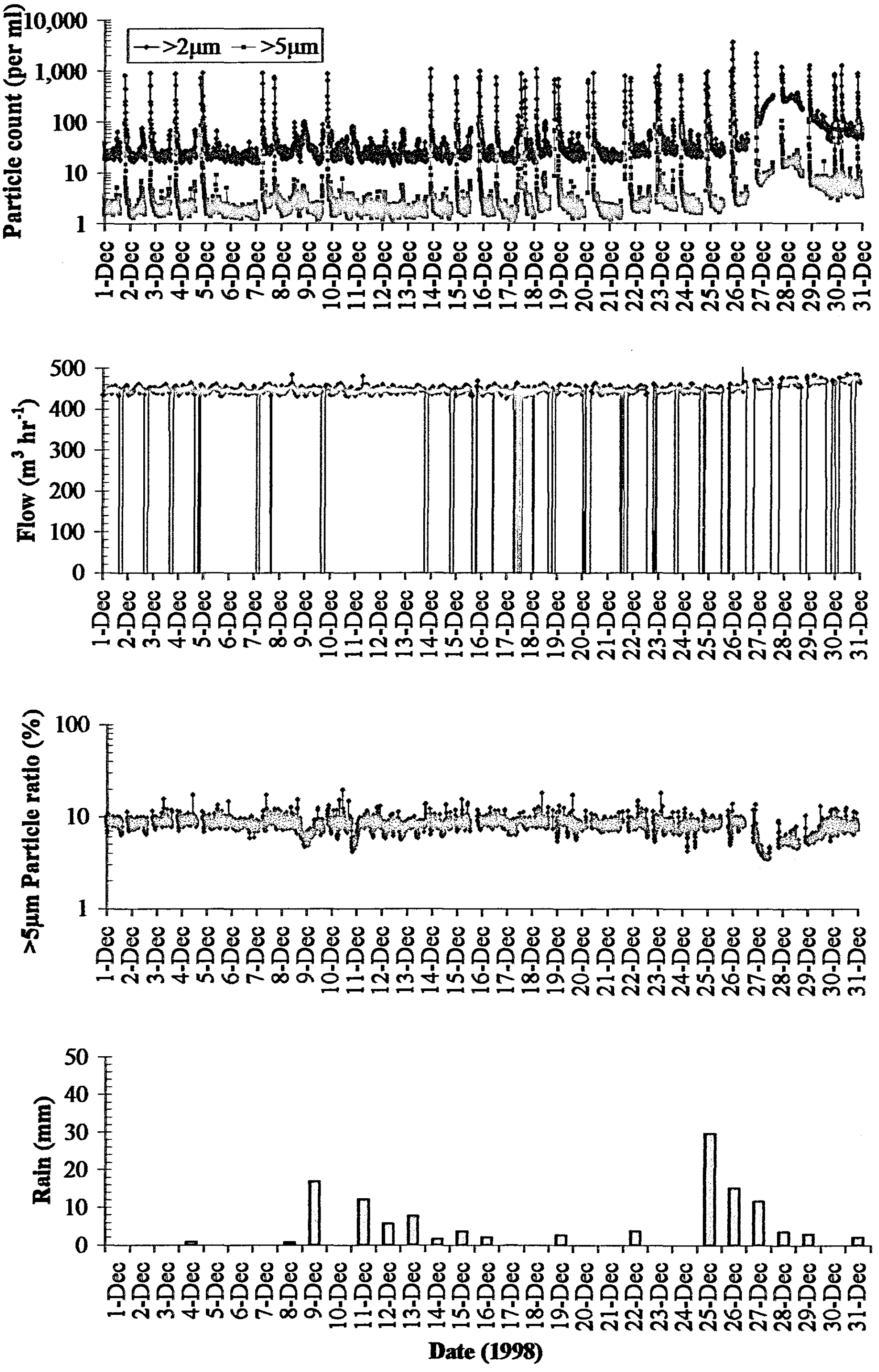


Figure 7.13 *Newmarket WSW: Initial monitoring - December, 1998.*

7.8.1.2 Sample surveys

In the repeat monitoring, a comparison between particle counter and turbidimeter readings was possible. On the 7th August particle counts and turbidity began to rise two hours after the start of heavy rainfall (Figure 7.14, 7.15). The particle counter was seen to be much more sensitive in detecting this change than the turbidimeter. This was also seen previously using the sensitivity model (Figure 7.6). In Figure 7.14, whereas turbidity increased from 0.081 to 0.111 NTU (a 1.4-fold increase), particle index increased from 73 to 167 (a 2.3-fold increase). This also compares well with the particle counter whose total count increased from 326 to 1060 per ml, a 3.2-fold increase. I.e. particle index was around 1.7 times more sensitive than turbidity: compared to particle counts, which was 2.4 times more sensitive. This supports an earlier observation (Section 5.5) that, if particle sizing is not required, particle index monitors might be considered as a cheap alternative to particle counters. It is also worth mentioning that the turbidimeter did register a change albeit a small one.

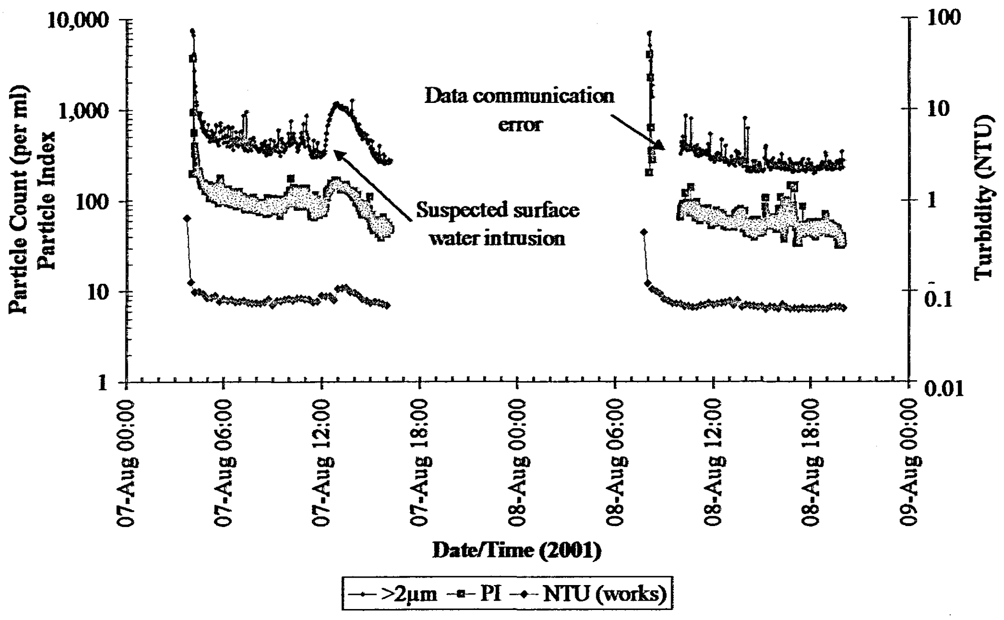


Figure 7.14 *Newmarket WSW: Particle trends 7th-9th August 2001.*

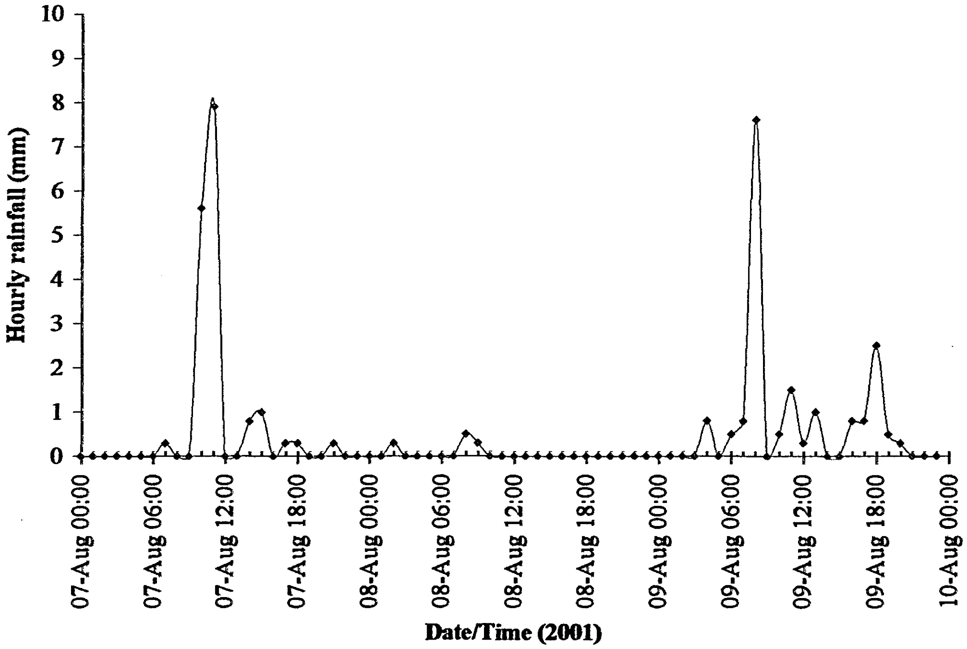


Figure 7.15 *Newmarket WSW: Rainfall 7th-9th August 2001.*

7.8.2 Monitoring problems

During the Feb/Mar 2000 survey, the particle index monitor gave readings that did not correspond at all with the other two monitors. On returning the monitor to the manufactures it was discovered that the instrument's diode was defective. More credible particle index data was obtained in the August 2001 survey after the diode had been replaced and the monitor recalibrated.

Another problem experienced was that whereas the 1998 monitoring was done on final (chlorinated) water, later monitoring was performed on an individual borehole sample tapped close to the point where the water emerged from the ground. Particle trends obtained in this later work contained a significant degree of noise. The exact cause of this noise is unclear, although it is believed that the monitors were affected by the intermittent degassing of carbon dioxide. This is despite all the monitors' being preceded by constant head weirs (Section 4.1.2 and 4.2.1), which serve as debubblers.

Such noise was not seen in Arundel or Burpham monitoring. This is presumably due to the fact that sample was sampled downstream from the point of abstraction, thus giving the water more time to degas. In the case of Arundel, the sample was taken post-chlorination and at Burpham the sample was taken immediately pre- and post-microfiltration. However, a high degree of noise was seen in particle monitor trends taken from another chalk borehole at Otterbourne WSW (not detailed here) where a similar sampling set-up to the later Newmarket monitoring was used. In this instance the sample was drawn from a tap located within metres of the point of abstraction (Figure 7.16). Although the noise is undesirable and perhaps shows the need for care when selecting a groundwater sampling location, ultimately it does not detract from the real aim of the work: the effects of surface water intrusion were still visible (Figure 7.14 and 7.15).

A final problem encountered in the Newmarket monitoring concerns the ABB turbidimeter used on the mobile rig. During the 2001 survey, the turbidimeter appeared gave wildly high readings, in contrast to previous studies. It was therefore assumed that the turbidimeter had developed a fault and was sent back for servicing.

Fortunately, by this time, a Hach 1720C turbidimeter installed at the works had been linked to telemetry and so was used as a replacement.

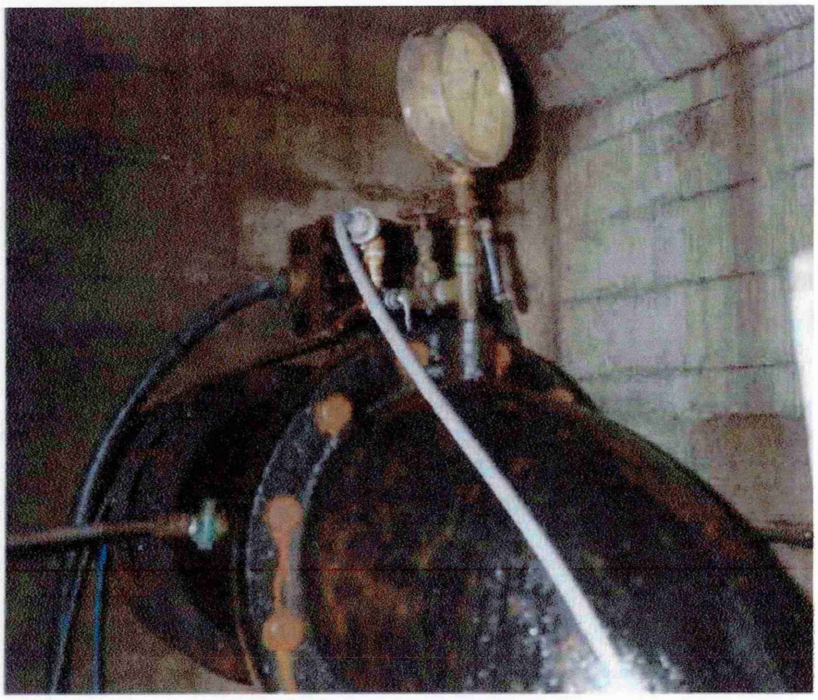


Figure 7.16 *Otterbourne WSW: Sampling point*

7.9 DISCUSSION

7.9.1 What do particle counters show

As discussed, particle counters can be useful in three ways: (a) their higher sensitivity at low turbidity, (b) their higher sensitivity to larger particle sizes, and (c) their particle sizing ability.

It is apparent from the works studied here that in terms of sensitivity, there are negligible advantages to be gained from installing particle counters on high turbidity groundwater sources such as Arundel and Burpham. At lower turbidity groundwater sites such as Newmarket 1C, some additional sensitivity is seen although whether this justifies permanent installation of counters is still highly questionable. This is because even relatively small changes in particle counts seen during suspected surface water intrusion were also picked up by turbidimeters (Figure 7.14).

In terms of their particle size distribution, particles were seen universally to adhere to the inverse power size distribution (Section 5.1). A 'typical' balance between small and large particles was observed in all groundwater (unfiltered) samples (a generally lying in the range -0.5 to 0.5). In no instance, was a predominance of larger particle sizes seen that would be best monitored by light obscuration particle counters. Although particle size data provided some interesting information (mostly in relation to the performance of the particle counters themselves), in most cases, what few changes were seen appeared to be of little operational interest. It is therefore assumed that little would be gained from the long-term monitoring of particle size distribution.

7.9.2 What monitors to use

In Section 6.7.1, it was suggested that particle counters were mainly useful as an occasional optimisation tool. At surface water treatment works, there are many controllable factors that affect treated water quality. Bellamy *et al.* (1993) compiled a comprehensive list of these, which includes raw water type, coagulant type, dose and mixing speed, etc. However, as far as groundwater abstraction is concerned, there are less controllable factors, less scope for process optimisation and therefore a reduced role for particle counters.

Abstracted groundwaters are typically of very high quality. So long as each works complies with routine chemical and microbiological checks laid out in the 1989 Water Supply (Water Quality) Regulations (DoE 1989), they are considered fit for human consumption. Groundwater sites are usually unmanned and operated remotely using RICAS telemetry. Currently turbidimeters have been installed only at around a third of groundwater works. These are shut-down when treated water turbidity exceeds an predetermined internal operating value (typically 1 NTU).

In such an operating environment, it is highly unlikely that particle counting, a fine-tuning tool, will be beneficial.

If a company wishes use particle monitors to reduce *Cryptosporidium* risk at its works, then the most obvious step would be to embark upon a programme of turbidity reduction at those thought to be of significant risk. Another way forward would be to reduce groundwater abstraction during periods of high turbidity although this is not always straightforward because of water supply constraints. A more drastic solution would be to install an additional level of treatment (e.g. membrane filtration). As discussed in Section 7.9.1, there could be some limited reward in using these to monitor very low turbidity groundwaters such as Newmarket 1C. They could be used, for example, to detect subtle levels of surface water intrusion following rainfall. This would only be sensible, however, if and only if this source still carried a significant *Cryptosporidium* (or other microbial) risk. However, for such works, the installation of a microfiltration or an ultra-violet light irradiation plant might be a more sensible way forward.

Arguably, the most successful use of particle counters in this chapter, was the use of particle removal percentages to optimise the microfilter run-time at Burpham. This is not strictly a 'groundwater' application since the benefits mainly accrue from monitoring the very low turbidity microfilter effluent. This is in accordance with observations made using the sensitivity model (Section 5.3). The use of particle removals in this way was an unexpected success and shows that there can be value in using particle counters on microfiltration (or similar) plants. It is not known whether the continuous monitoring of particle removal across more conventional filter plants at surface water sites would be a valuable exercise. This has not been studied here. Even at Burpham, it could be argued that particle counters need only to be installed temporarily at the works i.e. whilst the plant is being optimised. Their value as a process monitor in the longer-term is less clear.

On balance, microfiltration plants notwithstanding, the role of particle counters at groundwater treatment works would appear to be extremely limited. From the works studied here, it would seem that they would only be useful in monitoring a source which (a) has very low turbidity (<0.1 NTU) and (b) very high *Cryptosporidium* risk.

7.9.3 What parameters to use

Data taken from all three groundwater works show that particles (detected by the counters) adhere to the inverse power distribution between number and size. Where particle counters are being used, it is recommended that attention be given only to two main parameters: (a) a particle count parameter such as the total count (>2µm), (b) a particle size parameter such as β or the >10µm particle size ratio. As with the surface water works studies (Section 6.6.4), it is recommended that particle count and turbidity data be compared using the sensitivity model.

Because of the perceived, limited role for particle counters at groundwater works, a detailed study of these and other parameters (such as the particle count differential) has not been conducted here. A comprehensive study of these has already been provided in Chapter 6.

The monitoring at Burpham WSW (Section 7.7.1) suggests that there may be some benefits in continuously for particle removal across certain processes. Here this deterioration in performance towards the end of filter runs. When using particle removals as an absolute performance measure (rather than just a trend facility) it is important to consider any changes that might occur in particle size distribution across the filter. For example, the >2µm removal data presented in Figure 7.11 underestimates plant performance since the filters also effect a reduction in mean particle size (Figure 7.10). When assessing plant performance using a removal percentage, it would seem necessary to make some representation of particle size distribution (e.g. using β or the >10µm ratio) in the inlet and outlet water.

7.9.4 How often to monitor

At groundwater sites, the main function of any particle monitor would be detect surface water influence. This typically lasts for hours and so a relatively large interval (e.g. 15 minutes) would be sufficient ample to detect any significant change. Ideally a shorter period (e.g. 1,2 or 5 minute intervals) is preferred as it will (a) provide greater trend definition and (b) detect levels of noise as seen, for example in the later Newmarket studies (Section 7.8.2).

Again, because of the perceived limited role for particle counter on groundwater works, this subject has not been analysed in great detail here, having also been discussed in some detail previously (Chapter 6).

7.9.5 Other practical considerations

Problems thought to be caused by sample degassing (Section 7.8.2.1) suggest that care should be taken when installing particle counters. These problems were encountered despite the installation of debubbling devices. It would appear that particle counters monitoring groundwater should ideally be installed as far downstream as possible from the point of abstraction.

7.10 SUMMARY

On balance, although this study has shown that particle counters can be a useful research tool, especially at very low turbidity (less than 0.1 NTU), the author does not believe the permanent installation of particle counters at groundwater sites would yield significant benefits to process monitoring.

Although not strictly a groundwater issue, where microfiltration plants have been installed, there may be benefits in continuously monitoring for particle removal across this process.

Chapter 8: SLUDGE TREATMENT STUDIES

8.1 INTRODUCTION

The recycling of contaminated washwater to the head of a treatment works is thought to be at least partially responsible for several high profile outbreaks of cryptosporidiosis. These include the 1989 outbreak in Swindon and Oxfordshire (Lisle and Rose 1995) and the 1993 outbreak in Milwaukee (Solo-Gabriele and Neumister 1996).

It is clear from published data that used filter washwater often contains many times more particles than works influent water. Particles counted in the recycle streams at one works cited in Burris *et al.* 1998 were measured at 47,000 per ml (in the *Cryptosporidium* oocyst size range). This compared to only 1,700 per ml counted in the works raw water. Oocysts measurements also show a similar discrepancy (Table 8.1).

Table 8.1 *Cryptosporidium concentrations given in Burris et al. (1998).*

		Cryptosporidium (oocysts l^{-1})		
		Plant raw water	Used filter w/water	Clarified sludge
Burris *et al.* (1998)	Works A	0.06-1.4	8-9	n/a
	Works B	0.2	165	26
Cornwell and Lee (1994)	Works C	0.05-3*	>150*	n/a
	Works D		8-14*	n/a

* Cryptosporidium and Giardia cyst concentration combined

In a survey of treatment works in the US (Pedersen and Calhoun 1995; cited in Burris *et al.* 1998), only 27% of those that recycled filter backwash water, treated the recycle stream). In a more recent survey reported in Hamele and Bonner (1998) this proportion had increased to 45%, although 87% of these employed only a simple sedimentation or coagulant-aided sedimentation system to treat the water. In pilot-scale oocyst seeding trials, Scott *et al.* (1997) found that a coagulant-aided sedimentation system only removed 0-0.98 log (i.e. less than 90%) of oocysts. Comparing this with figures given in Table 8.1, it is apparent that this may still have led to very large numbers of oocysts being recycled back to the head of the works.

In the UK, the 1995 Badenoch report recommended that *'The supernatant, if recycled, should be treated by specialised filtration techniques or disinfection.* (As the Report points out, the latter option is probably inappropriate because of the formation of disinfection byproducts). In the US, the recent Filter Backwash Rule (EPA, 2001) stipulates only that recycled filter backwash water (or clarifier sludge) must be returned to a location such that all processes of a plant's conventional treatment processes (coagulation, clarification, filtration) are employed.

At Southern Water washwater recycle plants incorporating microfiltration have been built at four treatment works: Beauport, Brede, Burham and Hardham. Only two of these plants, those at Beauport and Burham, were in operation during this study. None of the four supply works are thought to be of highest risk status as far as *Cryptosporidium* is concerned (Chapter 9).

Because the practice of washwater recycling can be a significant source of *Cryptosporidium* risk, a programme of particle monitoring was conducted to evaluate the two operating washwater recycle plants. As with previous chapters, the study also aimed to determine possible future uses of particle monitors at these works and to investigate practical concerns such as where to locate particle counters and what size ranges to use etc.

8.2 METHODS

8.2.1 Works descriptions - Burham

Water is abstracted from the River Medway via a surface water storage reservoir (Eccles Lake). At the time of the study, the water was dosed with ozone, chlorine, aluminium sulphate and a cationic polyelectrolyte (CIBA LT27), before subsequent clarification and rapid gravity filtration (Figure 8.1).

Washwater and clarifier sludge is collected and undergoes further clarification and microfiltration before being pumped back to the head of the works. In normal conditions, the clarifiers discharge a dilute sludge stream with a suspended solids content typically between 100mg/l and 2,000mg/l on a continuous basis and at a rate of up to 3.5 Ml/d. This stream falls by gravity to the clarifier sludge holding tank. In addition, the rapid gravity filters, which backwash automatically several times a day, create a periodic flow of backwash water equivalent to a maximum of 3.5 Ml/d with suspended solids content typically between 50mg and 500mg/l. This second dilute sludge falls by gravity to the RGF backwash water holding tank.

Flows from the clarifier sludge tank and the RGF tank are pumped to the spiral separators. Two Polymetron TXPRO2 suspended solids (SS) monitors (fitted with RD200 Series probes), marketed by Dr. Lange Ltd., have been installed on each separator inlet. These provide a nephelometric particle measurement similar to turbidity. At the time of the monitoring, polyelectrolyte (CIBA LT27) was dosed into the separator inlets at a concentration between 1.0 mg l^{-1} (at 300 mg l^{-1} SS) and 2.0 mg l^{-1} (at and above 1500 mg l^{-1} SS). This was added to compensate for the short residence time of water within the spiral separators.

The sludge from the separators is pumped to three 90m^3 holding tanks to await being tankered offsite. Supernatant from the separators flows into the supernatant holding tank, which provides a buffer between the separators, and the microfilter feed pump. If the supernatant turbidity from the spiral separators exceeds the maximum level suitable for filtration by the microfilters (currently set at 100 NTU) for a set period of time, then the microfiltration operation ceases and the supernatant tank is allowed to overflow directly to the lagoon.

Water from the supernatant holding tank is pumped to the Kalsep Fibrotex filter plant. This consists of four AX300 filter units (labelled A-D). The microfilters are designed to process between 2 and 7 Ml/d of supernatant. Each unit consists of six Fibrotex filter elements within sealed vessels. Each AX300 unit backwashes (with chlorinated potable water) in sequence (with a minimum duration of 75 minutes between backwashes) or may jump the sequence if the differential pressure setting is exceeded, i.e. the unit becomes clogged. On completion of its backwash, the element starts its rinse cycle. The rinse water passes through the drain pipeline and flows to the wastewater holding tank along which overflows into the lagoon.

8.2.2 Particle monitoring - Burham

Two PMS Liquilaz E20 particle counters were installed to monitor a Kalsep feed and effluent from Filter unit A as shown in Figure 8.1. Additional data was taken from the works' computer archive. This included separator suspended solids measurements and inlet flows, filter flows, differential pressures and pre- and post-Kalsep turbidities (Hach 1720C).

8.2.3 Monitoring problems

The Liquilaz E20 particle counter is a relatively old model and has a narrow aperture (0.5 x 1.0mm) through which the sample has to pass. After the particle counter had been running for a few hours, it was noted that the flow through the monitor began to drop off as the aperture became blocked. This is further discussed in Section 4.2.1. Only data that could verified through continuous on-site flow checks has therefore been presented.

Although Kalsep feed and filtered particle counts fall well within the 10% coincidence limit of 12,000 total counts per ml specified by the instrument manufacturers, it is possible that some degree of coincidence error may also have arisen from the high proportion of larger particles (>10μm) in the samples.

Figure 8.1

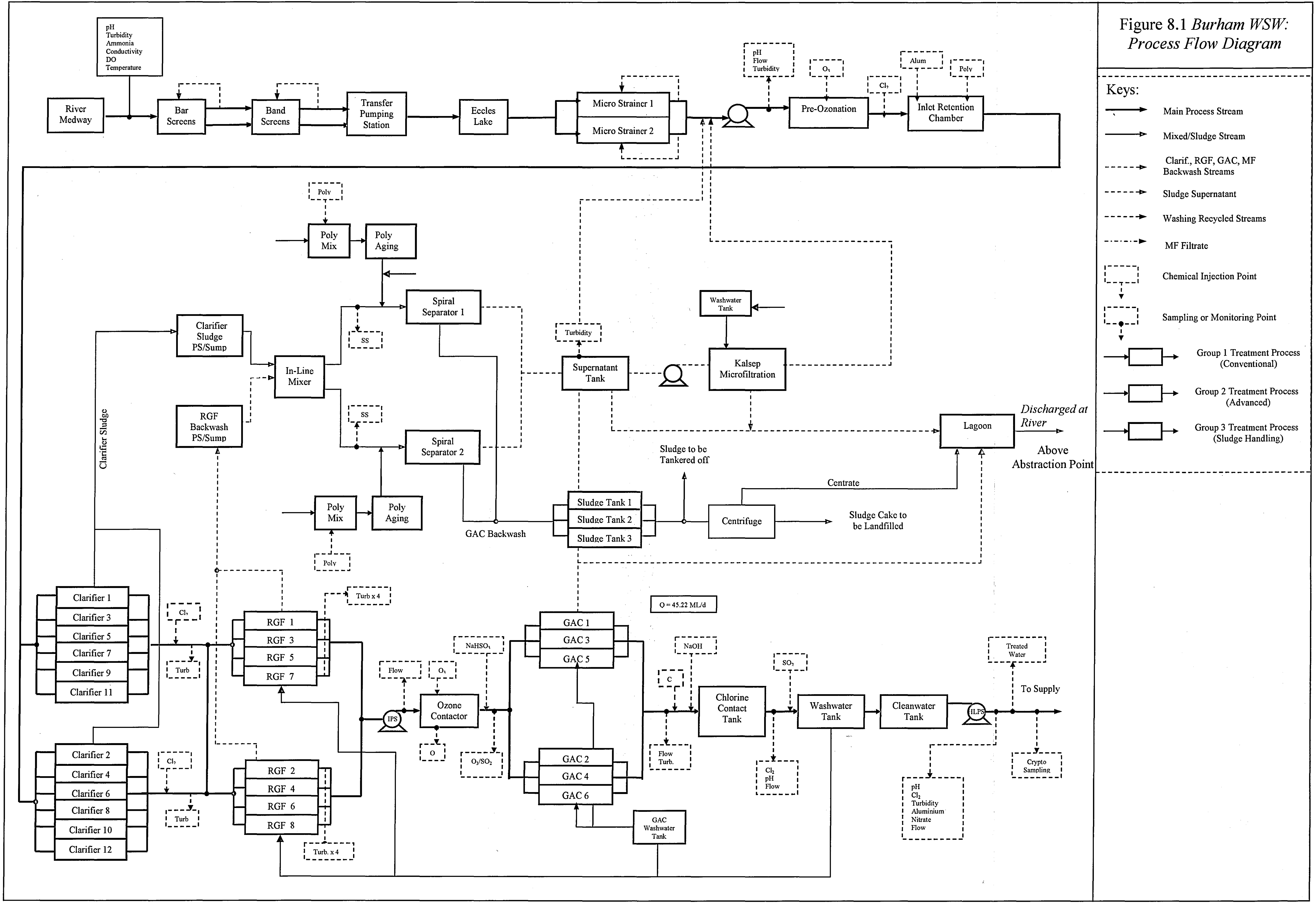


Figure 8.1 *Burham WSW: Process Flow Diagram*

8.2.4 Works description - Beauport

At Beauport, up to 28 Ml/d of water is abstracted pumped from Darwell raw water storage reservoir. At the time of the study, ferric chloride was added as coagulant together with a polyelectrolyte (CIBA Nalco 71471). This water then passes into one of four superpulsator clarifiers. The clarified water is prechlorinated before passing through one of six rapid gravity filters. A more detailed schematic of the works is presented in Figure 8.2.

The washwater plant at Beauport is designed to treat 1.5 Ml/d of used RGF washwater. Recovered backwash liquors collect in two mixing chambers before being pumped via fixed speed submersible pumps to a 7.6m diameter flat-bottomed clarifier. The supernatant then gravitates to a 10m^3 buffer tank before being pumped to a Kalsep filtration unit. This single unit (AX200) comprises four separate wound fibre, "Fibrotex" elements. This unit is backwashed (with post-Kalsep water) on exceeded filter run-time (1 hour).

The microfiltration plant is commissioned to treat feed water between 5-35 NTU turbidity. In the works' site manual, Kalsep effluent turbidity is expected to be around 4 NTU. Unlike the Burham washwater plant, no polyelectrolyte is added to the washwater prior to clarification. In addition the sludge from the main plant clarifier is not recycled, but is pumped to waste, as is settled sludge from the washwater treatment plant clarifier.

8.2.5 Particle monitoring - Beauport

Particle monitoring at Beauport was carried out using the portable mobile rig described in Section 4.1.2. This was connected to either a Kalsep feed or filtrate tap., which sampled across the four elements in the AX200 unit. During Kalsep down-time, remnant water residing in the units and the connected mains was of sufficient volume to supply the particle counters with a continual sample although some settlement was observed in the particle count, presumably due to settlement of particles in the sample mains.

In addition, data from other on-line instruments was logged manually. This included clarifier inlet flow, supernatant tank level, and Kalsep inlet flow and differential pressure. Two Great Lakes Model 95T turbidimeters had also been installed to monitor pre- and post-Kalsep turbidity. However, these are no longer being maintained as the works' operators found them to be excessively prone to blocking. The turbidity data presented was taken solely from the ABB 7997/202 turbidimeter, installed on the mobile rig.

8.2.6 Monitoring problems

None of the three monitors on the rig showed any significant blockage problems. However, the counting of particles in the Kalsep feed and filtrate was seriously compromised by coincidence error. Particle counts frequently exceeded 12,000 counts per ml, the 10% coincidence limit, specified by the manufacturers.

A latex bead experiment performed to confirm coincidence error was presented in Evans (1997) and in Hamilton *et al.* (2000). This yielded a formula for estimating the degree of coincidence error associated with particle counting. Although the experiment was carried out on a PMS Liquilaz E20 counter, it is assumed that this result is similar to the Met-One used here. This is because both monitors are light obscuration sensors and have identical 10% coincidence error limits.

$$\textit{Coincidence error}\ (\%) = 2.190 \times 10^{-3} \times \textit{particle count}\ (>2\mu m) - 15.8 \quad \text{(Eq. 8.1)}$$

At Beauport, filtrate particle counts were measured at around 16,000 per ml (>2μm). Using Equation 8.1, this suggests that this measurement is subject to a coincidence error of around 20%, i.e. the actual count would be somewhere in the region of 19,000-20,000 counts per ml. Care must be taken when using particle size statistics (e.g. β, >10μm particle ratio) or removal percentages as these are also likely to be affected by coincidence error. In this case, the number of small particles (2-5μm) will be underestimated and the number of larger particles overestimated as the sensor fails to distinguish between the smallest particles.

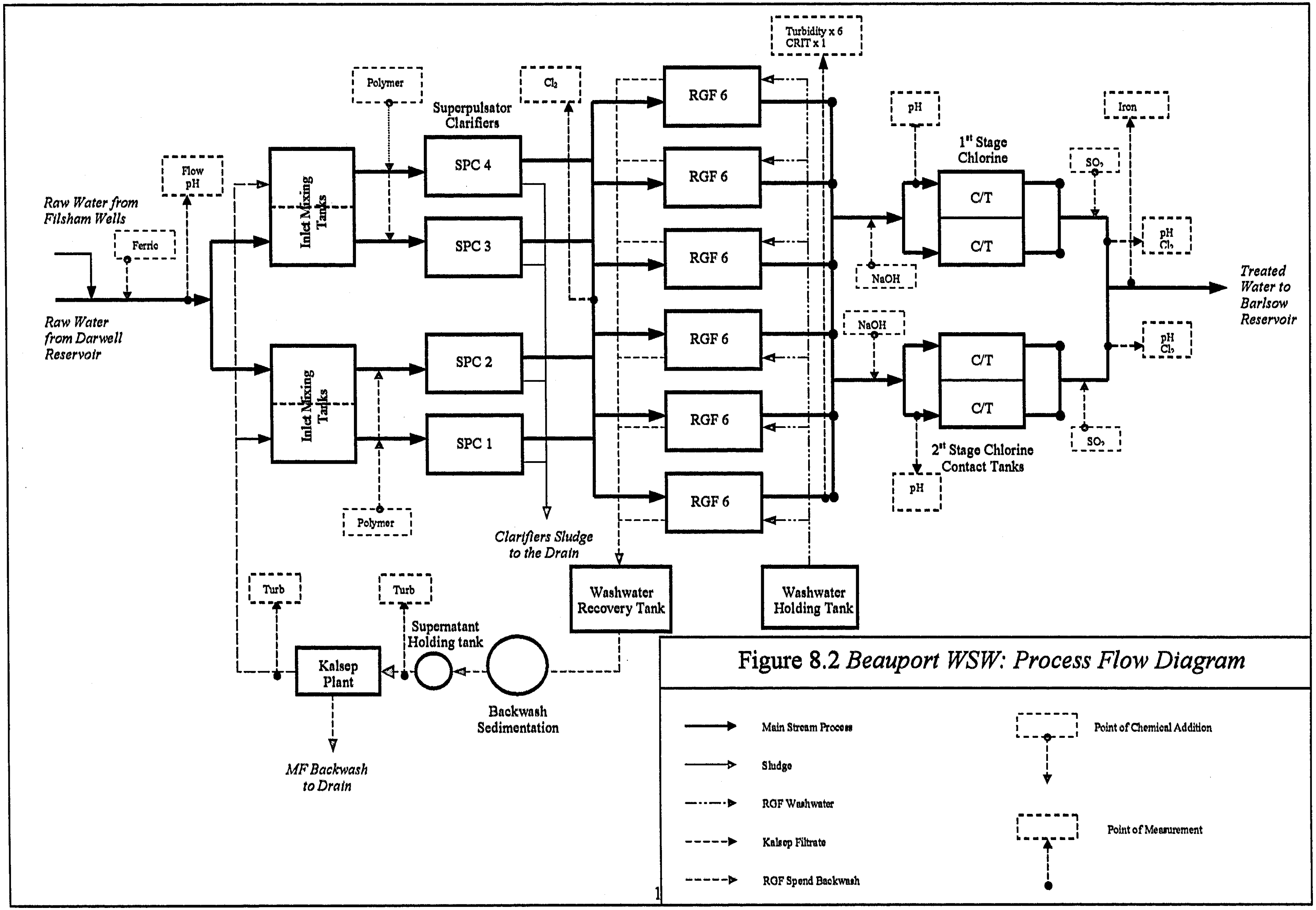


Figure 8.2 *Beauport WSW: Process Flow Diagram*

8.3 BURHAM - RESULTS

8.3.1 What the particle counters show

Although data was collected intermittently for a period of three weeks, only data from two days' monitoring has been presented here to demonstrate the main findings of the work.

8.3.1.1 *Particle monitoring: 1st September, 1999*

Particle count data taken from this day showed large increases in particle counts occurring towards the end of filter runs (Figure 8.3). These increases were seen more clearly in particle counts than in turbidity, despite the relatively high turbidity baseline (around 0.2-0.3 NTU). The sensitivity issue is a highly significant finding within the context of the study. The microfilter feed and filtrate water contained large aluminium floc particles, with the >10μm size range accounting for between 7 and 30% of the total particle count. The large increase in particle counts seen was consistent with the particle monitor sensitivity model (Section 5.3). The dip in turbidity and particle counts seen at the start of each filter run (Figure 8.3) are thought to be caused by a remnant of filter rinse water residing in the filter and adjoining mains.

In terms of particle removal (Figure 8.4), the performance of the Kalsep plant was generally satisfactory although removal percentages did fall from above 90% to 70% by the end of the filter runs. Performance also suffered when there was a sudden increase in feed particle count seen at 14:30 (from around 4,000 to 10,000 per ml) whereupon particle removal fell to around 30%. This suggests that the Kalsep microfilters respond poorly to a sudden increase in inlet turbidity. The increase coincided with a step-increase in flow through the separator inlet (from 4.0 to 6.5 Ml/d) caused by the backwashing of main plant rapid gravity filters.

Despite the samples' containing an unusual size distribution of particles, little change was seen in this distribution as shown by the relatively flat >10µm ratio trend-line (Figure 8.3). This suggests that although particle size distribution has an important effect on monitor sensitivity, it may not be so interesting as an on-going concern.

Finally, on another occasion (not shown), the Kalseps feed water turbidity increased above 100 NTU causing the recycling plant to shut-down (i.e. the separators were run to waste). However, this was not before a substantial deterioration was seen in the number of particles passed by the filter (from around 40 to 850 counts per ml). Correspondingly, particle removal rates fell from 97 to 44 %). This deterioration lasted for approximately 20 minutes before the plant's inlet was diverted to waste.

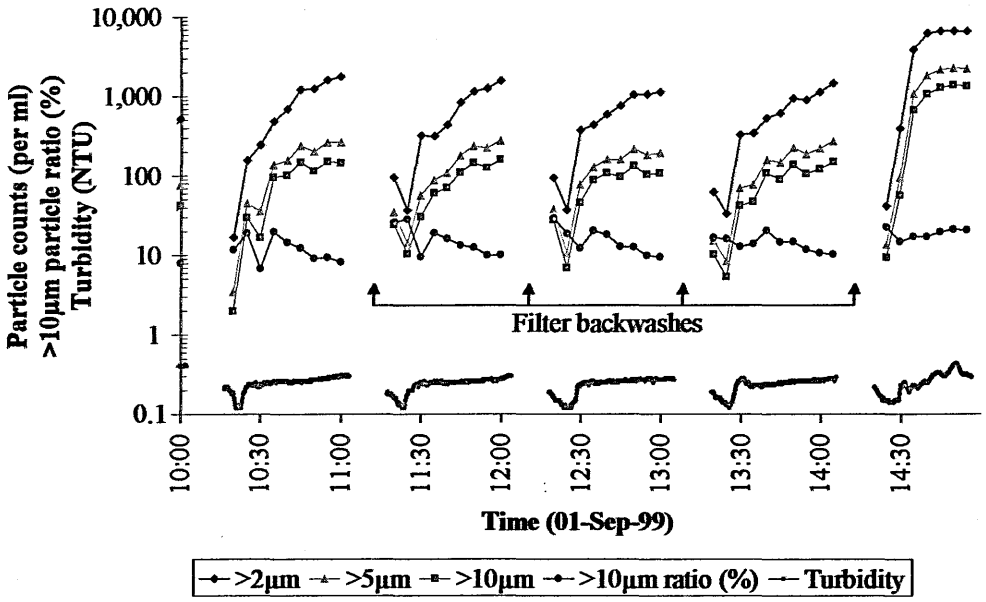


Figure 8.3 *Burham WSW: Treated washwater particle trends, 01-Sep-99 (1).*

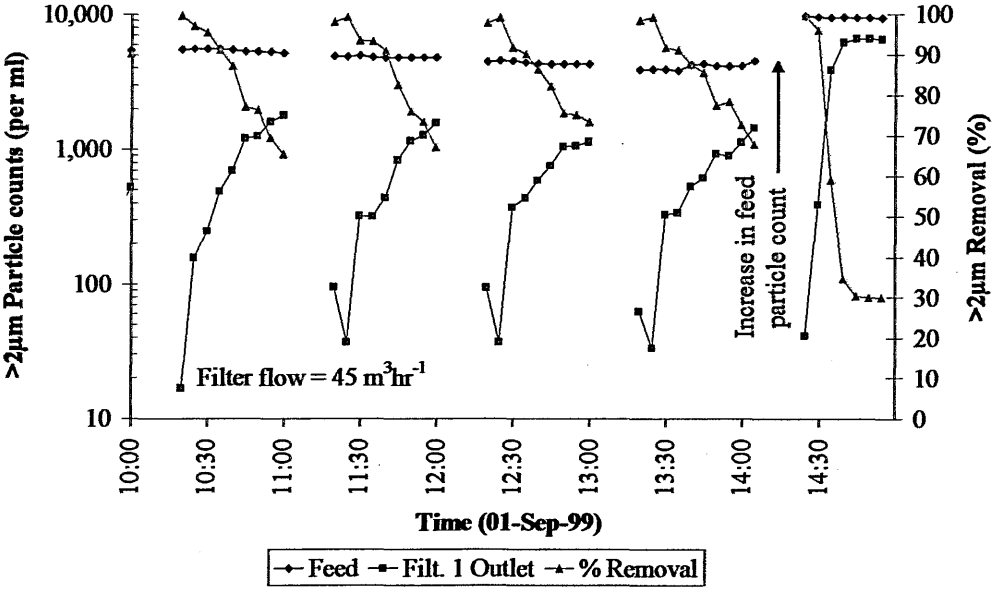


Figure 8.4 *Burham WSW: Treated washwater particle trends, 01-Sep-99 (2).*

8.3.1.2 *Particle monitoring: 20th September, 1999*

In subsequent monitoring filter performance appeared to improve as exemplified by data taken from the 20th September. Again particle counts were seen to increase toward the end of each filter run (Figure 8.5), although the maximum values attained were much lower than in the previous example, less than 300 counts per ml compared to over a thousand. A similar particle size distribution was seen with the >10μm particle ratio lying between 10-20%. As predicted by the sensitivity model, the particle counters again registered these changes in particle count more sensitively.

The improvement in Kalsep performance is shown by the particle removal trend (Figure 8.6), which did not fall below 90% in the four-hour monitoring period. This exact reason for this improvement is unknown. One disappointing result, however, was that the filters were unable to process the 3.5 Ml/d (149 m^3hr^{-1}) that they were designed for. As filter flow rates were increased beyond 50 m^3hr^{-1}, the run-times became critically short because of increasing differential pressure.

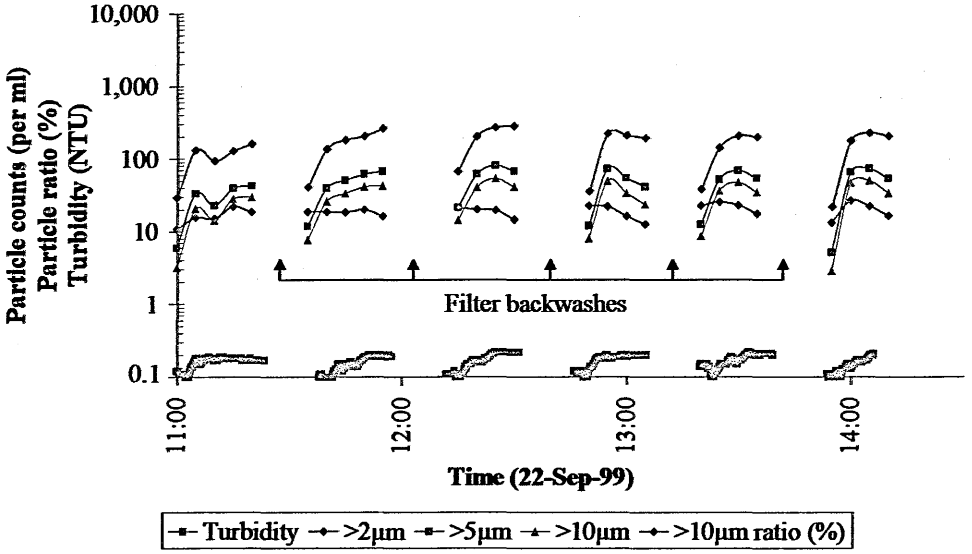


Figure 8.5 *Burham WSW: treated washwater particle trends, 22-Sep-99 (1)*

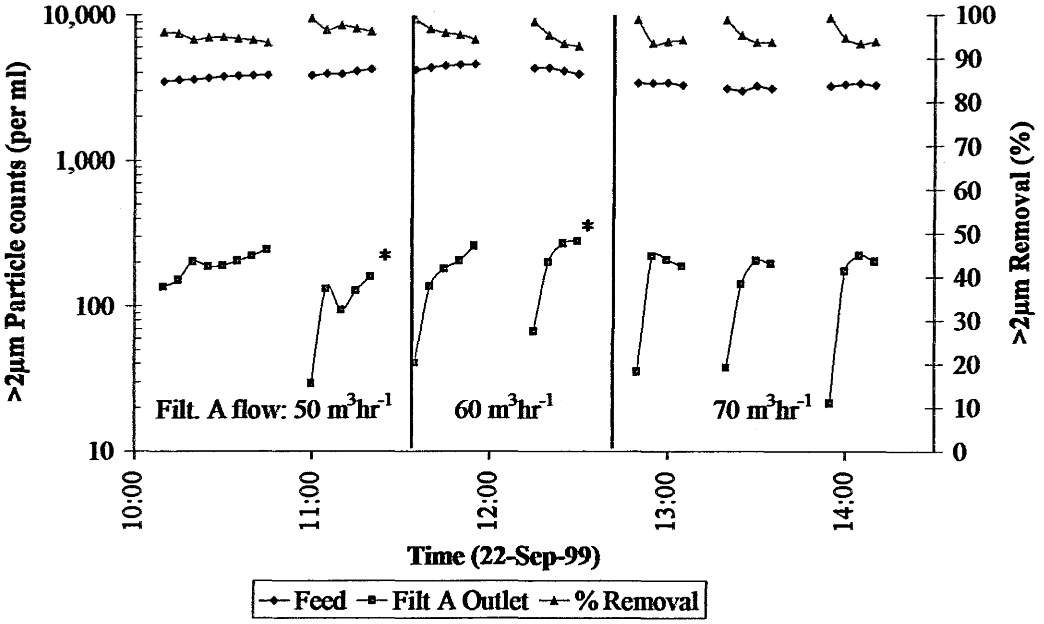


Figure 8.6 *Burham WSW: treated washwater particle trends, 22-Sep-99 (2)*

8.4 RESULTS - BEAUPORT

8.4.1 What the particle counter shows

8.4.1.1 Particle monitoring: 19th October, 1999

After the particle counter had been installed, the particle counter was run briefly on filtrate then feed sample lines to provide an initial performance assessment of the works. The particle counter quickly stabilised to provide the readings shown in Figure 8.7.

The numbers of particles counted were very high, around 18,500 and 11,000-14,500 counts per ml in the Kalsep feed and filtrate respectively. As far as the feed sample is concerned, this was well in excess of the 10% coincidence limit (12,000 counts per ml). Without sample dilution, therefore, these measurements were likely to be highly inaccurate both in terms of total count and size distribution. For the filtrate sample, only those falling below the 100% coincidence limit were thought to be of sufficient accuracy.

All three particle monitor trends were relatively flat (although some longer-term changes may have occurred). Because of the likelihood of coincidence error in the highest filtered particle counts, it has not been possible to analyse the relative sensitivity of the monitors. Considering (a) the filtrate sample's particle size distribution ($a \approx 0.8$), observed when the particle count was less than 12,000 counts per ml, and (b) the baseline turbidity (2.9 NTU), the sensitivity model predicts that the particle counter would have only four-fifths the sensitivity than the turbidimeter in detecting changes. There would therefore appear to be little benefit to be gained in using particle counters on this plant from a sensitivity point of view.

8.4.1.2 Particle monitoring: 23th March, 2000

The readings previously described were taken shortly before the plant was shut down in order to make repairs to the stirring mechanisms in the settlement tank. Monitoring recommenced in March after the plant had been reinstated. On this occasion a comprehensive record of works on-line data was kept so that a more meaningful could be made of particle monitor data in relation to filter running.

This time, the particle counts readings were even higher than in the previous monitoring (>16,000 counts per ml in feed: >14,500 in filtrate). It is therefore virtually impossible to make any serious observations based on this data. Only turbidity trends would appear to be accurate.

It is also difficult to derive any accurate information from the >10μm particle ratio trend shown (Figure 8.8). With the high level of coincidence error, the number of smaller particles will be underestimated. As a result, any further increase in particle counts will be seen more clearly the in larger particles, giving a higher *a* value even though no real shift in particle size distribution has occurred. Despite questions over the accuracy of the data, particles nevertheless appeared to adhere to the inverse power size distribution detailed previously (Section 5.1).

8.4.2 Other points of interest

Although the samples contained a relatively large number of particles, the particle counter used at Beauport did not appear to block during monitoring, although its sensor was routinely cleaned as a precaution (Section 4.2.2). The aperture of the Met-One PCX is wider than the PMS Liquilaz E20 counter: 0.75 x 0.75mm compared to 0.5 x 1.0mm.

On many occasions during the monitoring period, flow through the filters ceased periodically (indicated in Figure 8.7-8.9). The exact reason for this became clear in the March monitoring, described below. The Kalsep plant has been set-up to operate when the level lies between 20-30% and thus is prone to continual stop/starts. This appeared to have a negative impact on water quality since more particles are passed by the filters when restarted).

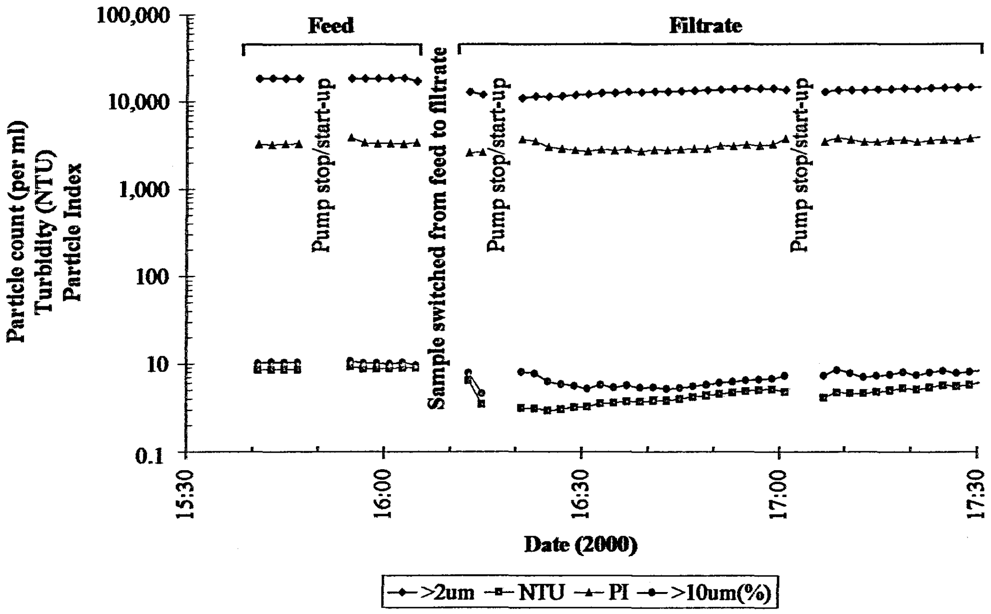


Figure 8.7 *Beauport WSW: Pre- and post-Kalsep particle counts 19th October, 2000.*

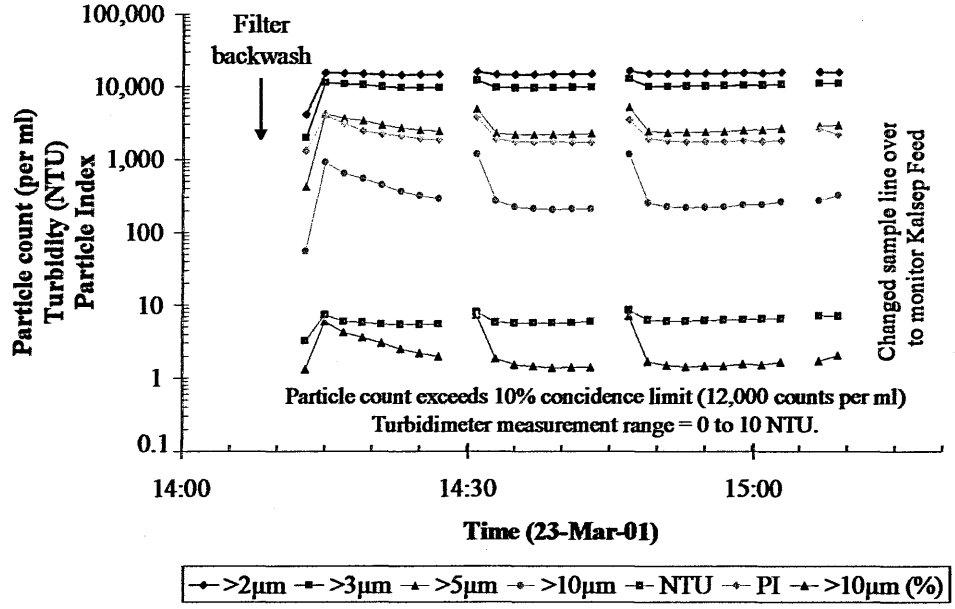


Figure 8.8 *Beauport WSW: Pre and post-Kalsep particle trends, 23rd March 2001.*

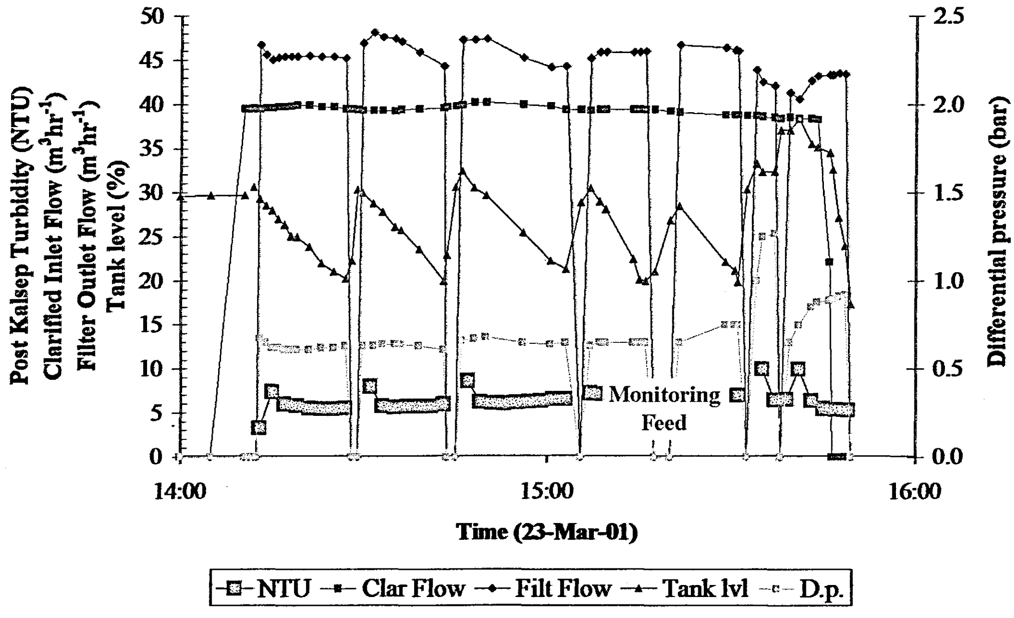


Figure 8.9 *Beauport WSW: Other on-line data, 23rd March 2001.*
(Data excluded when mobile rig was switched to monitored Kalsep Feed water, 15:05 – 15:30)

8.5 DISCUSSION

8.5.1 What the particle counters show

8.5.1.1 More sensitive at lower turbidity / More sensitive to larger particles

The link between particle size and monitor sensitivity has already been demonstrated (Section 5.3). At Burham WSW, the Kalsep feed and filtrate sample contained an abnormally high proportion of large particles (a>1). Despite the sample's having a relatively high turbidity, particle counters were more able to detect the deterioration in particle counts seen at the end of a filter run.

This increase appears to be some form of particle breakthrough. This was reviewed in Section 2.6.2. Generally, there appears to be two types of filter 'breakthrough'. In the first of these, a change in particle counts is seen hours ahead of a change in turbidity as demonstrated by Kavanaugh *et al.* 1980, Keay 1995, Murray 1995 and Saunders *et al.* 1999. This breakthrough occurs first for large particles (>1µm) as shown in bead suspension experiments (Mackie and Bai 1993, Clark *et al.* 1992, Moran D.C. *et al.* 1993, Moran M.C. *et al.* 1993). In this context, 'filter breakthrough' is likely to be caused by 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). Ginn *et al.* argued that increases in particle sizes through the filter can be attributed almost entirely to these detachment mechanisms.

In other studies (Lewis and Manz 1991, Pizzi and Rodgers 1998 and Hall and Croll 1997), 'breakthrough' was seen to occur simultaneously in turbidity and particle counts. In Section 2.6.2, it was speculated that this type of breakthrough might relate more to the passing through the filter of particles in the influent water, rather than detached particles.

This latter type of breakthrough is what is believed to have been seen in the Burham monitoring. It is interesting that no change in particle size distribution was seen at Burham during this time. This is further evidence against the particle detachment theory.

The work shows that particle counters are not only more sensitive where there is a shift increase in particle size (e.g. particle detachment), but also where the particle size distribution is consistently biased towards larger particles. Just how many sludges share such a particle size distribution is unclear. At Beauport WSW, for example, there appears to be a more even particle size distribution ($a \approx 0.8$, Table 8.2); putting this into the model defined previously (Section 5.3.3) (Table 8.2), particle counters appear to have only four-fifths of the sensitivity of turbidimeters around the 3 NTU mark. Kavanaugh *et al.* (1980) presented relatively high β values of 4.2 for a digested sludge and 3.3 for an activated sludge, which suggests that the size distribution seen at Burham ($\beta \approx 0.5$-2.5) is relatively uncommon. Only a very rough comparison can really be made between the Kavanaugh *et al.* values and the Burham and Beauport data since different size channels have been used to calculate β (Section 5.2.3).

Because of the unusual particle size distribution of the sample, the plant makes an ideal site to test the sensitivity of new particle monitors. It would be interesting, for example, to see how a particle index monitor would respond to the changes in particle numbers.

8.5.1.2 The value of particle sizing

Although particle sizing has been discussed in the previous section, this was to show only how particle counts and turbidity responded to changes in particle numbers. In fact the particle size distribution of sample need not be known to take advantage of particle counter's high sensitivity. This could be accrued from a single-channel particle counter.

In Chapters 2, 7 and 8, relatively little information has been gained from monitoring a sample's particle size distribution, especially as an on-going concern. Arguably its greatest use in this study has been in investigating particle monitor sensitivity (Chapter 5, Section 8.5.1.1). The monitoring of particle size at Burham, however, perhaps provided some of the most interesting information on particle size seen in the whole three-year study. This is best illustrated using the following comparison of Burham and Beauport particle size data (Table 8.2). This data has been selected to compare the size distributions of particles in the two recycled sludges. It is not intended to be a strict comparison of the two Kalsep plants, since other factors would obviously need to be taken into consideration such as filter throughput and run-time etc.

Table 8.2 *Samples taken from the two washwater recycling processes.*

Works Sample Date/Time	**Burham** 01-Sep-00 14:50	**Beauport** 19-10-00 16:00
Main plant coagulant	Alum	Ferric chloride
Sludge treated	Clarifier sludge and Filter washwater	Filter washwater only
Polyelectrolyte added?	Yes	No
Clarifier	Lamellar	Settle Tank
Microfilter	Kalsep AX200	Kalsep AX200
Pre Kalsep turbidity (NTU)	10	8.8
Post Kalsep turbidity (NTU)	0.38	2.9
Pre Kalsep particle index	n/m	3411
Post Kalsep particle index	n/m	3030
Post Kalsep >2μm per ml	6,568	11,391
Post Kalsep >5μm per ml	2,262	3,054
Post Kalsep >10μm per ml	1,374	716
Post Kalsep >10μm % of total	20.9 (a=1.3)	6.3 (a=0.80)
Post Kalsep particle vol. (μm^3 per ml)*	2.62×10^6	1.78×10^6

*estimated

On inspecting the turbidities (0.38 NTU Burham and 2.9 NTU Beauport) and total particle counts (6,568 per ml Burham and 11,391 per ml Beauport) leaving the Kalsep microfilters it appears that the Burham recycle plant produces the cleanest recycled effluent. However, by considering the >10μm particle count (1,374 per ml Burham and 716 per ml Beauport) and the estimated particle volumes (2.62 x 10^6 Burham and 1.78 x 10^6 Beauport), the Beauport plant performs better overall. This shows three things:

(a) Particle size distribution can be important consideration when assessing filter performance. Ideally, when looking at plant performance (or setting plant performance criteria) some consideration should be given to particle size (e.g. using the >10μm particle ratio) or particle volume in addition to the total count. This reinforces a point made in Section 7.9.3.

(b) Just because a (sludge) plant produces water with a low turbidity does not necessarily mean that it has a low solids content.

(c) Conversely, when adapting a process' design or operation, an increase in turbidity may be acceptable if a net reduction in particle size can be effected.

Particle size information can also be used to research the two 'problems' seen at Burham, namely (a) the filters' tendency to blind at higher loading rates and (b) the deterioration in filter performance seen toward the end of each run. Darby and Lawler, 1990, in experiments with monomodal latex bead suspensions showed that headloss gain was greater when filtering a suspension of very small (0.6μm) particles compared to a suspension of larger particles (2μm). This has also been corroborated by other authors e.g. Mackie and Bai (1993). This slightly contradicts the findings at Burham where filter blinding occurred with a high proportion of large particles in the influent water. More apposite to the Burham example, perhaps, was the observation made by Hutchinson (1985) who referred to the '*problems of excessive coagulation which forms large visible floc that remains on the filter media surface as opposed to the microscopic floc needed for maximum bed penetration…* '.

One factor, which may have contributed to the unusual particle size distribution at Burham, was the fact that it recycles a mix of filter washwater and clarifier sludge: the

Beauport plant treats filter washwater only. Although it is tempting to link the unusual particle size distribution with the blinding of the filters, other factors may also be pertinent such as the type and amount of polyelectrolyte dosed or the type of particles being treated. In the case of Burham, for example, most of the particles in the sludge are loosely formed aluminium floc particles, which may behave differently to other particles in the filter media.

It is also slightly paradoxical that a filter so prone to blinding should also shown signs of 'breakthrough' towards the end of a run. However, as discussed in Section 2.6.2 and 8.5.1.1, because no increase in particle size distribution was seen during this 'breakthrough', it was not thought to be caused by particle detachment within the filter, but may relate more to a direct reduction in filter efficiency.

All this shows that particle sizing can be a useful diagnostic tool, although the information it provides need to considered against other chemical and physical properties of the sludge being treated. It is recommended that particle size be a focus of any further optimisation studies on the sludge recycling plant at Burham WSW.

8.5.2 What monitors to use

8.5.2.1 Particle counters

This study finds that portable particle counters can be an excellent process evaluation and optimisation tool, which can be used to monitor e.g. when the works is first being commissioned and (b) in any subsequent optimisation work. However, it falls short of recommending that particle counters be permanently installed at all washwater recycling plants. There are three main reasons for this.

Firstly, as shown by the work at Beauport, because of the high concentration of particles in the sample, the readings taken from >2µm light obscuration sensors are frequently impaired by coincidence error. It is possible that the use of a different sensor (e.g. one counting particles in a larger size range) or the use of on-line batch particle counters that dilute the sample, may remedy this problem although this has not been tested here.

Secondly, particle counters are prone to blockage when monitoring sludge samples. It is significant that the operators at Beauport have lost confidence in the turbidimeters installed on the Kalsep feed and filtrate because of their propensity to blocking. It is unlikely that particle counters, which have a vastly narrower aperture, through which this sample has to pass, would fare better in this regard.

Thirdly, particle counters will only be useful if the sludge monitored has a high proportion of larger particles. Work at Beauport WSW revealed a more 'typical' particle size distribution in the sludge. Particle counters responded less sensitively than turbidimeters to changes in particle number at this works.

Because of the unusual particle size distributions seen at the Burham plant, it could be argued that particle counters might be worthy installations at this plant. Indeed, two Hach 1900WPC particle counters (currently marketed as Great Lakes AccuCount+ counters) have been installed to help optimise the process. These was chosen because they employ an in-situ sensor with a wider aperture (1 x 2mm). Unfortunately, the particle counters have shown a tendency to clog, which has restricted their use thus far. With better sampling arrangements, it is hoped the situation might be improved.

8.5.2.2 Turbidimeters

Burham and Beauport WSW are not thought to be of high *Cryptosporidium* risk as shown by previous raw and treated water sampling programmes (not detailed). In addition, no outbreak has ever been linked to backwash recycle plants that employ microfiltration. However, historically, washwater recycling plants (with inferior treatment) have contributed significantly played a part in a number of high profile outbreaks (Section 2.1) and for this reason it would seem appropriate to apply the same level to diligence to recycled washwater treatment as is currently applied to the main plant treatment.

With this in mind, it is desirable that the company installs some working on-line particle monitor as a quality check on these processes. From the study, it appears that in most cases, this is best achieved using nephelometric turbidimeters. The role of particle counters, if there is one, is very much a secondary issue.

8.5.2.3 Other particle monitors

The work at Burham in particular, has shown that there could be a role for a robust, high sensitivity monitor that can analyse samples containing a high proportion of large particles. Several products might already fulfil these criteria such as the particle index monitor, or the various suspended solids monitors on the market but these have not been rigorously tested here. The unusual particle size distribution detected at Burham WSW would make this works an ideal location for testing these and other monitors.

8.5.3 How to use particle monitors

A sensible first step towards *Cryptosporidium* risk minimisation would be to start a programme to reduce the turbidity of recycled sludge. For this, it is crucial that turbidimeters and appropriate telemetry are installed. In Section 8.3.1.1, it was detailed how on one occasion during the particle monitoring study, Kalsep feed turbidity rose above 100 NTU following cleaning of the main plant clarifiers, causing the Kalsep plant to shut-down. In retrospect, it is clear that steps could have been made to isolate the recycling plant during this period so that the sludge discharged in the lagoon. This shows that in many cases extra diligence is required rather than new technology.

Where water is being recycled, ideally as much interest should be given the recycle plant alarms as to those on the main plant. Facilities should be installed to allow treatment operators should to identify these problems as they occur and, where possible, to take steps to minimise turbidity. In the long-term, effort could can be made to reduce plant shut-down limits. For example, from the data collected in this trial, it is believed that plant could and should be shut-down when feed turbidity reaches 50 not 100 NTU. It is also recommended that the feed and filtrate turbidities be continuously checked (e.g. on a weekly basis) to identify any long-term changes in plant performance.

As far as particle counters are concerned, it is recommended that portable instruments be used more as a 'research tool' to evaluate plant performance during commission or during specific process optimisation trials, e.g. during plant upgrading or as part of a dedicated optimisation program.

8.5.4 What size ranges to use

As with previous studies (Chapter 6 and 7), if particle counters are being used, then rather than looking at a broad range of particle counts, it is recommended that monitoring be focused on three main parameters: (a) a single particle count e.g. >2μm, (b) a particle size statistic e.g. a or β, and (c) turbidity. It is also recommended that the sensitivity model be used to compare unusual changes in particle counts and turbidity data.

The study also shows that it is not always possible to compare recycled sludge quality merely in terms of absolute particle counts or NTU since this will depend largely upon the particle size distribution of the sample. The imposition of a generic performance standard e.g. 10 NTU would be fairly meaningless especially where clarifier sludge is being treated, for example.

Two other parameters used here, which may be of interest, are particle volume (estimated from >2μm, >3μm, >5μm and >10μm counts) and particle removal, which has been used to assess filter performance.

8.5.5 How often to measure

This subject has also been examined previously (Chapters 6 and 7). Because of the very short run times seen (sometimes less than 30 minutes), a short sample interval (e.g. every minute) is desirable to provide clear trend definition especially during the first few minutes of the filter run, where there can be a rapid change in particle count (Figures 8.3, 8.5 and 8.8).

8.6 SUMMARY

The author does not believe that the permanent installation of particle counters of particle counter would necessarily yield significant benefits at all washwater/sludge recycling plants, not least because of potential problems with sensor aperture blockage.

However portable instruments can be a useful research tool and are especially useful where the sludge contains a high proportion of very large particles (a>1). This may occur at works where clarifier sludge is being recycled in addition to filter washwater.

Just because a (sludge) plant produces water with a low turbidity does not necessarily mean that it has a low solids content. Conversely, when adapting a process' design or operation, an increase in turbidity may be acceptable if a net reduction in particle size can be effected.

Ideally, when looking at plant performance (or setting plant performance criteria) some consideration should be given to particle size (e.g. using the >10µm particle ratio) or particle volume in addition to the total count.

It is possible that the larger particles (>10µm) may be responsible for some of the other problems seen at the Burham plant e.g. the filter blinding and the reduction in filter performance towards the end of each run.

As far as minimising *Cryptosporidium* risk is concerned, this study recommends that water companies (a) ensure that working turbidimeters are installed to monitor recycled water quality, (b) to apply the same level of diligence to recycled water turbidity as is applied to treated water as and (c) where possible embark upon a programme of turbidity reduction on its recycle plants. The role of particle counters (if any exists) is secondary.

8.6.1 Recommendations for future research

Of all the topics included in this study, arguably the monitoring of sludge particles raises the most possibilities in terms of future research. It would be especially interesting to examine the performance of different particle monitors (particle counters, particle index monitors, turbidimeters, suspended solids monitors etc.) at works such as Burham where there is a large mean particle size. Such work should look at monitor sensitivity and at remedying the problems of sensor blocking and coincidence error. Another facet of the work could be the impact of recycling water on main plant water treatment. This has not been studied here.

It is recommended that any further optimisation of the recycling plant at Burham should look the effects (if any) on Kalsep performance of particle size.

Chapter 9: CRYPTOSPORIDIUM RISK STUDIES

9.1 INTRODUCTION

The subject of *Cryptosporidium* in drinking water was reviewed earlier (Chapter 2). As discussed in Section 2.4, there appears to be strong evidence that, given that oocysts are present in the raw water, then a strong correlation exists between particle removal and oocyst removal across a treatment process. What is less certain is whether a more general link exists between particle and oocyst numbers, such that *Cryptosporidium* risk can be predicted directly or indirectly from particle monitor readings. For example, is a works that typically produces water of low turbidity (<0.1 NTU) less prone to *Cryptosporidium* to than works of higher turbidity? Previous chapters have shown that particle counters are generally best used as a fine-tuning tool below 0.1 NTU. In Section 2.7 it was speculated whether a works that produces water consistently below 0.1 NTU will carry a significant *Cryptosporidium* risk.

Relationships between particle monitors and *Cryptosporidium* oocysts are also of interest to Water Regulators. For example, as previously discussed (Section 2.5.2), to minimise risk in the US attention is given primarily to attaining (a) predicted levels of oocyst removal and (b) absolute levels of treated water turbidity. In particular, amendments to the Surface Water Treatment Rule (EPA 1998) stipulate that 95% of treated water samples taken each month comply with a 0.3 NTU standard. In the UK, however, more importance is attached to reducing anomalies in turbidity trends rather than compliance with an absolute value.

9.2 OBJECTIVES

This chapter comprises two separate studies. The first of these contains an analytical overview of Southern Water *Cryptosporidium* and turbidity data. Detected levels of *Cryptosporidium* are discussed in light of treated water turbidity found at these works. On-line turbidity/particle count trends have also been scrutinised to see if anomalies in turbidity and particle count data coincided with increases in positive *Cryptosporidium* detections.

The second study comprised a series of microbial sample surveys conducted at Newmarket WSW, a groundwater supply works with a perceived *Cryptosporidium* risk. This study focused in on specific deteriorations seen in water quality namely (a) immediately a borehole pump is started and (b) several hours after heavy rainfall. This work attempted to discover more about the type of particle present in water during these deteriorations and to further explore any possible relationship between particle/turbidity increases and *Cryptosporidium* risk.

9.3 STUDY 1: Analysis of *Cryptosporidium* and turbidity data

9.3.1 METHODS

9.3.1.1 *Cryptosporidium* analysis

Daily composite *Cryptosporidium* samples were collected at works deemed to be of high risk in accordance with DWI guidelines outlined in the 1999 Water Supply (Water Quality) (Amendment) Regulations (DWI, 1999). This standard method uses the Genera Technologies Filta-Max^{TM} sampling and elution system. Immuno-magnetic separation is then carried out using Dynal Dynabeads^{TM}.

The detection of *Cryptosporidium* oocysts in water samples is notoriously inefficient, as reviewed in Badenoch 1995, for example. This quoted oocyst recoveries for a previous standard method (filtration-elution-centrifugation) as ranging between 9-59%. Guidelines set out in DWI 1999, suggest that recoveries with the new Filta-Max/Dynabead method should achieve recoveries of 50% or greater with a minimum recovery of 30%. The laboratory's own analytical procedure is routine checked according to Analytical Quality Control (AQC) guidelines provided in DWI 1999. The Filta-Max^{TM} filters are spiked with a known number of *Cryptosporidium* oocysts and then analysed to estimate the percentage of oocysts that are recovered. A summary of the percentage recoveries attained in 2001 is shown in Figure 9.1. A beta distribution model has been fitted to the data. This model has been used because the data is bounded on a closed interval [0%, 100%], which often results in a skewed frequency distribution. In fact, the data in Figure 9.1 is reasonably symmetric around its mean oocyst recovery of 39% with an associated 95% confidence interval of [10%, 76%]. These results compare favourably with the recoveries quoted in Badenoch, 1995, although admittedly only 69% of the data complies with the 30% recovery target suggested down by the DWI.

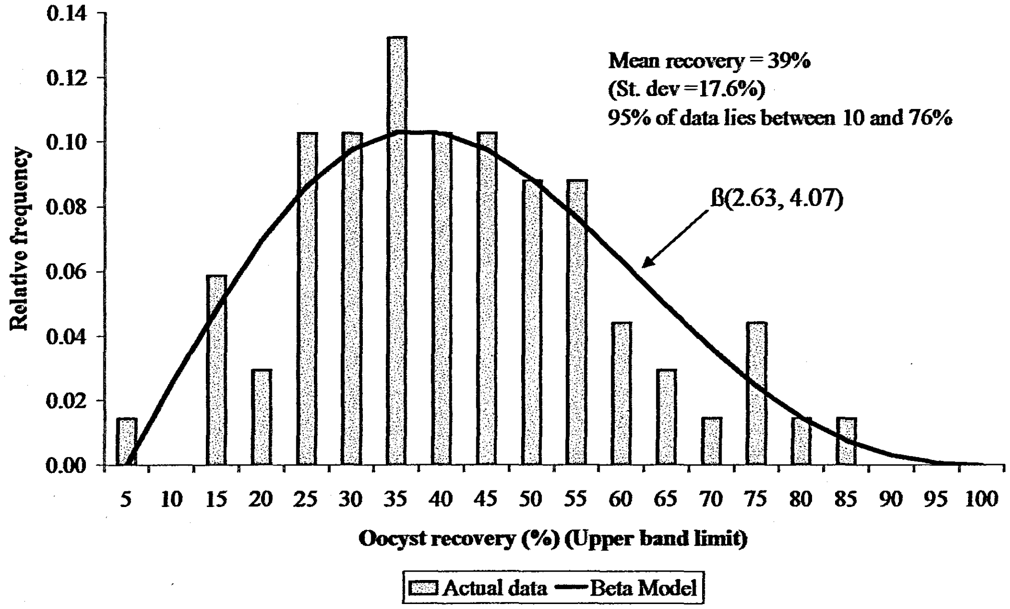


Figure 9.1 *Sussex Laboratory Cryptosporidium AQC data, 2001.*
(Here β describes the probability distribution not the inverse power coefficient used previously)

9.3.1.2 The lognormal probability plot

Cryptosporidium data has been analysed using a lognormal probability plot as described in Ongerth (1989) and Gale (1996). If a set of log-transformed data is plotted against its percentile values on a lognormal scale then the non-zero values fall upon a virtual straight line. One application of this plot is to analyse positive detections of *Cryptosporidium* oocysts (or similar organisms) in water samples as documented in several recent papers, notably in, Ongerth (1989), and Gale (1996). The lines upon which the data falls can be cross-compared according to (a) their slope which reflects the variability in the size of the Cryptosporidium positives, and (b) their placement on the horizontal axis which describes the frequency of positive detections. It is possible therefore to differentiate between treated water where oocysts are frequently detected but in small concentrations (e.g. in water taken from a well-operated surface water treatment plant) to one where they might be rare but more concentrated (e.g. in water taken from a unprotected groundwater source).

9.3.1.3 Turbidity data retrieval

Turbidities were downloaded from a central data archive known as PI. Readings on PI are stored at 15-minute intervals. Originally, a comprehensive analysis of turbidity data from all key works was intended. However, not all turbidimeters were linked to the PI archive. Some works' data was only available as a manual records or chart recordings. Only a small number of works therefore were analysed (Table 9.1).

Table 9.1 *Southern Water supply works designated for continuous 24 hour Cryptosporidium monitoring.*

WSW	*Water source*	*Treated turbidity data stored on PI?*
Arundel	Ground	Yes
Burham	Surface	Yes
Burpham	Ground	Yes
Carisbrooke	Ground	Yes
Hardham	Surface & Ground	Yes
Newmarket	Ground	Yes (post Apr 01)
Otterbourne	Surface & Ground	Yes (Ground only)
Sandown	Surface	No
Testwood	Surface	No

9.3.2 RESULTS

9.3.2.1 Lognormal probability plots

The results of the continuous *Cryptosporidium* data monitoring in 2000-1 has been summarised in Figures 9.2 and 9.3. Several points of interest arise from these charts. From the 2000 data, it appears that Testwood (surface) and Arundel (groundwater) WSWs had the highest number of oocysts in their treated water. In 2001, Burpham (groundwater) and Arundel WSWs were the highest.

Some small differences in the gradients of the lines are also visible. In Figure 9.2, for example, the Burham (surface) line is less steep than the others suggesting that oocysts are either present in very low concentrations in the raw source or else are strongly removed across that treatment process. In Figure 9.3, the line fitted to the Hardham data is much more gradual than the others. By contrast, Carisbrooke WSW, for example has fewer detections, but a much steeper gradient, suggesting that over a long period of time, this works may be more likely to produce a high oocyst concentration. In fact, detections at both these works are very low compared to the treatment standard of 1 oocyst per 10 litres. The results must also be considered in light of discrepancies in *Cryptosporidium* analysis (Section 9.3.1.1). It is also questionable whether much can be determined from a plot containing only two or three points.

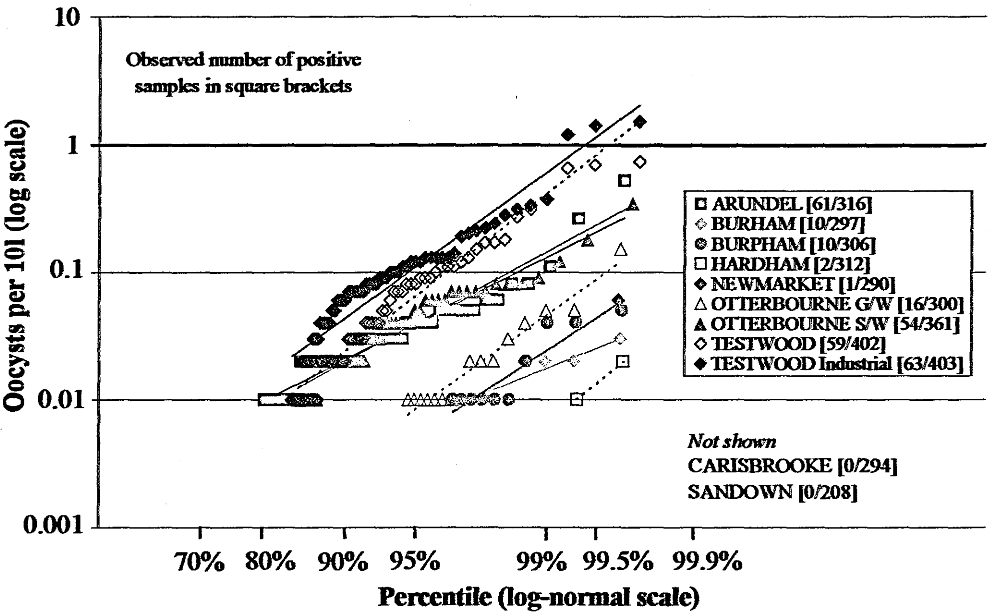


Figure 9.2 *Lognormal probability plot: Cryptosporidium data 2000.*

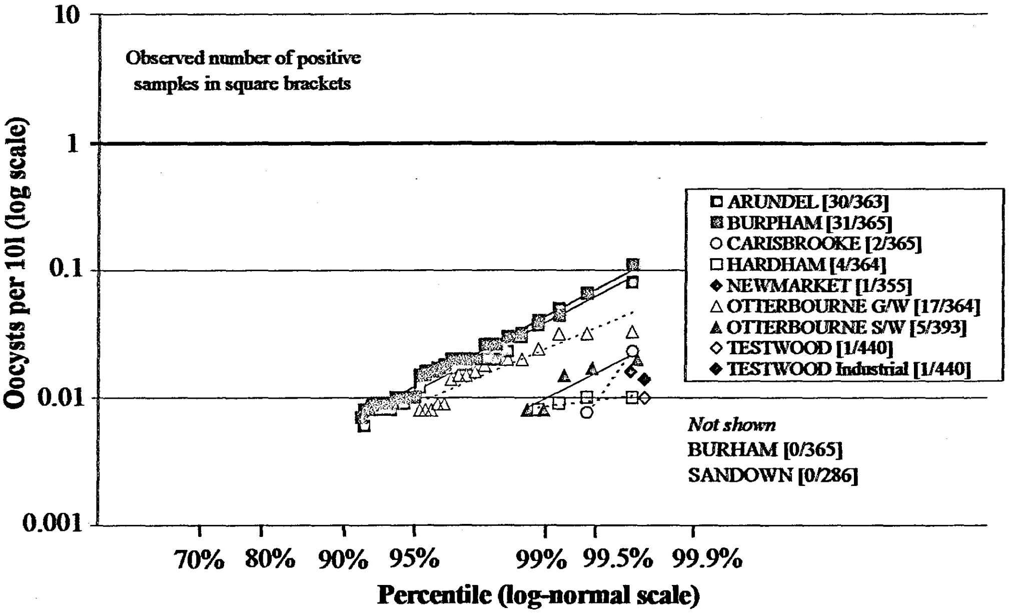


Figure 9.3 *Lognormal probability plot: Cryptosporidium data 2001.*

It is interesting that the numbers of *Cryptosporidium* oocysts found at some works such as Testwood WSW differ vastly between 2000 and 2001. In 2000, 14.7% of treated water samples taken at Testwood WSW registered positive for *Cryptosporidium*, more than at any other works monitored. However in 2001, this percentage dropped sharply to 0.2%. Although this could signify the transience of *Cryptosporidium* in raw water sources, some doubts remain about the accuracy of the 2000 data especially in the first two months of monitoring, in which most of the Testwood positives were detected (Figure 9.4). Retrospective internal laboratory checks have queried whether the organism detected in this period was *Cryptosporidium* or whether it was an unspecified organism that merely had a passing resemblance to *Cryptosporidium* under the microscope.

9.3.2.2 Comparison between oocyst and particle monitor data

Looking at the Testwood WSW turbidity and oocyst data sets for this critical two-month period, it appears that there was no obvious correlation between the two trends. This suggests that *Cryptosporidium* oocysts (or the "pseudo oocysts") are not ubiquitous in the River Test but occur sporadically and unpredictably. It is also noticeable that relatively large oocyst concentrations can be found even low turbidity treated water. For example, in the first half of March 2000 (Figure 9.4), oocyst concentration rose above 0.3 per 10ml on three separate occasions. Treated water turbidity remained below 0.1 NTU throughout this period. Conversely, large increases in raw and treated water turbidity did not guarantee increased *Cryptosporidium* occurrence. It would appear therefore that one cannot always (or indeed regularly) predict the composition of particles in water merely by looking at their number.

One anomaly is worth special consideration. On 4th-6th April, 2000 raw water turbidity rose sharply during river spate conditions. Treated water turbidity also rose as the operators attempted to maintain an optimum coagulant dose under the rapidly changing raw water conditions. More details of this are provided in Section 6.5.1. A relatively high number of oocysts (more than 0.6 per 10 litres) were counted during this period. Although this could be coincidental, it is possible that the two events are connected i.e. some turbidity spikes may carry a particular risk. It is interesting that, although in terms of turbidity removal, performance did appear to deteriorate slightly (from 2.3 to 1.8 log-removal), this was still higher than on other occasions, especially when the works was receiving water from Testwood Lake (Figure 9.5).

A general lack of correlation was also seen in data taken from other works scrutinised such as Burpham WSW (Figures 9.6-9.11), which had the highest percentage (8.5%) of positive *Cryptosporidium* detections in 2001. For example, in August (Figure 9.9), treated water turbidity regularly exceeded 0.2 NTU and even peaked at 2.0 NTU on several occasions. However, no *Cryptosporidium* oocysts were detected during this period. Conversely, most of the positives occurred in January and February (Figure 9.6), when the turbidity was very low (around 0.04-0.05 NTU).

As with Testwood WSW, there were times at Burpham WSW where spikes in turbidity and *Cryptosporidium* coincided. This can be seen on the 5th-7th May (Figure 9.8) and or 10-12th October, 2001 (Figure 9.10) for example. Although this suggests that some turbidity spikes may carry a higher *Cryptosporidium* risk, it must be noted that such correspondence is rare and could be coincidental.

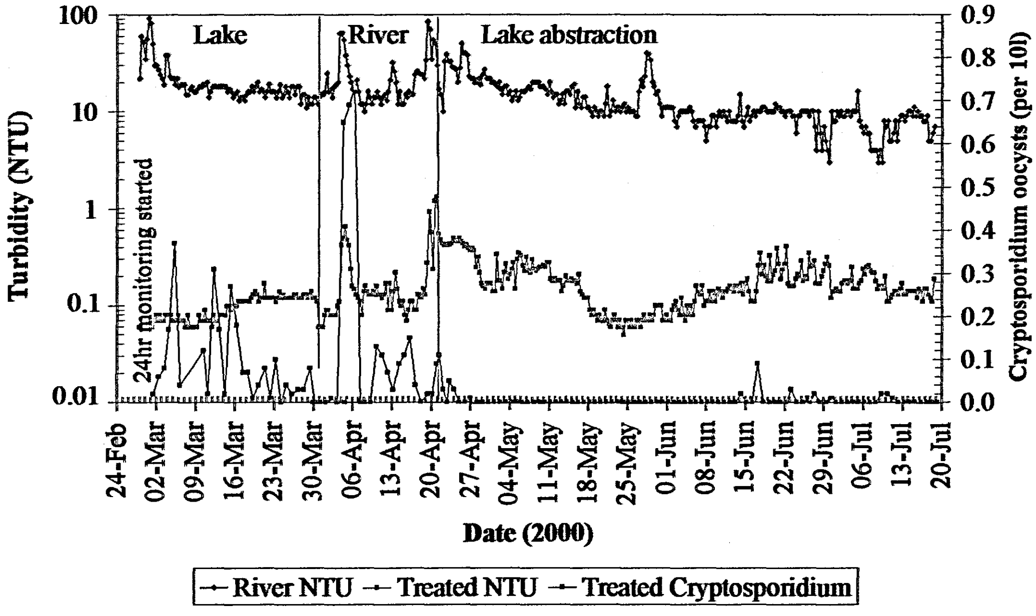


Figure 9.4 *Testwood WSW: Turbidity vs. Cryptosporidium data (24th February – 20th July).*

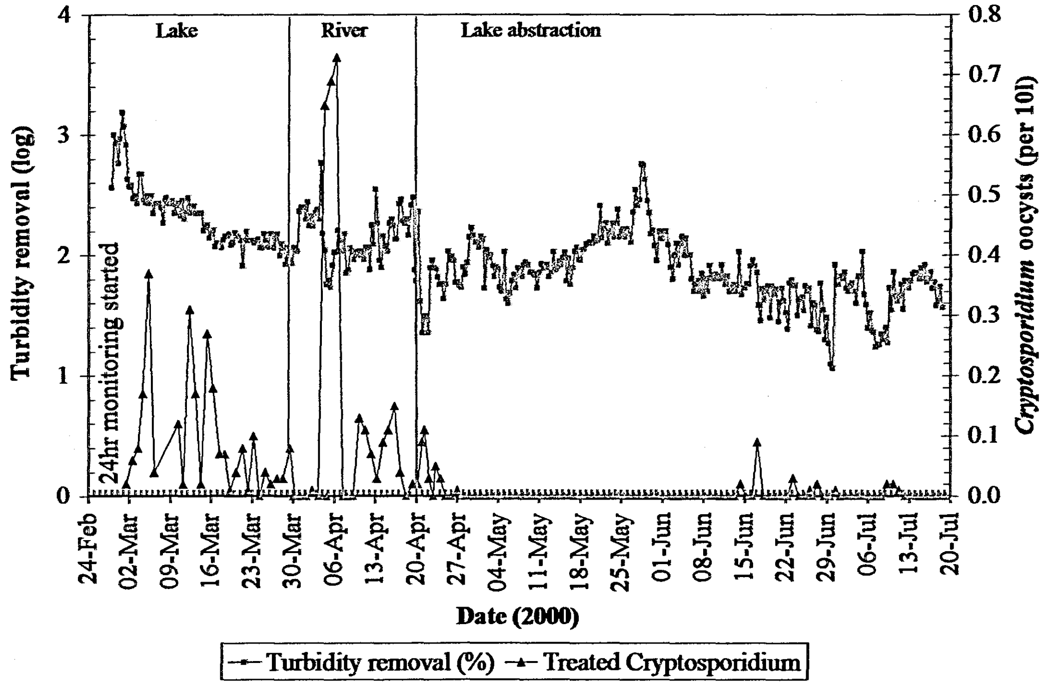


Figure 9.5 *Testwood WSW: Turbidity removal vs. Cryptosporidium data (24th February – 20th July).*

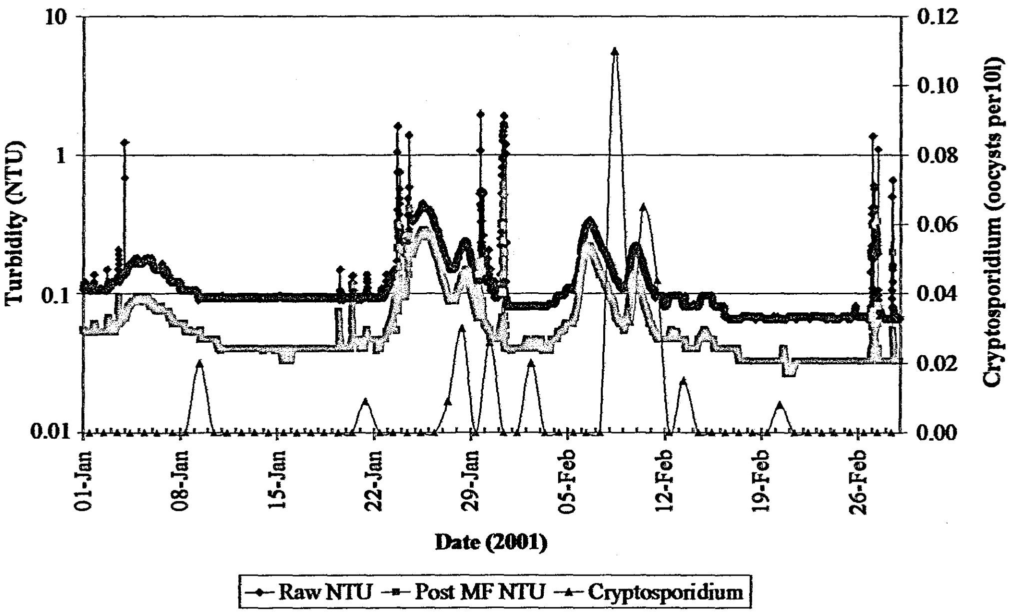


Figure 9.6 *Burpham WSW: Cryptosporidium vs. online turbidity data Jan-Feb 2001.*

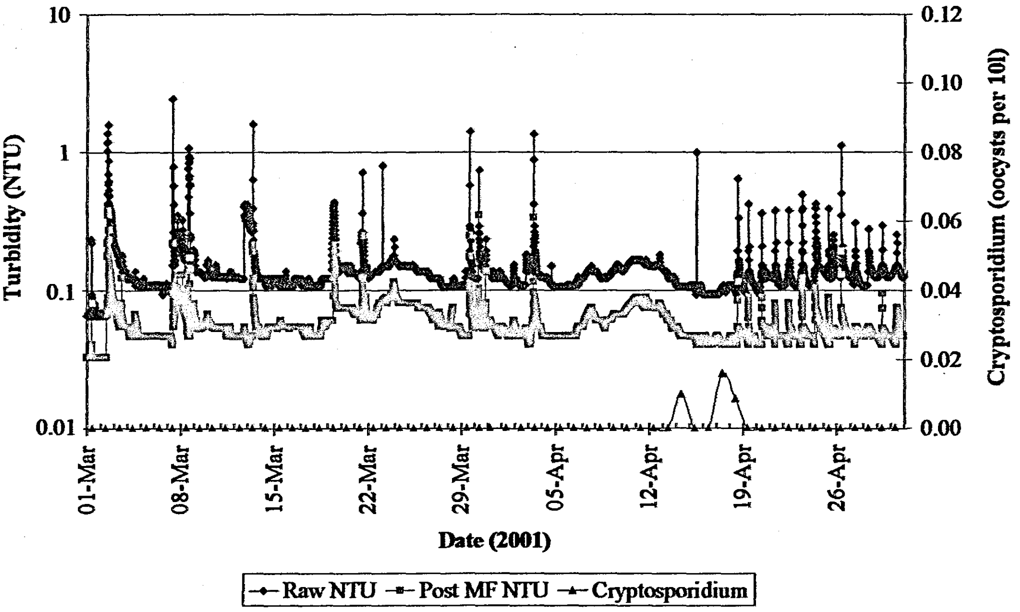


Figure 9.7 *Burpham WSW: Cryptosporidium vs. online turbidity data Mar-Apr 2001.*

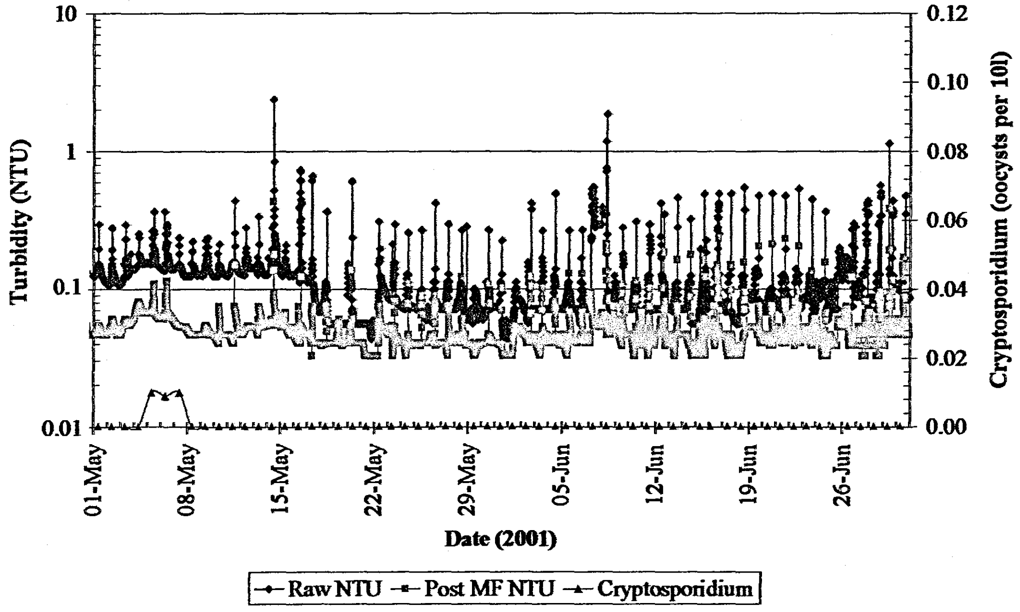


Figure 9.8 *Burpham WSW: Cryptosporidium vs. online turbidity data May-Jun 2001.*

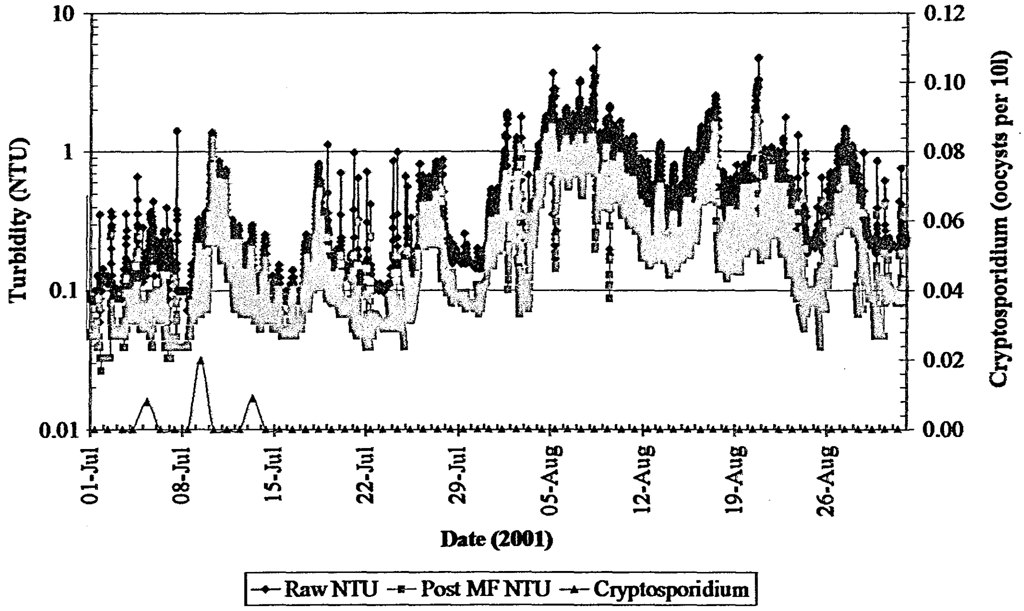


Figure 9.9 *Burpham WSW: Cryptosporidium vs. online turbidity data Jul-Aug 2001.*

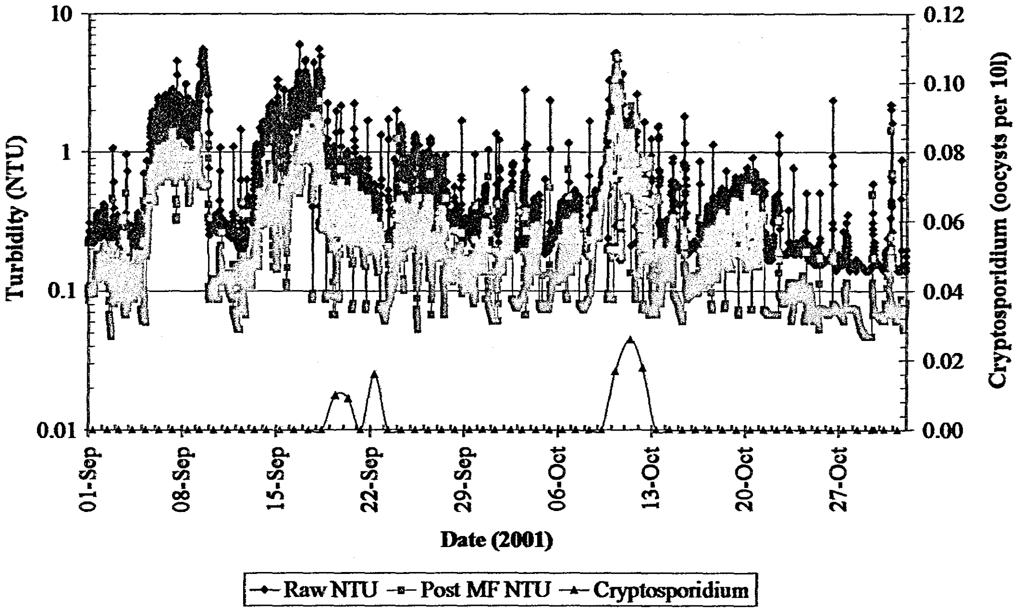


Figure 9.10 *Burpham WSW: Cryptosporidium vs. online turbidity data Sep-Oct 2001.*

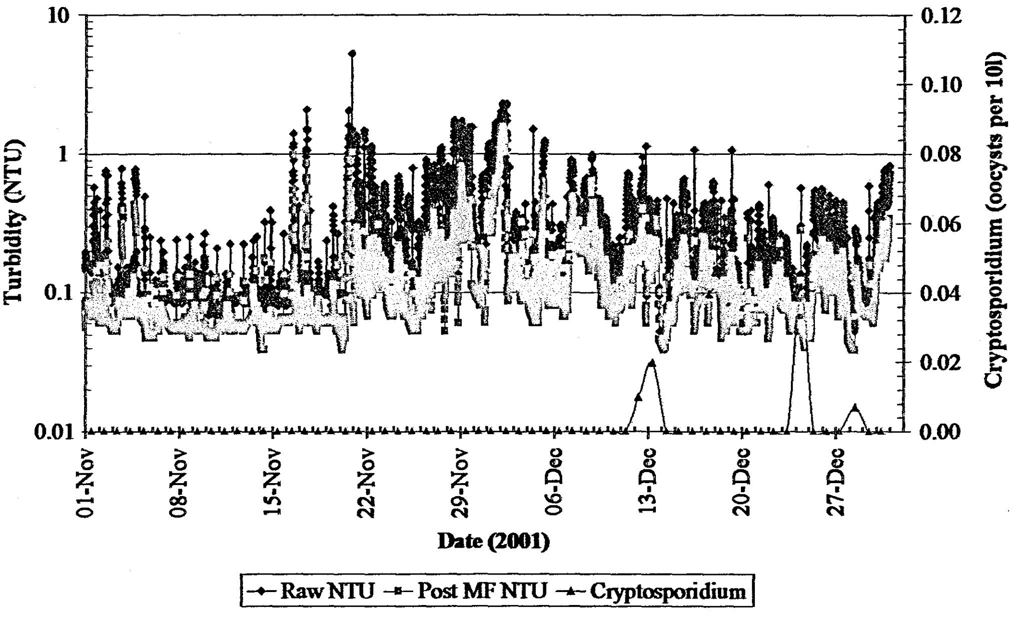


Figure 9.11 *Burpham WSW: Cryptosporidium vs. online turbidity data Nov-Dec 2001.*

9.4 STUDY 2: Newmarket Sample Survey

A sample survey was conducted to examine any possible relationships between particle counts/turbidity and *Cryptosporidium* at Newmarket (1C) WSW. This works was selected as a focus for this study for two reasons. Firstly, in 1998, a *Cryptosporidium* risk assessment of groundwater supply works in the company classified this works as having the highest risk. In this risk assessment, groundwater sources were ranked in ten weighted categories based on qualitative (rather than quantitative) factors such as the condition of the well or borehole, surrounding land use etc. In fact, subsequent analysis of this works, detailed in Section 9.3.2, shows that there is probably only a very small/negligible *Cryptosporidium* risk at this works. Secondly, Newmarket (1C) WSW is a works where abstracted groundwater turbidity is typically low (<0.1 NTU) and as therefore could be a suitable location for using particle counters as discussed in Sections 5.4.1 and 7.9.1.

Various sample were taken to see if any increases in *Cryptosporidium* surrogate parameters e.g. total and faecal coliforms, faecal *streptococci*, microbial colony counts could be found during suspected periods of surface water ingress. The study is an interesting addition to the previous study (Section 9.3) as it looks at changes in *Cryptosporidium* risk status associated with specific particle count/turbidity anomalies.

In previous particle monitoring at Newmarket WSW (Section 7.8.1) increases in particle counts/turbidity were seen on two occasions, (a) immediately after a borehole was switched on and (b) several hours after heavy rainfall. It was not known whether these increases were due to the stirring up of sediment in the borehole in connected fissures and mains, or due to surface water intrusion. For example, when a pump starts up, water could be drawn down from the surface as the characteristic zone of depression is formed around the borehole.

9.4.1 METHODS

A detailed description of Newmarket WSW and the particle monitors used at this works is given in Section 7.5. During the two sample surveys undertaken, the mobile particle monitor rig was used to record particle count, turbidity and particle index (Section 2.2.3). Particles were counted in the following size ranges: >2µm, >3µm, >5µm, >10µm, and >20µm.

A list of the chemical and microbiological analytical methods used is shown in Table 9.2. Prior to sampling on each day, the tap was flamed to reduce the risk of microbial contamination of the samples. This was performed in accordance with Southern Water's sampling method protocol. Filtration of the samples (for dissolved metals analysis) was performed on-site using Pall Gellman Acrodisc® filter disc which have a nominal 0.45µm poresize. No *Cryptosporidium* samples were taken. This was because (a) this would have been very expensive and (b) many samples would probably have had to be taken to realise one positive.

After some early samples were taken in February/March, 2000, some correlations were starting to emerge between the particle monitor trends and the laboratory samples. However, further samples were needed to strengthen the statistical significance of these results. A repeat survey was therefore conducted in August, 2001.

Table 9.2 *Newmarket sample survey – analytical methods.*

Parameter	*Method*
Total calcium Dissolved calcium Total iron Dissolved iron	Standard "blue book" method (Standing Committee of Analysts, 1980)
Total coliforms Faecal coliforms Faecal *streptococcus* Colony count 1 day/37°C Colony count 3 day/22°C *Clostridium perfringens* spores	Standard "blue book" method (Environment Agency, 1994)

9.4.2 RESULTS

The particle count, coliform and 22°C colony count data from this study can be seen in Table 9.3 and Figures 9.12-9.14. Other chemical and microbiological parameters measured are shown only in Table 9.3. Turbidity and particle index data was also collected but is omitted here since a more detailed comparison between the three particle monitors at this works has already been provided (Section 7.8.2.2). Possible reasons for the noise seen in the trends have also been discussed as has the link between particle counts and rainfall (Section 7.8.2.1).

After the first set of samples taken in February-March, certain links between particle counts and different microorganisms started to emerge. Firstly, there appeared to be a predictable increase in total coliforms, 22°C colony counts and, to a lesser extent faecal coliforms, during periods of suspected surface water intrusion following rain (Figure 9.12-9.13). These relationships were tested using simple linear regression, each yielding significance levels of $p=0.01$, 0.09 and 0.12 respectively. This correlation was strengthened by the addition of the 2001 survey data (Figure 9.14). Corresponding p-values increased to <0.01, 0.06 and 0.10 respectively (Table 9.4). Indeed, similar patterns also started to emerge with other microbiological parameters namely faecal *streptococcus* ($p=0.10$) *and Clostridium perfringens* spores ($p=0.10$). From the samples taken, however, it was not possible to distinguish a clear link between particle count and the 37°C colony count (p=0.25). This may be because these organisms may occur more sporadically in the water environment.

There was also evidence of a significant increase in the microbiological parameters during the pump start-up phase: higher total coliforms, 22°C colony counts and faecal coliforms were found on these occasions (p=0.03, 0.07 and 0.08 respectively, Table 9.4).

As far as the metals data was concerned, a relatively high insoluble calcium concentration was seen after the pump was started up (p=0.03, Table 9.4). This is believed to be due to the stirring up of sediment in the borehole. In addition, and a low dissolved calcium concentration, probably a dilution factor, was observed after heavy rainfall (p=0.05). These correlations were derived largely from the results from the 3rd March, 2000, (Figure 9.15). No link could be distinguished between particle counts and total calcium (p=0.14). This is because data taken from the 7th and 8th March (Figure 9.16) showed little variation in total calcium all day despite wide changes in particle counts.

On the subject of the metals data, it is worth observing several inconsistencies in the analysis. In many cases (Table 9.3), a higher metal concentration was detected in the 'dissolved' (filtered sample) than the 'total' (unfiltered sample). Although it is just feasible that labels may have been stuck to the wrong bottles, it is more likely, in the opinion of the author, that an analytical error was introduced either at the filtration stage (performed on-site) or during the rest of the analysis (performed by Southern Water's laboratory). It is recommended that in light of these discrepancies, the metals concentrations should be treated with caution: further evidence is probably required before drawing firm conclusions from this data.

The samples were analysed for iron because it is an abundant mineral in soil and was thought could be present in significant quantity in the borehole during periods of water ingress. Iron might also have been introduced into the samples through rusty mains or fittings. The results, however, seemed to suggest that it was present only in a negligible quantity and in retrospect one could question the need to analyse for this parameter at this borehole.

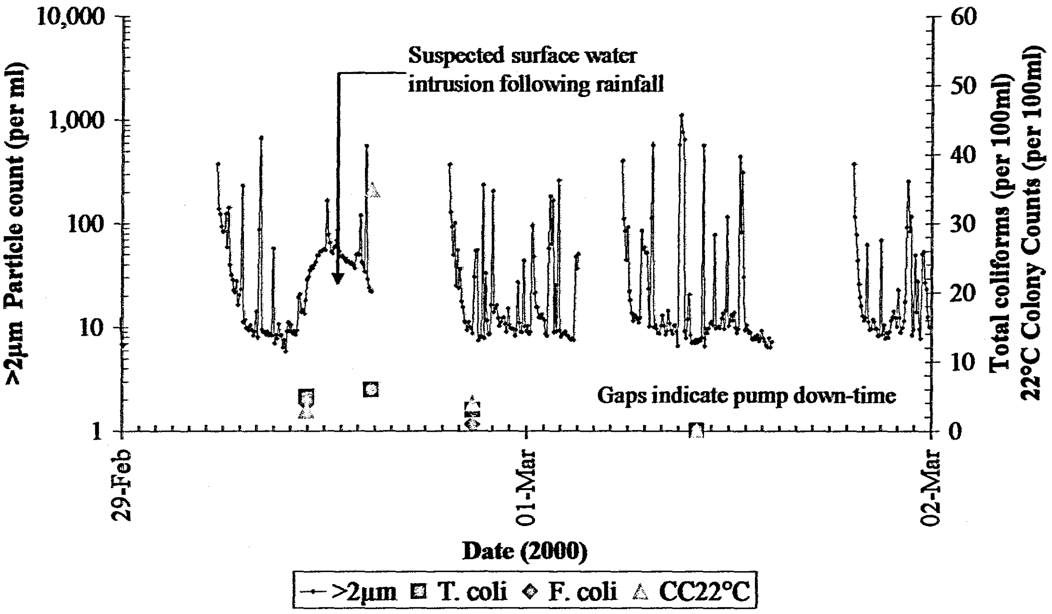


Figure 9.12 *Newmarket WSW: Groundwater particle counts, total and faecal coliforms, and 22°C colony counts, 29th February-1st March, 2000.*

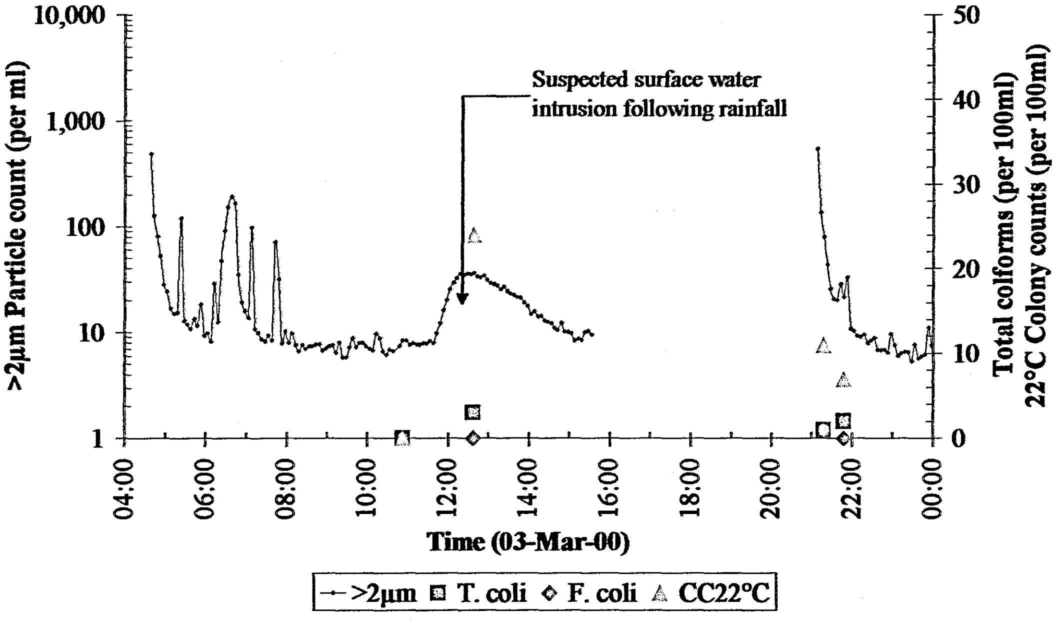


Figure 9.13 *Newmarket WSW: Groundwater particle counts, total and faecal coliforms and 22°C colony counts, 3rd March, 2000.*

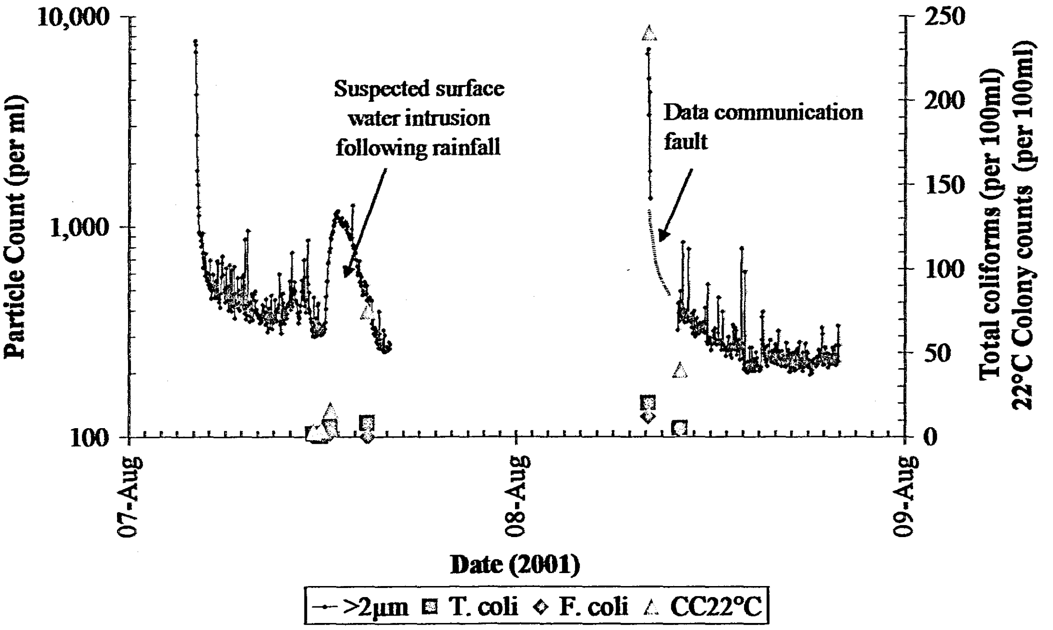


Figure 9.14 *Newmarket WSW: Groundwater particle counts, total and faecal coliforms and 22°C colony counts, 7th – 8th August, 2001.*

Table 9.3 *Newmarket WSW: Sample survey raw data.*

Sample	*Date/Time*	*>2µm (per ml)*	*T. Coli (per 100ml)*	*F. Coli (per 100ml)*	*F. Strep (per 100ml)*	*CC 1d/37℃ (per 100ml)*	*CC 3d/22℃ (per 100ml)*	*Clostridium (per 100ml)*	*Tot Ca (mg/l)*	*Dis Ca (mg/l)*	*Insol Ca (mg/l)*	*Tot Fe (mg/l)*	*Dis Fe (mg/l)*	*Insol Fe (mg/l)*
1	29-Feb-00 11:01	29	5	4	0	0	3	0	93	96	-3	<0.01	0.02	-0.01
2	29-Feb-00 14:52	22	6	6	2	4	35	1	94	100	-6	<0.01	0.02	-0.01
3	29-Feb-00 20:52	9	3	1	0	0	4	0	97	98	-1	<0.01	0.04	-0.03
4	01-Mar-00 10:11	7	0	0	0	0	0	0	94	102	-8	<0.01	0.03	-0.02
5	03-Mar-00 10:53	8	0	0	0	0	0	0	96	108	-12	0.02	<0.01	0.01
6	03-Mar-00 12:40	36	3	0	0	0	24	0	90	111	-21	<0.01	<0.01	0.00
7	03-Mar-00 21:20	79	1	1	0	1	11	0	101	101	0	<0.01	<0.01	0.00
8	03-Mar-00 21:51	21	2	0	0	0	7	0	104	102	2	<0.01	<0.01	0.00
9	07-Aug-01 11:29	463	2	0	0	4	3	0	101	103	-2	0.02	<0.01	0.01
10	07-Aug-01 11:57	335	0	0	0	7	4	0	101	100	1	0.06	0.03	0.03
11	07-Aug-01 12:30	888	6	2	6	8	16	1	101	100	1	0.02	0.02	0.00
12	07-Aug-01 14:48	449	8	0	16	12	75	0	99	96	3	<0.01	<0.01	-
13	08-Aug-01 08:10	3381	20	12	40	29	240	0	102	99	3	<0.01	<0.01	-
14	08-Aug-01 10:08	495	5	5	29	9	40	0	100	98	2	<0.01	0.01	-

🟦 Sample taken during suspected SW ingress after rainfall

🟦 Sample taken after borehole pump start

☐ Normal operating conditions

Table 9.4 *Testing for differences between sampled parameters during control conditions (C), during suspected surface water ingress following rainfall (R) and following pump start-up (S).*

		T. Coli (per 100ml)	*F. Coli (per 100ml)*	*F. Strep (per 100ml)*	*CC 1d/37°C (per 100ml)*	*CC 3d/37°C (per 100ml)*	*Clostridium (per 100ml)*	*Tot Ca (mg/l)*	*Dis Ca (mg/l)*	*Insol Ca (mg/l)*
Mean	Control ($\bar{c}$)	1	0.0	0.0	3	2	0.0	98	103	-5
	SWI after rain ($\bar{r}$)	6	2	5	5	31	0.4	95	101	-5
	Pump start-up ($\bar{s}$)	3	2	7	3	16	0.0	101	100	1
Variance	Control	1	0.0	0.0	12	4	0.0	13	12	35
	SWI after rain	3	7	45	27	752	0.3	20	37	87
	Pump start-up	3	5	210	19	275	0.0	8	4	2
One-tailed test for diff. between $\bar{r}$ and $\bar{c}$*	t_{test}	5.0	1.8	1.4	0.7	2.1	1.4	1.0	0.7	0.0
	prob	**<0.01**	**0.06**	**0.10**	0.26	**0.04**	**0.10**	0.18	0.24	0.49
One-tailed test for diff. between $\bar{s}$ and $\bar{c}$*	t_{test}	2.3	1.6	1.0	0.1	1.6	-	1.2	1.9	2.2
	prob	**0.03**	**0.08**	0.18	0.46	**0.07**	-	0.14	**0.05**	**0.03**

* For each parameter, a one-tailed test has been used to test for a difference between means $\bar{r}$ and $\bar{c}$, and $\bar{s}$ and $\bar{c}$. Where $\bar{r}$ or $\bar{s}$ is lower than the control mean, $\bar{c}$, its t-value has been shown in red to indicate a negative relationship.

For the purpose of these tests, it is assumed that all the samples analyses (control and non-control) have a similar population variance. The hypothesis test critical region for $\bar{r}$ and $\bar{c}$, for example, is therefore given by

$$t = \frac{\bar{r} - \bar{c} - 0}{s_p\sqrt{1/n + 1/m}} \geq t_\alpha(n+m-2), \text{ where } s_p = \sqrt{\frac{(n-1)s_r^2 + (m-1)s_c^2}{n+m-2}}$$

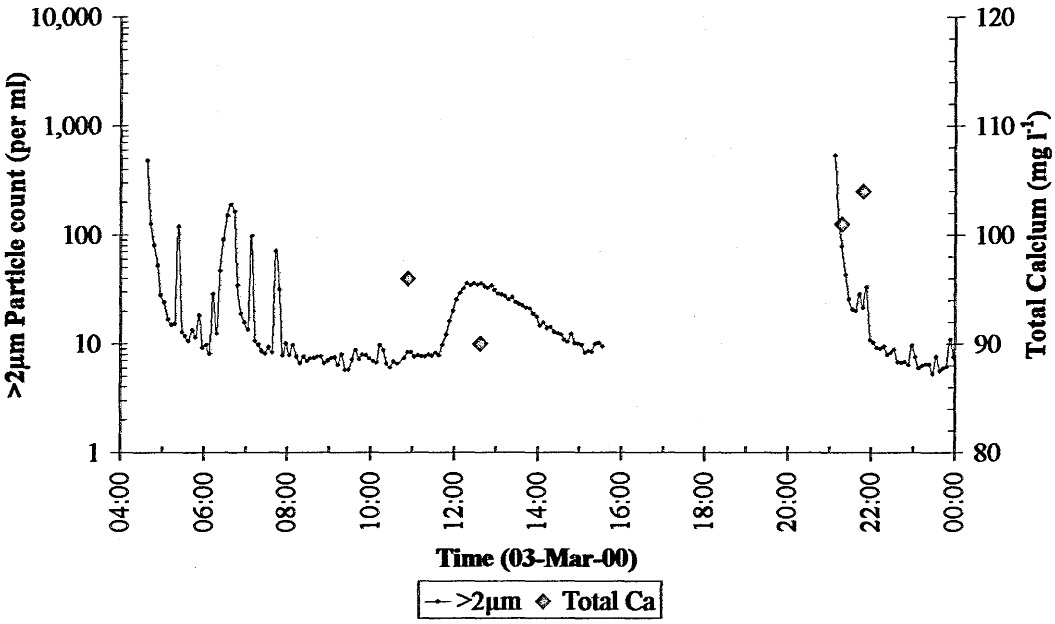


Figure 9.15 *Newmarket WSW: Groundwater particle counts and total calcium concentration, 3rd March, 2000.*

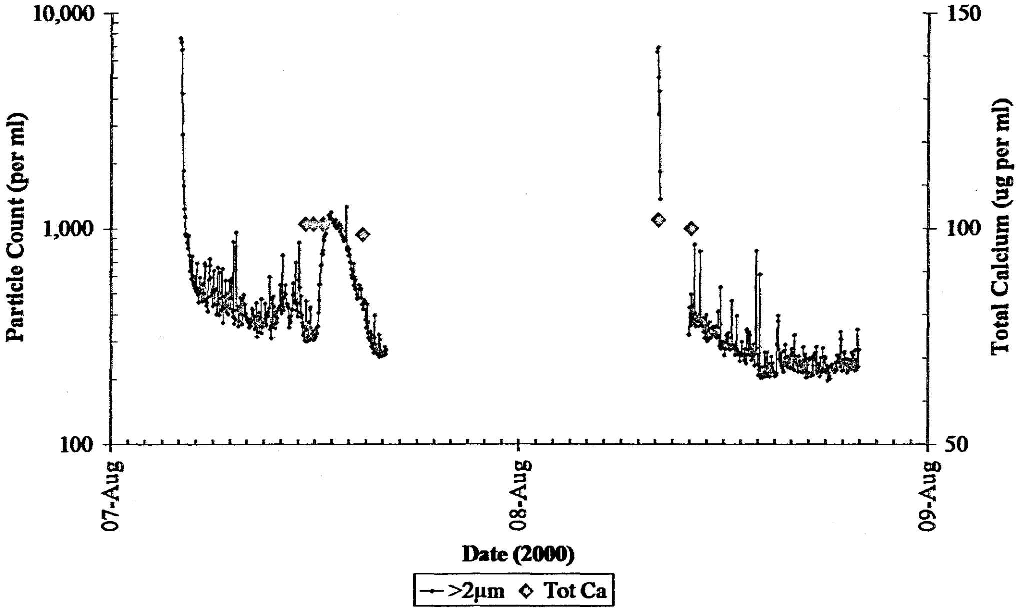


Figure 9.16 *Newmarket WSW: Groundwater particle counts and total calcium concentration, 7th – 8th August, 2001.*

9.4.2.1 Multiple regression analysis

A simple regression analysis of the data suggests that there is a direct linear link between particle counts and certain microbial parameters such as total coliforms (Figure 9.17). In fact upon examining the raw data (Table 9.3), it is apparent that this is an unsatisfactory oversimplification of the relationship. On 29th February, 2000, for example, a sample was taken immediately after a pump start-up. Six coliforms per 100ml were found in this sample despite the fact that its particle count was relatively low (22 counts per ml). On 7th August, 2001 a sample was taken which had 335 counts per ml (around 15 times increase), but yet contained no detected coliforms. This incongruity is also shown in Figure 9.17; without the point located on the extreme right of the graph the correlation between particle counts and total coliform concentration falls from $p<0.01$ to $p=0.14$.

In order to better assess the relationship between particle counts and total coliforms, the data was analysed using multivariable regression techniques, with the best-fit model shown below (Equation 9.1).

$$Total\ coliform\ (per\ 100ml) = -0.5 + 0.0051X + 4.7R + 2.66S \qquad (9.1)$$

where X = >2µm particle count (per ml),
R = rainfall dummy variable (0 or 1),
and S = pump start-up dummy variable (0 or 1).

Not only did this model fit the data ($p<0.01$), but also each of the three variables contained within the model were significant inclusions within the model: the inclusion of R variable within the existing single variable model (Figure 9.17) led to a significant improvement ($p=0.01$) with the inclusion of the S variable leading to a further improvement ($p=0.02$). Although there is some correlation between particle and coliform counts, the model shows that high particle counts do not always guarantee high coliform concentrations. Generally speaking the highest coliform counts will be found following pump start-ups and rainfall: the exact size of the increase in particle counts on these occasions is only of secondary importance.

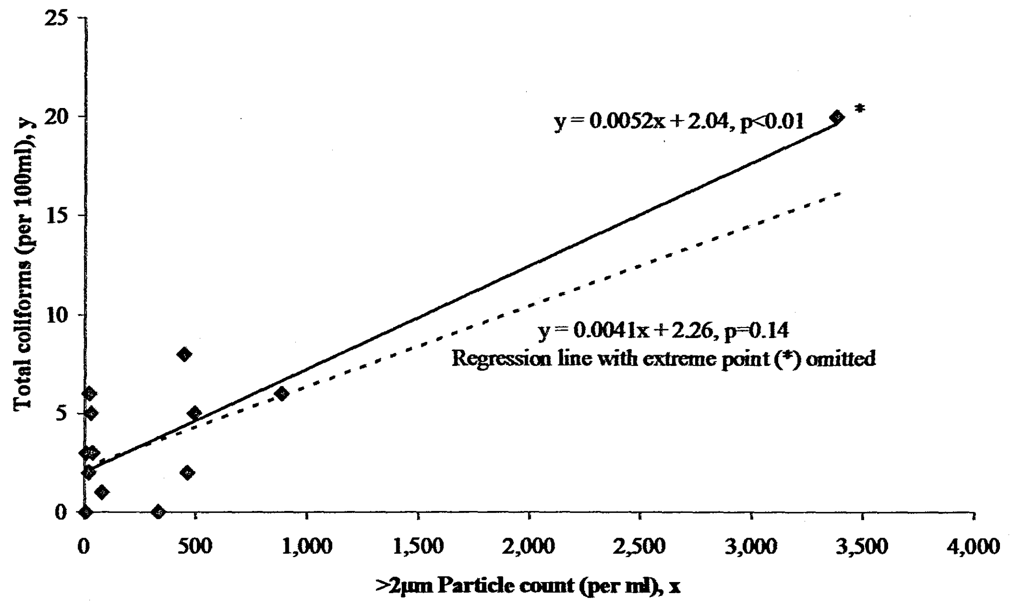


Figure 9.17 *Newmarket WSW groundwater – total coliform vs. particle count.*

9.5 DISCUSSION

9.5.1 Study 1: Analysis of *Cryptosporidium* and turbidity data

The first study suggests that, generally speaking, there appears to be no obvious correlation between *Cryptosporidium* and turbidity (or particle counts) in treated water. This corroborates with results from other studies: Wilson and Morse (1999), Morse *et al.* (2000) and Payne (2000). In Section 2.4, a link was shown between particle and oocyst removal. (One exception to this is where bioparticles are being generated within a system.) Although this showed that the reduction of turbidity (or particle counts) in treated water is desirable, low turbidity is not a guarantee of safe drinking water.

The work suggests therefore that *Cryptosporidium* oocysts do not necessarily occur in drinking water during periods of high raw and/or treated water turbidity, but are more sporadic. Other factors such as the incidence of cryptosporidiosis in local human or animal communities may be more important.

Because its occurrence is unpredictable, the only true way of assessing *Cryptosporidium* risk appears to be to monitor specifically for that organism. For this reason, this study finds that continuous monitoring for oocysts has some merit especially at higher risk works such as Arundel, Burpham, Otterbourne, and Testwood WSW's. For lower risk works such as Burham, Carisbrooke, Newmarket, Hardham and Sandown WSW's where detections are very rare and small, one might question the value of continuous monitoring. Arguably, resources could be better directed towards works improvements.

9.5.2 Study 2: Newmarket sample survey

The Newmarket study is interesting because it presents a slightly different perspective. Here increased numbers of total and faecal coliform bacteria, and 22°C colony counts were seen in groundwater samples during suspected periods of surface water ingress following rainfall and the borehole pump start-ups. This appears to contradict results from the first study as it implies that, if oocysts are present in the surface water environment some turbidity/particle count spikes in the groundwater may carry a higher *Cryptosporidium* risk.

However, this does not necessarily mean that such deteriorations necessarily carry a significant risk. As discussed in Section 9.5.1, *Cryptosporidium* occurrence appears to be highly sporadically in both surface and groundwaters. Whereas links may be found between particle numbers and 'ubiquitous' organisms such as total coliforms, for example, it is unlikely that the occurrence of *Cryptosporidium* oocysts, would be so predictable. This was also seen with the Newmarket 37°C colony count data, for example.

The work again shows that *Cryptosporidium* data is crucial when assessing the real risk status of groundwater supply works. As mentioned previously (Section 9.4), only very low levels of *Cryptosporidium* have been detected so far at Newmarket WSW; the works is therefore likely to be of relatively low risk. In addition, the existence of an ultra-violet light treatment plant should further reduce this risk. At works where

Cryptosporidium oocysts (or other microbial pathogens) are perceived to be more of a problem, however, one could argue that efforts should be made to minimise any anomalies in turbidity or particle count trends. For example, one could operate a borehole pump using a slow-start up strategy similar to those used when bringing filters back on-line (Section 6.1.2.1). Alternately, problematic boreholes could be taken out of service at key times. Finally, one also could install additional treatment processes (e.g. membrane filters). There is strong evidence that ultra-violet light provides an effective barrier to *Cryptosporidium* although this is currently not recognised by UK regulators (Section 2.1).

On balance, there appears no generic link between turbidity (and particle counts) and *Cryptosporidium* risk. However, for surface water treatment works, it appears that if (and only if) oocysts are present in the raw water then inferior turbidity/particle removal can lead to increased risk. As far as certain groundwater sources are concerned, if *Cryptosporidium* is present in the surface water, the intrusion of surface water into the boreholes may also have a similar effect.

9.5.3 Implications for particle monitoring

In the UK, as discussed in Sections 2.5.1 and 9.1, emphasis is given to reducing anomalies in water treatment. The actual level of baseline turbidity is considered less important. At Burpham WSW, however, turbidity was seen to vary wildly as a result of many influences (Section 7.7.1 and 9.3.2, and Appendix A) and yet *Cryptosporidium* seemed to occur entirely independently of this and was even found in significant numbers at very low turbidity (less than 0.1 NTU). This would suggest that although there is a need to minimise particle numbers in treated water, as far as *Cryptosporidium* is concerned, it is virtually impossible to assess what level of turbidity (or particle counts) is acceptable or unacceptable. In this way, these studies concur with Ginn *et al.* (1997) that reducing the number of particles in treated water is more important than adherence to an absolute standard.

In the opinion of this author, as discussed at length in Section 6.6.1, practically all process control needs are catered for by turbidimeters which are cheaper, easier to calibrate, and more precise than particle counters. As identified in Chapter 2.6 and

5.1, particle count and turbidity trends are often very similar effectively making particle counters redundant. In theory, there are only two possible instances where particle counters might have some use in process control (a) where turbidity is consistently very low or (b) where the sample contains abnormally large particles either sporadically as with filter breakthrough (particle detachment) or more consistently (as with Burham sludge recycle plant). Even in both these instances, it is believed that monitoring needs might be served by portable particle counters rather than permanently installed ones.

The 1998 Bouchier Report recommended that processes should be operated to produce water within specified turbidity limits, determined on a site-specific basis. In the US, 95% of treated water samples taken are expected to meet a turbidity standard of 0.3 NTU. Although these types of treatment rules have some value, it is important to realise that these compliance with either of these limits such does not guarantee that a process is free from *Cryptosporidium*. Arguably these targets will only be of value if they effect some reduction in turbidity or particle counts, i.e. if treatment operators/optimisers can take some remedial action.

As described in Section 2.5.2, the 1989 Surface Water Treatment Rule (EPA 1989) recommended using particle counters verify the overall effectiveness of particle removal during treatment. The monitoring for log-removal has not been a focus of this study. However, after observing (i) the strong relationship between particle and oocyst removal (Section 2.4) and (ii) the fact that significant numbers of oocysts can still be present in low turbidity water, it might be interesting to look at treatment as maximising particle/turbidity removal rather than just adhering to a fixed treated water standard.

As discussed in Section 2.4, care needs to be taken when calculating turbidity removals because of the declining sensitivity of turbidimeters below 0.1 NTU. Similarly, some particle removal figures may be biased because of high coincidence error in the 'raw' particle count. Problems also arise from the generation of particles in biologically active processes. Finally, in order to assess fully the value of particle removals, it would be desirable to have raw and treated *Cryptosporidium* data, which was not available here.

9.5.4 The role for particle counters

Although particle counters do not appear to have a highly significant role in process control, they can have an important secondary role in process optimisation and evaluation. This is especially evident from the fact that significant numbers of *Cryptosporidium* oocysts were detected in low turbidity treated water (Section 9.3.2).

The option currently preferred by this author would be to invest in portable particle counters only and use them in targeted process optimisation trials as discussed in Section 6.6.3.1.

9.6 SUMMARY

There appears no generic link between turbidity (and particle counts) and *Cryptosporidium* risk. However, for surface water treatment works, it appears that if (and only if) oocysts are present in the raw water then poor turbidity/particle removal can lead to increased risk. As far as certain groundwater sources are concerned, if *Cryptosporidium* is present in the surface water, the intrusion of surface water into the boreholes may also increase this risk.

Cryptosporidium oocysts were found even when treated water turbidity was very low (<0.1 NTU). This shows the value for fine-tuning treatment processes below 0.1 NTU and highlights a potential optimisation role for particle counters.

Although there is a need to minimise particle numbers in treated water, as far as *Cryptosporidium* is concerned, it is virtually impossible to assess what level of turbidity (or particle counts) is acceptable or unacceptable. In this way, these studies concur with Ginn *et al.* (1997) that reducing the number of particles in treated water is more important than adherence to an absolute standard.

Turbidity targets (such as those proposed by EPA 1998 or Bouchier 1998) can be a useful aid to quality control. However, compliance with these does not guarantee low

Cryptosporidium risk. Such targets will only be useful in minimising *Cryptosporidium* risk if they effect some reduction in the number of particles in treated water as a result of process optimisation.

Because its occurrence is unpredictable, the only true way of assessing *Cryptosporidium* risk appears to be to monitor specifically for that organism.

9.6.1 Recommendations for future research

They may be benefits in employing a slow start-up strategy when starting borehole pumps.

Because *Cryptosporidium* oocysts were seen in relatively low turbidity treated water, there may be some value in viewing treatment as maximising the removal of turbidity/particles across a process rather than just achieving a specific treated water standard as advocated in EPA (1989).

9.6.2 Suggested way forward

In terms of a way forward for Cryptosporidium risk management, the following three-step approach is therefore recommended:

1) Water companies should keep up-to-date risk assessment of *Cryptosporidium* at its works, based largely upon available *Cryptosporidium* data sets.

2) At works believed to be at high risk, water companies should initiate programmes to reduce treated water turbidities.

3) Water companies should also invest in portable particle counters and promote their use in optimising process design and operation.

Chapter 10: CONCLUSIONS

10.1 LITERATURE REVIEW

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.

10.2 SENSITIVITY MODEL

The sensitivity model is a useful comparative tool that can be used to determine the best applications of particle counters at different water treatment works.

Particle counter sensitivity varies according to an inverse power relationship with turbidity. Particle counters are therefore generally best used to fine-tune processes below 0.1 NTU. For processes that consistently produce very low turbidity water e.g. membrane filters, there may be some value in using particle counters in process control.

The work also shows the value of existing turbidimeters. These are usually as sensitive as particle counters around 0.1 NTU and remain more important in terms of minimising *Cryptosporidium* risk.

The size distribution of particles in water samples, as defined by particle ratios or the inverse power law β coefficient, has a significant effect on monitor sensitivity and can affect the suitability of using particle counters at some works. This can be assessed using the sensitivity model.

The model can also be used to compare new high sensitivity instruments. There is limited evidence to suggest that particle index monitors are as sensitive as particle counters below 0.1 NTU.

It can also be used to compare unusual changes in on-line particle count and turbidity trends. For this purpose, it is recommended that where particle counters are being used, a particle size ratio or a similar size statistic be trended alongside turbidity and particle counts.

10.3 SURFACE WATER TREATMENT STUDIES

10.3.1 Particle monitoring

Particle counters provided some interesting information on filter performance utilising (a) their high sensitivity to changes in particle number below 0.1 NTU and (b) their particle sizing ability. However this information was mostly useful from a process optimisation/evaluation point of view and not a primary operational concern.

Apart from processes that consistently produce very low turbidity water, most routine particle monitoring needs are catered for by turbidimeters. At most treatment works, the permanent installation of particle counters is not likely therefore to be a cost-effective exercise, especially in the long-term. Instead, water companies should promote the use of portable particle counters in targeted plant optimisation/evaluation studies.

Turbidity will remain the most important particle measurement especially with regards to routine process monitoring and control. To minimise *Cryptosporidium* risk, water companies should first look at reducing treated water turbidity at high-risk works. The implementation of a statistical quality control system based on turbidity such as that described by Bouchier (1998) or Edwards *et al.* (2000) is arguably more desirable than the permanent installation of particle counters or similar instruments.

No evidence of filter breakthrough (that might be best monitored using particle counters) could be found during the study. For treatment processes that encourage deep bed penetration, there may be a greater role for permanently installed particle counters to detect filter breakthrough. However, it would probably be more cost-effective to first try to use portable particle counters to optimise filter run-times.

A high degree of similarity was seen in particle trends measured across different sizes. This can lead to a ‘data overload’ situation where valuable information can be overlooked. To minimise the number of trends, this study suggests that where particle counters are used it would seem prudent to focus attention on two key parameters: (a) a total count (>2µm) to monitor changes in particle count, and (b) a particle size statistic such as the >10µm particle ratio (%) to monitor changes in particle size.

Contrary to other published work, this study found particle size statistics such as β and particle size ratios to be reasonably reliable. Some noise was seen in these trends although only where the total count was less than 1 per ml. If these statistics are not used then arguably there is no real reason for buying a multi-channel particle counter. A simple single-channel particle counter or a particle index meter would suffice.

A sample interval of 15 minutes was sufficient to pick out all the major changes seen in water quality. A shorter interval (e.g. 5 minutes or lower) is preferable, however, as it provides greater trend definition.

If a water company wishes to use a particle count standard for controlling processes (e.g. for works that consistently produce treated water with a very low turbidity), it might be worth implementing a local alarm system based on the particle count differential parameter to flag up significant changes in water quality. Where particle counters are not being used, a similar system based on turbidity readings could be beneficial.

It is recommended that unusual particle count and/or turbidity readings be compared using the sensitivity model. Turbidimeters appeared to respond especially sensitively to increases in particle number associated with coagulation control problems at Testwood. Its response was much higher than that predicted by the particle monitor sensitivity model, which may indicate an abnormally high number of submicron particles in the sample. Not all particle monitor data therefore is effectively modelled by the sensitivity model. Such anomalies, however, may be of special interest and are well highlighted by the model.

Although this study has exclusively looked at >2µm sensors, monitoring below 1µm might yield some more unusual particle size distribution shapes especially during periods of sub-optimal coagulant dosing.

Whatever the investment in particle counters (permanently installed or portable), it is important to realise that particle counters do not minimise *Cryptosporidium* risk by themselves. Water companies should ensure that they provide sufficient manpower to pursue specific optimisation projects e.g. fine-tuning coagulant dosage, filter start-up strategies etc. Ultimately the success of such an investment may depend upon promoting their use as optimisation tools to company staff.

10.3.2 Other related issues

The implementation of a delayed filter start-up strategy at Hardham led to no improvement in ripening. It actually led to a net deterioration in filter performance because the addition surface loading placed upon the other filters created problems in treatment.

Care should be given to filtered water turbidity/particle counts when increasing surface loading rates onto filters especially during filter ripening.

10.4 GROUNDWATER STUDIES

On balance, although this study has shown that particle counters can be a useful research tool, especially at very low turbidity (less than 0.1 NTU), it does not believe the permanent installation of particle counters at groundwater sites would yield significant benefits to process monitoring.

Although not strictly a groundwater issue, where microfiltration plants have been installed, there may be benefits in continuously monitoring for particle removal across this process.

10.5 SLUDGE TREATMENT STUDIES

The author does not believe that the permanent installation of particle counters of particle counter would necessarily yield significant benefits at all washwater/sludge recycling plants, not least because of potential problems with sensor aperture blockage.

However portable instruments can be a useful research tool and are especially useful where the sludge contains a high proportion of very large particles (a>1). This may occur at works where clarifier sludge is being recycled in addition to filter washwater.

Just because a (sludge) plant produces water with a low turbidity does not necessarily mean that it has a low solids content. Conversely, when adapting a process' design or operation, an increase in turbidity may be acceptable if a net reduction in particle size can be effected.

Ideally, when looking at plant performance (or setting plant performance criteria) some consideration should be given to particle size (e.g. using the >10μm particle ratio) or particle volume in addition to the total count.

It is possible that the larger particles (>10μm) may be responsible for some of the other problems seen at the Burham plant e.g. the filter blinding and the reduction in filter performance towards the end of each run.

As far as minimising *Cryptosporidium* risk is concerned, this study recommends that water companies (a) ensure that working turbidimeters are installed to monitor recycled water quality, (b) to apply the same level of diligence to recycled water turbidity as is applied to treated water as and (c) where possible embark upon a programme of turbidity reduction on its recycle plants. The role of particle counters (if any exists) is secondary.

10.6 CRYPTOSPORIDIUM RISK STUDIES

There appears no generic link between turbidity (and particle counts) and *Cryptosporidium* risk. However, for surface water treatment works, it appears that if (and only if) oocysts are present in the raw water then poor turbidity/particle removal can lead to increased risk. As far as certain groundwater sources are concerned, if *Cryptosporidium* is present in the surface water, the intrusion of surface water into the boreholes may also increase this risk.

Cryptosporidium oocysts were found even when treated water turbidity was very low (<0.1 NTU). This shows the value for fine-tuning treatment processes below 0.1 NTU and highlights a potential optimisation role for particle counters.

Although there is a need to minimise particle numbers in treated water, as far as *Cryptosporidium* is concerned, it is virtually impossible to assess what level of turbidity (or particle counts) is acceptable or unacceptable. In this way, these studies concur with Ginn *et al.* (1997) that reducing the number of particles in treated water is more important than adherence to an absolute standard.

Turbidity targets (such as those proposed by EPA 1998 or Bouchier 1998) can be a useful aid to quality control. However, compliance with these does not guarantee low *Cryptosporidium* risk. Such targets will only be useful in minimising *Cryptosporidium* risk if they effect some reduction in the number of particles in treated water as a result of process optimisation.

Because its occurrence is unpredictable, the only true way of assessing *Cryptosporidium* risk appears to be to monitor specifically for that organism.

10.6.1 Suggested way forward

In terms of a way forward for Cryptosporidium risk management, the following three-step approach is therefore recommended:

1) Water companies should keep up-to-date risk assessment of *Cryptosporidium* at its works, based largely upon available *Cryptosporidium* data sets.

2) At works believed to be at high risk, water companies should initiate programmes to reduce treated water turbidities.

3) Water companies should also invest in portable particle counters and promote their use in optimising process design and operation.

Chapter 11: RECOMMENDATIONS FOR FUTURE RESEARCH

Of all the topics included in this study, arguably the monitoring of sludge particles raises the most possibilities in terms of future research. It would be especially interesting to examine the performance of different particle monitors (particle counters, particle index monitors, turbidimeters, suspended solids monitors etc.) at works such as Burham WSW where there is a large mean particle size. Such work should look at monitor sensitivity and at remedying the problems of sensor blocking and coincidence error.

The following questions have also been raised and might be considered as future research topics:

1. What will be gained from the company's decision to permanently install particle counters on (a) combined rapid-gravity filter outlets and (b) post GAC filters?
2. What are the benefits of counting particles around and below 1 μm (especially, for example, during periods of sub-optimum coagulation dosing)?
3. Is there a role for other high sensitivity particle monitors such as particle index monitors?
4. Because *Cryptosporidium* oocysts were seen in relatively low turbidity treated water and appeared to occur independently of raw and treated water turbidity, would there be any benefit in maximising the removal of turbidity/particles across a process rather than just achieving a specific treated water standard?
5. Would there be any benefits in employing a slow start-up strategy when starting borehole pumps?

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APPENDIX A

The use of particle size counting in minimising *Cryptosporidium* risk at a groundwater supply works

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The use of particle size counting in minimising *Cryptosporidium* risk at a groundwater supply works

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ABSTRACT

This paper examines the value of particle size counting and turbidimeters at a groundwater supply works in various roles, from the early commissioning of a full-scale microfiltration plant, through to process optimisation and monitoring. The relative strengths and weaknesses of particle size counters and turbidimeters are discussed in terms of their application.

Key Words: ***Cryptosporidium*****; groundwater; microfiltration; particle size counting**

INTRODUCTION

Cryptosporidium parvum is a parasitic organism that can cause acute gastrointestinal disease in humans and cattle. The disease is usually self-limiting but can be life threatening in immuno-compromised individuals such as AIDS patients or the elderly. Infected hosts pass many millions of *C. parvum* oocysts in their faeces. An oocyst is a hard-coated, highly resilient, dormant form of the organism, some 4-6μm in diameter, as shown by microscopy.

Although most groundwater supplies in the UK are free from significant oocyst contamination, those under the influence of surface waters may carry a more serious risk, especially those with river catchments containing large numbers of livestock or a discharge from a wastewater treatment works. Several large outbreaks of cryptosporidiosis have been linked with contaminated groundwater supplies(1), including the 1997 outbreak in North London and Hertfordshire, which led to 345 confirmed cases of the disease(2).

Minimising *C. parvum* risk in groundwater supplies is a problem that needs to be tackled on many fronts. Improving the design and operation of water treatment works are two examples. *C. parvum* oocysts show resistance to traditional chlorine disinfection processes(3) and, because of this, modern water treatment in the UK has concentrated upon physical removal of the organism through such processes as microfiltration. The need to ensure appropriate treatment has been intensified by new legislation, passed in the UK(4), which makes it a criminal offence for a water company to supply drinking water containing more than 1 oocyst, viable or non-viable, of any *Cryptosporidium* species, per 10 litres of drinking water sampled.

Since no on-line oocyst monitor is available or likely to be in the short-term future, there has naturally been increased interest in using particle monitors as a *Cryptosporidium* risk management tool. Several types of particle monitors are commonly used in the Water Industry, notably turbidimeters and particle size counters. These instruments have been widely documented elsewhere, e.g. in Hargesheimer and Lewis(5). In brief, turbidimeters give a single measurement based on the amount of light scattered by a cloud of particles in the sample stream, whereas particle size counters not only count but size each particle within a number of specified, discrete size ranges.

A key question in the industry is whether particle size counting offer any additional benefits over conventional turbidity measurements. Two major benefits of particle size counts have been reported. Firstly, it has been widely demonstrated that whereas turbidimeters respond more significantly to submicron (<1μm) particles (5), particle size counting is a more sensitive measure of *C. parvum* oocyst-sized particles(6-9). This extra sensitivity appears to be most pronounced when dealing seen with filtered water quality below 0.1 NTU(6,7). Large differences between particle size count and turbidity readings have also been seen with certain chemically pretreated samples e.g.

preozonated filtered water samples(10) and flocculated water samples(11). Secondly, the sizing ability of particle size counters may also be of additional value at some works. For example, it has been reported that the ineffective operation of a backwash water recycle pump at one particular works was signalled by an increase in the number of 1-2μm particles measured in filtered water(12).

Southern Water, which supplies drinking water to areas in Hampshire, Sussex, Kent and the Isle of Wight first used a particle size counter at one of its works in 1992. It is currently working through a programme of site-based trials to assess potential uses of particle monitors at its ground and surface water works. This paper is a summary of work conducted to date at Burpham Water Supply Works.

Burpham Water Supply Works

Burpham is one of a number of groundwater supply works forming part of a water distribution network serving approximately 120,000 customers in West Sussex.
The works receives water from four boreholes sunk into the chalk of the South Downs. Southern Water is licensed to abstract up to 25 megalitres per day (Ml/d) from these boreholes, but typically takes only around 15 Ml/d because of deteriorating water quality at higher rates.

The groundwater in this area has historically been high in turbidity, aluminium and iron. This is thought to be due to fissure connections (Figure 1) at depth drawing water from the tidally influenced River Arun which flows over 1km distant from the boreholes. In 1995, the Company installed an Atkins Fulford 'Filtomat' MT38P microfiltration plant at the works to reduce turbidity and to provide additional protection against *C. parvum*. A Filtomat unit is a depth filter with a nominal poresize of 5μm. The plant at Burpham operates as a two-stage process with up to five units used in the first stage and four in the second, on a rotating basis. Each unit processes up to 300m^3/hr of water and is automatically configured to run in either stage following a backwash. A schematic diagram of the works is provided (Figure 2) along with a tabulated summary of treatment at the works (Table 1).

MATERIALS AND METHODS

Particle size counters

Since 1996, Southern Water has used several makes of particle size counter at Burpham. Initially PMS (Particle Measuring Systems) Liquilaz E20 units with 2-150μm sensors were used on-line to monitor works' 'feed', 'combined filtrate (first stage)' and 'combined filtrate (second stage)' as shown in figure 2. These were superseded by permanently installed Met-One PCX monitors with 2-750μm sensors. Each instrument was set up with a constant head weir to regulate sample flow rates and to debubble the samples. A third make of particle size counter, namely a Hiac Versacount monitor, with a 2-100μm sensor, was also used by the WRc to performance test the Filtomat plant during its commissioning.

After the Met-One PCX counters had been installed, a Liquilaz counter was kept on the feed sample for comparison. Apart from an initial problem in maintaining the required sample flow rate of 70ml $min^{-1}$to the Liquilaz counter (not attributable to the monitor), a very high correlation was observed between the two data sets (Figure 3). In general, two calibrated sensors do not always match this well: one study showed that they can vary by as much as 45%(13).

In this paper, the word 'size' has been included alongside 'particle' and 'counter' to differentiate these instruments from those which provide information only on particle size, or particle number (within a single size range), but not both. It has been dropped where a size range is specified or understood e.g. as in '>5μm particle counts'. Unless a size range is specified, listed counts will refer to the >2μm range (also referred to as 'total' counts). In drinking water samples, comparatively few particles are detected above 15μm, effectively making redundant any differences between sensors as far as their upper sizing limit is concerned.

Coincidence errors

In particle size counting, coincidence error is caused by two or more particles passing in front of the sensor simultaneously and being counted as one larger particle. The probability of this occurring increases with the number of particle counts in the sample stream. At Burpham, this is an important issue because the incoming water quality varies quite significantly. In particular, coincidence errors may have a serious effect on parameters such particle removal statistics. Manufacturers typically quote a number of particle counts for which there is an expected 10% error in measurement. To verify manufacturer's data for the PMS Liquilaz E20 particle size counter, a dilution experiment was carried out. Apparatus was set-up to continuously recycle water from a large glass beaker. A peristaltic pump and constant head weir was installed upstream of the particle size counter. The experiment was carried out on 500ml of raw (surface) water taken from Testwood WSW. Water in the beaker was agitated using a magnetic stirrer and the system tested to ensure that this did not affect particle counts. The sample was then diluted down in steps from its initial concentration by adding a volume of works final water from an airtight container every ten minutes. This dilution water had previously been analysed so that its particle count could be subtracted from calculations.

Results from this experiment showed that coincidence error was significant only with counts above 12,000 per ml (>2μm) (Figure 4). For this count, a 10% error is anticipated. This data compares extremely well with the manufacturer's data, which also suggests a 10% coincidence error at 12,000 particle counts. Because feed and filtrate particle counts read at Burpham generally fall well short of this figure, the effect of coincidence error is considered to be negligible. At particle counts of 16,000 per ml, estimated coincidence error rose to around 20%. Combining the two equations in Figure 4 gives the following equation from which the level of coincidence error with the Liquilaz E20 sensor can be estimated.

$$\text{Coincidence error (\%)} = 2.190 \times 10^{-3} \times \text{particle count } (>2\mu\text{m per ml}) - 15.8$$

Filtomat commissioning trials

During commissioning of the Filtomat plant, a set of performance tests was conducted by the WRc on a portable pilot plant temporarily set up at the works. This plant comprised an inlet tank (3500l capacity) followed by two MT38P units connected in series and run to waste. These units were individually tested for (a) particle removal, (b) particle removal with AC fine test dust (an industry standard) having been added to the feed, and (c) removal of heat inactivated *C. parvum* oocysts. For each of these tests, the flow through the pilot plant was maintained at 6.3 m^3/hr. A Hiac Versacount particle size counter was used for tests (a) and (b). In the case of the heat inactivated *C. parvum* test, a spike of 1 x 10^8 oocysts was dosed into the inlet tank, equivalent to a concentration of around 30,000 oocysts per litre. Three 20l barrel samples were then taken sequentially from downstream feed and first and second stage filtrate sample points. The method of Ongerth and Stibbs(14) was used to recover the oocysts. These were then stained with a monoclonal antibody and analysed by epifluorescence microscopy at x400 magnification. The results from this work are discussed in the next section.

RESULTS AND DISCUSSION

Different uses of particle size counters at Burpham WSW are described below. These have been subdivided into three groups, showing how the monitors have been used (a) to assess plant performance during commissioning, (b) as an optimisation tool and (c) as a monitoring tool, to identify any deterioration in water quality which may signify high *Cryptosporidium* risk.

Plant commissioning

Particle size counters were first used at Burpham to assess Filtomat performance in commissioning trials as previously described. Two performance limits were originally selected as contractual performance guarantees: (a) final water turbidity of <1 NTU and (b) 98% removal of >5μm particles across the two stages of filtration.

The >5µm size band was chosen because it was thought to provide a robust measurement of *C. parvum* sized particles which are typically around 4-6µm in diameter although other size bands would arguably have been equally valid. Samples taken from the pilot plant temporarily set up at the works were analysed using a single Hiac Versacount counter. This indicated a particle removal percentage of 83% for the >5µm size fraction (Table 2). (Subsequent continuous monitoring of the live plant showed that, after optimisation, this removal rate did improve, regularly exceeded 90% and, at times, attained its 98% target.) Conversely, the oocyst removal percentage exceeded 99.99%, a '3-log' difference. Standard deviation for the *Cryptosporidium* data sets was low, suggesting a high level of precision in the results. The AC fine test dust test results also demonstrated a very high filter performance (99.8% removal of >5µm particles). This is despite likely underestimation of the feed count in this particular trial, due to coincidence error. If all these figures are accurate, then they suggest that the filters preferentially remove different particles, depending on their physical characteristics: shape, rigidity, surface characteristics etc. This demonstrates the difficulty in interpreting single value particle count measurements with regard to *Cryptosporidium* risk. Particle size counting therefore has some value as a commissioning tool but only when used in conjunction with other tests.

Plant optimisation

Rather than read too much into individual particle count measurements, arguably a more satisfactory use of the monitors is in trend analysis e.g. in plant optimisation work. Two examples of how this was used to optimise the Filtomat plant now follow. Firstly, optimum performance is maintained through backwashing filters either (a) when filter run time exceeds 24 hours, (b) when combined filtrate water turbidity exceeds 0.6 NTU or, as more commonly occurs, (c) when differential pressure (d.p.) across either stage exceeds 0.3 bar. This limit was originally set at 0.5 bar. However, it was noted from particle removal trends (Figures 5 and 6), that plant performance regularly deteriorated towards the end of a run. The decision was therefore taken to reduce the d.p. limit initially to 0.4 bar and then to 0.3 bar, thereby shortening filter runs and leading to a net improvement in water quality (Figure 5). Run-times could be shortened in this way because the Filtomat backwash process using treated water is relatively efficient. Each unit takes around eight minutes to wash and uses just under 2m^3 of water.

In addition, when backwashes were triggered by a high d.p. across the first stage of filtration, originally, only filters in that stage would be washed. However, when the system was changed to wash both stages in sequence, an improvement was seen in performance (Figure 6). Particle removals immediately rose to the highest percentages ever observed on the plant (97% for >5μm particles.) This required only a further 8m^3 of wash water. This new backwashing system was tested three times in different raw water conditions before being implemented on a permanent basis.

Other plant monitoring

These previous studies have largely been based on particle removal statistics, which are suited to optimisation work. In this section, a more general use of particle size counting is described: that of routine plant monitoring to identify deteriorations in water quality which may or may not be associated with increased *C. parvum* risk.

Two periods of concern have been identified at Burpham. Firstly, groundwater quality is clearly subject to a tidal influence (Figure 7). Experience has shown that the amplitude of the spikes is greatest during spring tides in the summer months June to October. Secondly, other water quality spikes are linked to borehole pump operation, especially pump start-ups (Figure 7). Although the pumps are variable speed and do have a brief two-minute slow start facility, some deterioration in water quality is nevertheless inevitable because of the disturbance of settled particles in the borehole and connected mains.

On-going areas of study

A risk assessment of all these spikes, including a microbiological survey, is on-going at Burpham, and other works, to determine whether there is evidence to link high particle size counts with increased *Cryptosporidium* risk. At least one author has argued that this association cannot be made with any certainty(9).

Other study areas include (a) using the particle count data with tide and groundwater levels, etc. to model groundwater quality enabling the prediction of possible higher risk periods, and (b) assessing whether particle size counters can be used as a process control tool to minimise this risk. For example, one or more boreholes could be taken out of service automatically when particle counts exceed a certain value. This work will focus not only on absolute particle counts (i.e. per ml) but also on changes in particle size distribution as characterised by 'particle size ratios', e.g. the percentage ratio of 'small' (2-5μm) to 'larger' (>5μm) particles. Interestingly, in a separate study, water abstracted from a chalk borehole elsewhere on the South Downs, showed an increase in the proportion of 2-5μm particles counted during periods of suspected surface water ingress. This is assumed to be rainfall influenced and is in direct contrast to the readings taken at Burpham where proportionally more >5μm sized particles were counted during suspected ingress at peak tide times (Figure 7).

Particle size counts versus turbidity

Particle size counting has provided the catalyst for some useful investigation and optimisation work at Burpham. In addition, particle counts were seen to vary over a wider range of readings than turbidity (Figure 8), thereby demonstrating higher sensitivity. On the other hand, correlation between the two parameters was very high suggesting that the instruments' readings are very similar. In on-going studies at other ground and surface water treatment works, to be published later, evidence is emerging that there are some treatment processes where there is a more obvious benefit in using particle size counting in addition to conventional turbidity monitoring. For this reason, it is important to prioritise investment in particle monitor technology. At Burpham, the investment is sound because of the interest in the performance of the microfiltration plant. Investment at other groundwater works is currently under review.

CONCLUSIONS

1. After optimisation, the Atkins-Fulford Filtomat microfiltration plant removed up to 98% of particles at and above *C. parvum* oocyst size (>5µm).
2. The suitability of particle counts and other testing materials (heat inactivated oocysts, AC fine test dust) as surrogates for 'live' oocysts is questioned.
3. Particle size counting has some value as a commissioning tool but only when used in conjunction with other tests.
4. Some periods of potentially high *Cryptosporidium* risk were identified and these will form the basis of on-going risk assessment being conducted by Southern Water. This work will focus on (a) any associations between particle size counts and Cryptosporidium risk, (b) water quality prediction models, and (c) potential uses of the monitors in process control to minimise risk during periods of suspected surface water ingress.
5. The value of installing particle size counters at other groundwater works is still under review.

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Table 1 *Burpham WSW – Summary*

Works Name	Burpham WSW				
Water Source	4 chalk boreholes				
Maximum Design Capacity	19 Ml/d				
Typical raw water quality* (Warningcamp borehole)		*n*	*5th %ile*	*median*	*95th %ile*
	pH	21	6.9	7.2	7.5
	Conductivity (µS)	76	490	540	640
	Chloride (mg/l)	75	29	32	37
	Total Ca (mg/l)	76	115	123	130
	Turbidity (NTU)	21	0.09	0.21	0.45
	Total Fe (mg/l)	21	<0.007	<0.007	0.021
	Total Al (mg/l)	21	<0.004	0.006	0.023
Coagulation	None				
Polyelectrolyte	None				
Pre-filter chlorine	0.25 mg/l (free chlorine)				
Filtration	9 Atkins-Fulford Filtomat (MT38P) microfilters (two-stage)				
Typical final water quality*		*n*	*5th. %ile*	*median*	*95th. %ile*
	Turbidity (NTU)	125	0.06	0.13	0.65
	Total Fe (mg/l)	24	<0.007	<0.007	0.023
	Total Al (mg/l)	124	<0.004	<0.004	0.028
Disinfection	0.60 mg/l (Main dose, free chlorine) Approximately 40-125 mins Ct depending on flow 0.35 mg/l (free chlorine after sulphur dioxide addition)				

*Based on Southern Water audit samples taken in 1997/98
'n' = 'number of samples', '%ile' = 'percentile'
Lower limits of detection for Fe and Al are 0.007 and 0.004 mg/l respectively
Internal drinking water standards (Company wide limits) = 1.0 NTU, 0.100 mgFe/l, 0.100 mgAl/l.
Prescribed concentration or value (UK statutory limits) = 4.0 NTU, 0.200 mgFe/l, 0.200 mgAl/l.

Table 2 *Results from commissioning trials of the Atkins-Fulford Filtomat microfiltration units at Burpham WSW*

Sample	Feed	Filtrate		% Removal	Log-removal
Parameter		first stage	second stage	across both stages	across both stages
Particle counts (per ml)					
>2μm	966	477	274	71.6	<1
>5μm	169	45	28	83.6	<1
2-5μm	797	432	246	69.1	<1
>2μm (in AC dust test)	279258*	10678	1287	99.5	2-3
>5μm (in AC dust test)	44711*	1248	91	99.8	2-3
2-5μm (in AC dust test)	234547*	9520	1196	99.5	2-3
C. parvum oocysts** (per l)					
Mean	3088	50.0	0.17	99.994	4-5
St. dev.	163	20.7	0.15	-	-

'nd' = 'not detected', 'pc' = 'particle counts'

* Background particle counts measured in the feed water before the addition of AC dust have been subtracted from these figures. These are comparatively very small (237 per ml for the >2μm size range). Feed counts are likely to be have been seriously underestimated through coincidence error, as are subsequent removal percentages.

** Heat inactivated oocysts used. Mean and standard deviations for 3 samples shown.

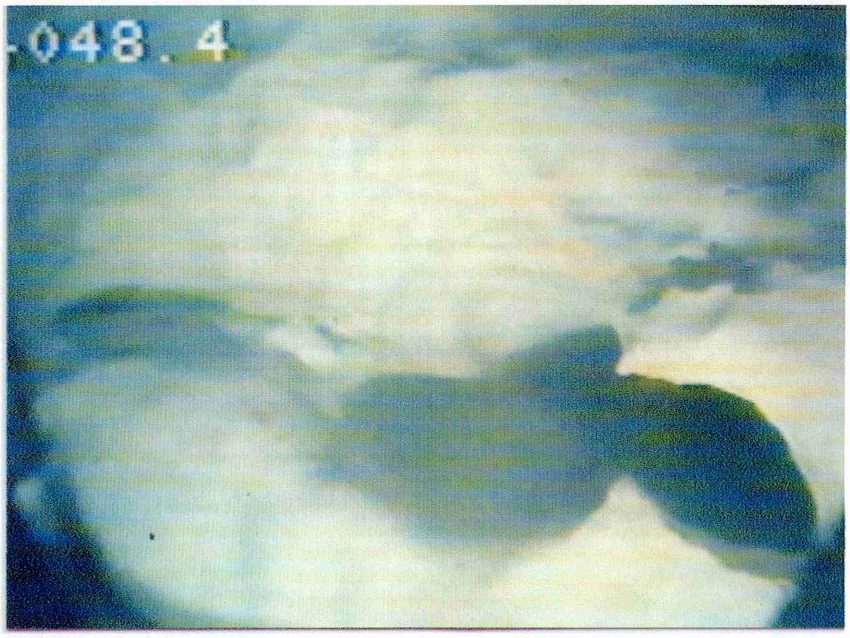

Figure 1 *Chalk fissures in a Burpham borehole at a depth of 48m from ground level. (CCTV still, 1992).*

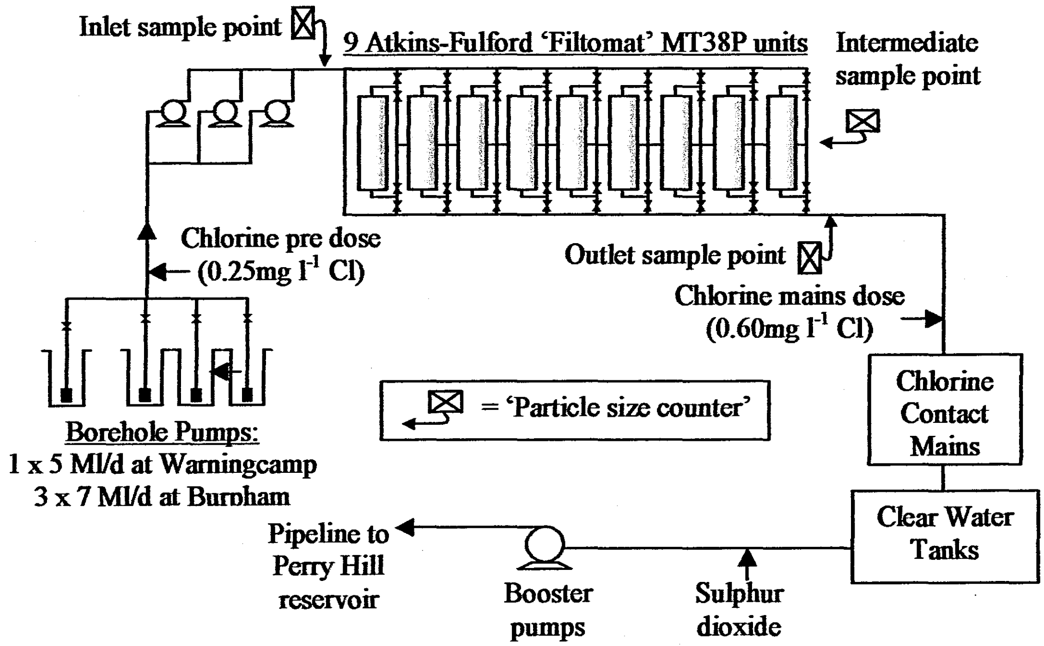

Figure 2 *Burpham Water Supply Works - Process flow diagram (Particle size counter sampling locations shown).*

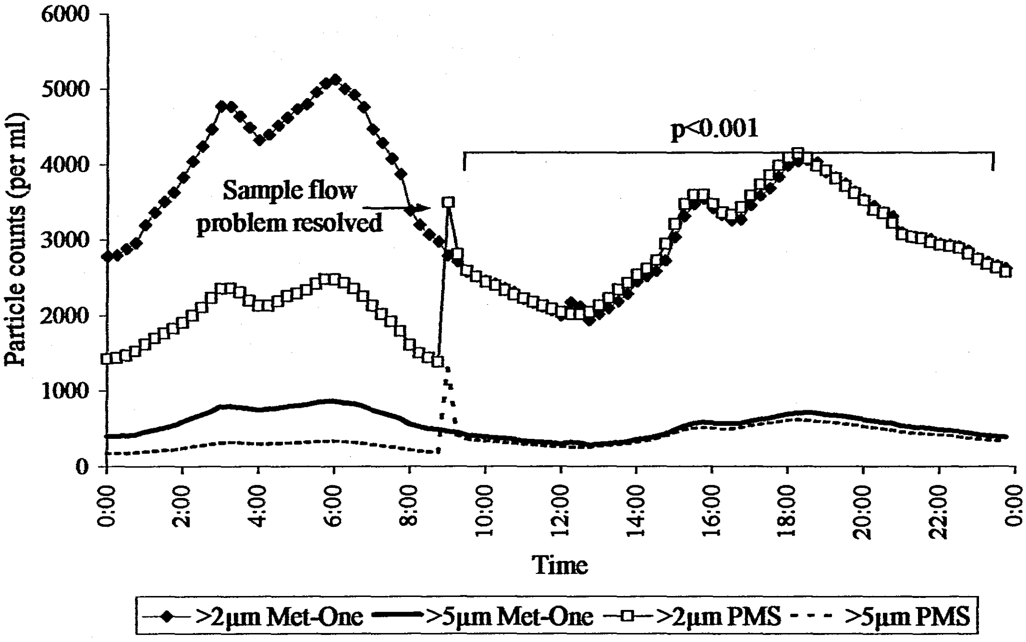

Figure 3 *Comparing a Met-One PCX and a PMS Liquilaz E20 particle size counter. Both monitors were set up on Burpham WSW raw water.*

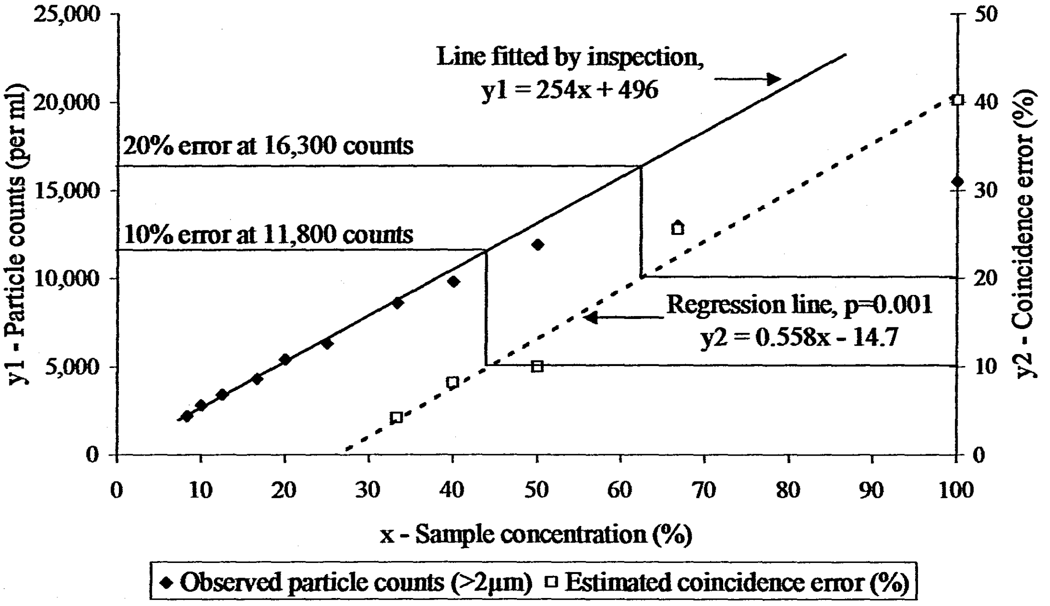

Figure 4 *Particle count measurements (Liquilaz E20) of ten different dilutions of a Testwood WSW raw water grab sample, showing the estimated levels of coincidence error associated with each measurement.*

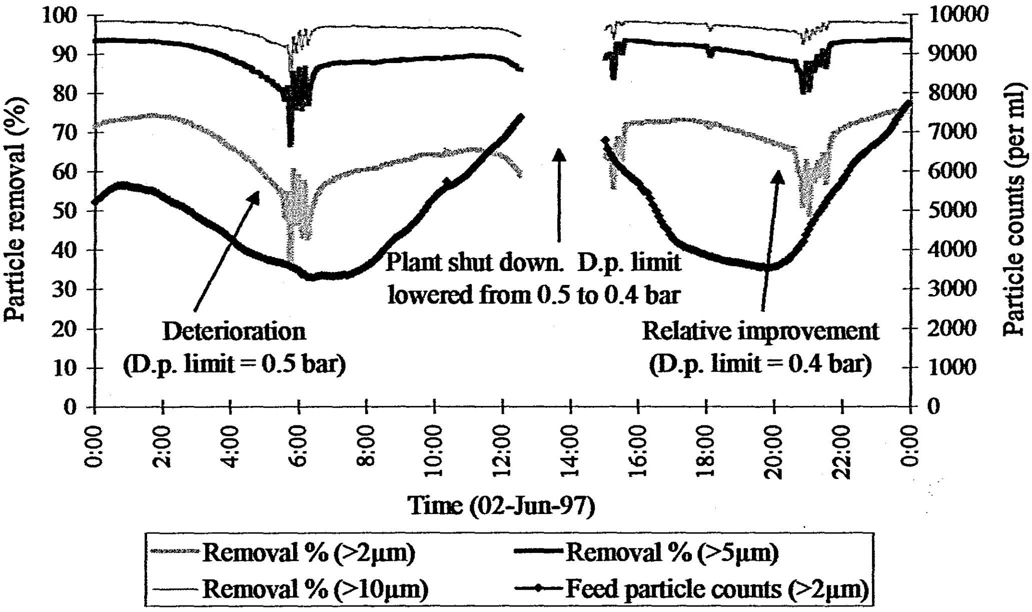

Figure 5 *Particle removal trends (Liquilaz E20) from the Filtomat plant at Burpham WSW, showing the relative improvement in filter performance at the end of a run obtained by lowering the differential pressure backwash trigger limit.*

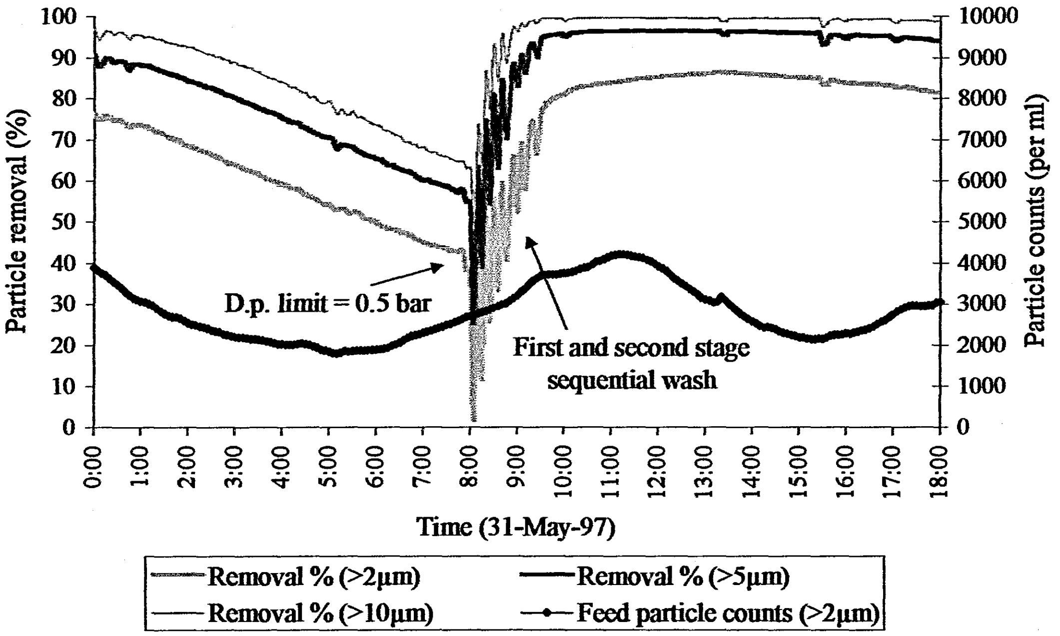

Figure 6 *Particle removal trends (Liquilaz E20) from the Filtomat plant at Burpham WSW, showing the benefit of a first and second stage sequential backwash.*

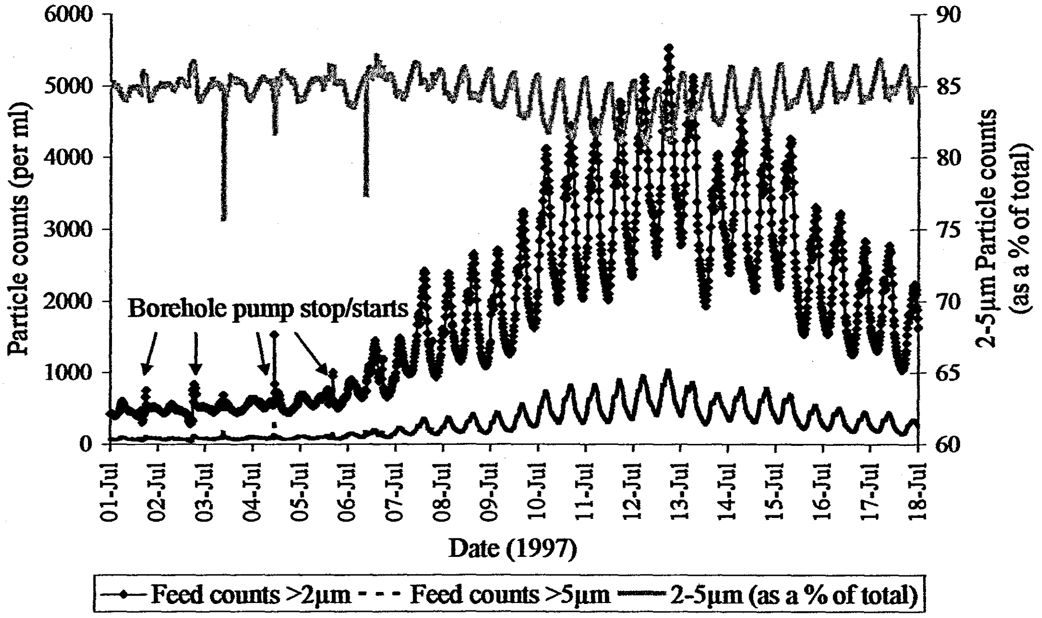

Figure 7 *Burpham WSW raw water particle count trend (Liquilaz E20) showing tidal and pump stop/start influences.*

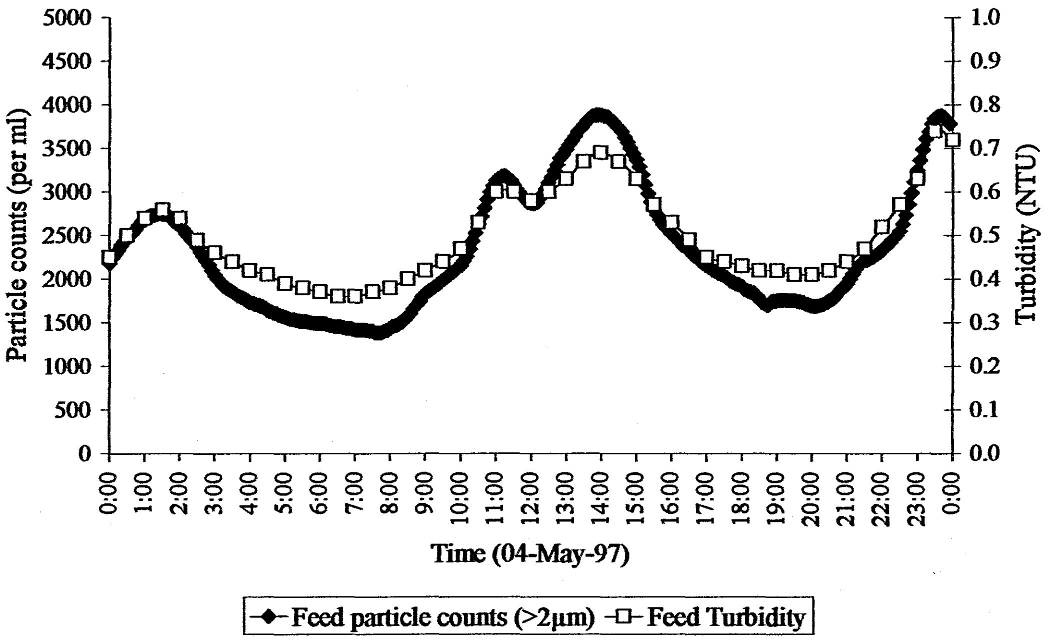

Figure 8 *A comparison of Burpham WSW raw water turbidity (Hach 1720C) and particle counts (Liquilaz E20).*

APPENDIX B

Good and bad particle counter use in potable water treatment.

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Good and bad particle counter use in potable water treatment.

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ABSTRACT

Over the last two decades, there has been much interest in whether particle counters hold any significant benefit over conventional nephelometric turbidimeters in monitoring, optimising and controlling potable water treatment processes. Southern Water, which supplies drinking water to two million customers living in Kent, Sussex, Hampshire and the Isle of Wight first used particle counters at one of its works in 1992. This paper presents the key results of a three year study, conducted in conjunction with Cranfield University to find the most beneficial use of these monitors, so that a sensible investment can be made.

This study comprised a series of monitoring trials, conducted at different ground and surface water treatment works. In many instances, there has been a strong similarity between turbidity and particle count trends, effectively making one of monitors redundant. On several occasions, however, particle counters did reveal useful information about a process, beyond that provided by turbidity. For example, the counters were able to more sensitively detect the influence of surface water on a low turbidity groundwater.

This issue of monitor sensitivity has been analysed using a regression model built from experimental data. For a given water sample, this model predicts how many more times sensitive particle counters will be, in detecting changes in water quality, compared to nephelometric turbidimeters. This indicated that whereas turbidimeters typically 'flat-line' at low values, particle counters are frequently more sensitive and so can be used as a fine-tuning optimisation tool. However, this sensitivity is also proportional to the particle size distribution of the sample, characterised here by a particle size ratio; particle counters are more suited to samples containing a high proportion of large particles (>10μm). This explains why particle counters are not always 'more sensitive' below 0.1 NTU.

The value of particle counters' sizing ability has also been assessed. In one example shown, particle size distribution data revealed a large difference in the volume of particles passed by two filtration plants. The study concludes that, where particle counters are used, there may be some value in routinely monitoring particle size distribution using a particle ratio or a similar statistic. Consideration is given to other practical concerns such as where and how to use particle counters and what parameters to measure.

INTRODUCTION

In the UK, the first major diagnosed outbreak of waterborne 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)[1,2] and Bouchier (1998)[3], 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 and particle counters.

Absolute particle monitor treatment standards in the UK are relatively relaxed: a treated water standard of 4 NTU is enforced through the 1989 Water Supply (Water Quality) Regulations[4]. However, the UK does have stringent *Cryptosporidium* legislation. Following the recent amendment to this Act[5], 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 water 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 recommendations are thought to be the best available guide. The Expert Groups have made several important recommendations with respect to particle monitors (Table 1).

Table 1 *Key Badenoch/Bouchier Recommendations on particle monitoring*

Reference	*Recommendation*
Recommendation 14.20 (Badenoch 1990)[1]	*'Water companies should install monitors to make it possible to measure the turbidity on each rapid filter... '*
Recommendation 22 (Badenoch 1995)[2]	*'Water utilities should ensure that the design and operation of treatment plants is optimised in a cost-effective way for particle removal taking into account the level of risk identified at each plant.'*
Recommendation 5.4.4 (Bouchier 1998)[3]	*'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 5.4.7 (Bouchier 1998)[3]	*'The Group encourages the use of particle count monitors to provide additional information to that provided by turbidity measurement.'*

Interestingly, although the Expert Group has set down clear guidance for the installation and use of turbidimeters, it has made no such provision in the case of particle counters. These are merely 'encouraged' as an additional optimisation tool. Also, under the UK system, the level of turbidity is not viewed to be as important as anomalous data; currently the Industry has so far resisted the imposition of low turbidity or particle count standards.

Particle counters vs. turbidimeters

A detailed description of these monitors has been published elsewhere[6-11]. In brief, most turbidimeters measure the amount of 90° light scatter from particles in a sample cell. This reflects the 'cloudiness' of water sample, relative to a known standard (usually formazine), and is typically expressed in NTU (Nephelometric Turbidity Units). Turbidimeters see a wide range of particle sizes (0.01µm upwards[8]) but their reading is mostly influenced by the number of submicron (<1µm) particles present in the sample as shown in latex bead experiments[10].

Conversely, most on-line particle counters measure a change in light intensity as particles pass through a laser beam. The 'shadow' (light obscuration) cast by each particle is proportional to its size within a defined size range. Particles are counted and sized within different, discrete bands, usually from one or two microns (µm) upwards, depending on the type of sensor used.

Despite the higher level of information provided by particle counters, some doubts still remain as to their real value. Particle counters are relatively more expensive to buy and run than turbidimeters and are of questionable accuracy and resolution[12,13]. They will only be valuable therefore if they relate something different to turbidity. In many instances, turbidity and particle count trends (measured over different size ranges) correlate strongly with each other[6,11,14-16], effectively making particle counters redundant. This is because particles (as sized by particle counters) tend to follow a characteristic size distribution, described by an inverse power relationship[6,17]. Indeed, one study[18] 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.'

A review of published particle counters applications is to be published separately[19]. This summarises the beneficial use of particle counters in the following three categories:

(a) Whereas turbidimeters frequently 'flat-line' at very low values, particle counters can be more sensitive to changes in water quality[6,11,20-22] and can therefore be used to fine-tune processes.

(b) Particle counters can also be more sensitive to changes associated with larger particle sizes. For example, they can sometimes give an early indication of filter breakthrough[17,23-25].

(c) The particle size distribution of a sample may also be of interest. Two studies[6,26] showed the proportion of larger particles in filtered water increasing towards the end of a filter run. Another[27] observed that the optimum coagulant dose of a pilot plant coincided at the point where there was a sudden shift in particles in the dosed water to larger sizes.

The following study set out to examine how particle counters can be best employed at Southern Water's treatment works. This has been conducted through a series of site-specific monitoring trials. Practical aspects of monitoring have also been examined such as where to install counters, how to use the data and what parameters to use.

METHODS

Light obscuration particle counters were temporarily installed at a number of surface and groundwater supply works (WSW) to monitor a wide range of sample types including several rapid gravity filter effluents, groundwaters and recycled washwaters. A brief description of the five works reported in this study is presented in Table 2. For works B, C and E, the same particle counter and turbidimeter were used. These were part of a mobile rig taken around different sites. The particle counters used were calibrated every 12 months as recommended by the manufacturers. They have not been count-matched[12,28]. Particles were counted in the following size ranges: >2μm, >3μm, >5μm, and >10μm. In addition, the >10μm particle (size) ratio has been used to characterise the particle size distribution. This is a simple expression of >10μm counts as a percentage of the total count. To provide a suitable scaling for this parameter, its logarithm, denoted by *a*, has also been utilized (Equation 1).

$$a = \log_{10}(Q_{>10\mu m}) \tag{1}$$

$$\text{where } Q_{>10\mu m} = \frac{>10\mu m \text{ particle count}}{>2\mu m \text{ particle count}} \times 100\% \tag{2}$$

Table 2 *List of works referenced in this study*

Works	*Source*	*Treatment*	*Sample*	*Particle counter*	*Turbidimeter*
A	Groundwater	Microfiltration(MF)* - chlorination	Pre MF	Met-One PCX	Hach 1720C
B	Groundwater	UV and chlorination	Pre UV	Met-One PCX	ABB 7997/202
C	Washwater/ clarifier sludge	Clarification-microfiltration**	Post MF	PMS Liquilaz E20	Hach 1720C
D	Washwater/ clarifier sludge	Clarification-microfiltration**	Post MF	Met-One PCX	ABB 7997/202
E	Surface water	Coagulation-clarification-RGF	Indiv. RGF outlet	Met-One PCX	ABB 7997/202

* Atkins Fulford Filtomat MT38P microfilters.

** Kalsep Fibrotex AX200.

RESULTS

Ineffective particle counting

As outlined previously, particle counters and turbidimeters regularly produce similar trend information. This was seen at several sites especially at the high turbidity groundwater sources monitored. For example, at Works A, although the particle counter did highlight some changes in groundwater quality caused by surface water influence, the same information was also seen in turbidity trends (Figure 1). In addition, little difference was seen between the particle count trends measured over the different size ranges. This shows that particle counters may not be especially useful at some works. In addition, the sizing ability offered by multichannel particle counts can also be of questionable value.

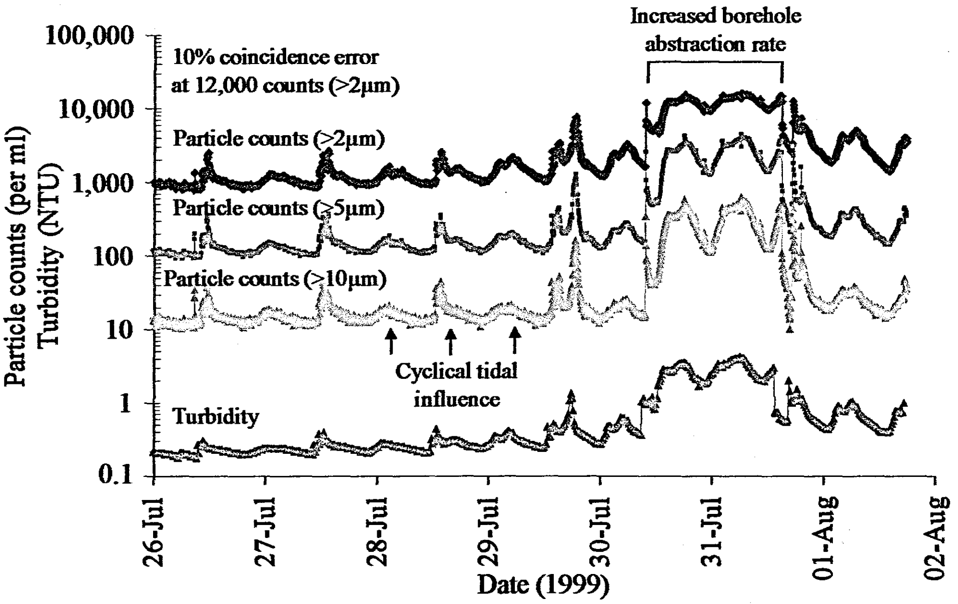

Figure 1 *Works A: high turbidity groundwater (>0.2 NTU).*

(This water undergoes microfiltration and chlorination before passing into supply.)

Particle counter can be more sensitive at lower turbidities

There were, however, several instances where particle counters did appear to have some beneficial use in the three categories highlighted previously. At a groundwater supply Works B, which generally produces low turbidity water (<0.1 NTU), particle counters were able to detect subtle surface water influence, which was not immediately clear from turbidity readings (Figure 2).

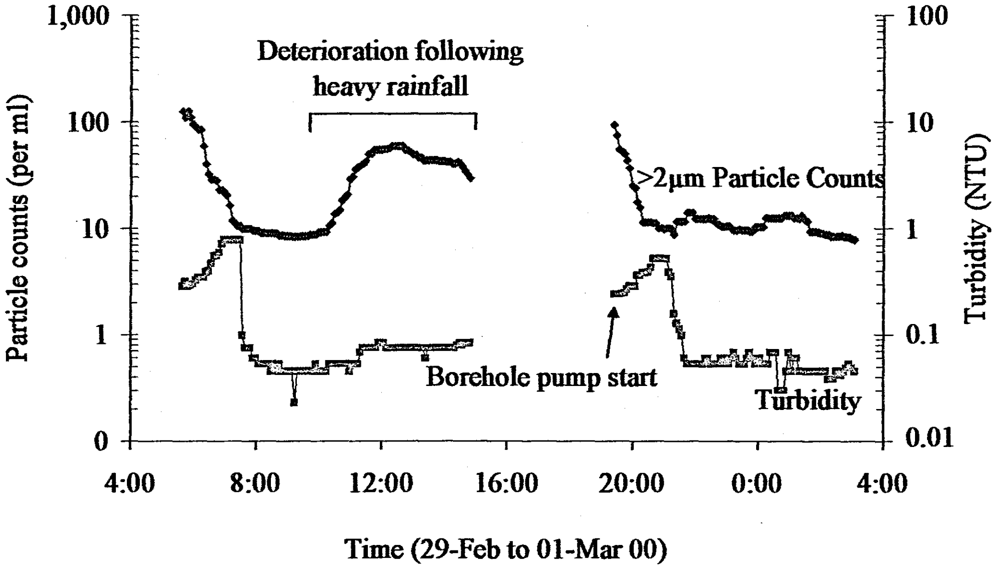

Figure 2 *Works B: low turbidity groundwater (<0.1 NTU).*

Particle counters can also be more sensitive to changes associated with large particle sizes

Although filter breakthrough has not been seen on any rapid gravity filter monitored during the study, an interesting observation was made during commissioning of a washwater/clarifier sludge recycle plant. Here, a blend of filter washwater and clarifier sludge is dosed with polyelectrolyte, undergoes settlement and microfiltration (Kalsep Fibrotex AX200) before being returned to the head of the works. The microfilter feed and filtrate water has an unusual particle size distribution because it contains large aluminium floc particles, with the >10µm size range accounting for between 7 and 30% of the total particle count.

As can be seen from Figure 3, compared with turbidity readings, the particle counter showed much more clearly the increase in particle numbers seen towards the end of each filter run. This suggests that particle counters may be more sensitive not only for samples where there is a shift increase in particle size (filter breakthrough), but also where the particle size distribution is consistently biased towards larger particles. Unfortunately, the particle counters monitoring such samples have shown a tendency to clog, which has restricted their use thus far. With better monitor design and/or sampling arrangements, the situation might be improved.

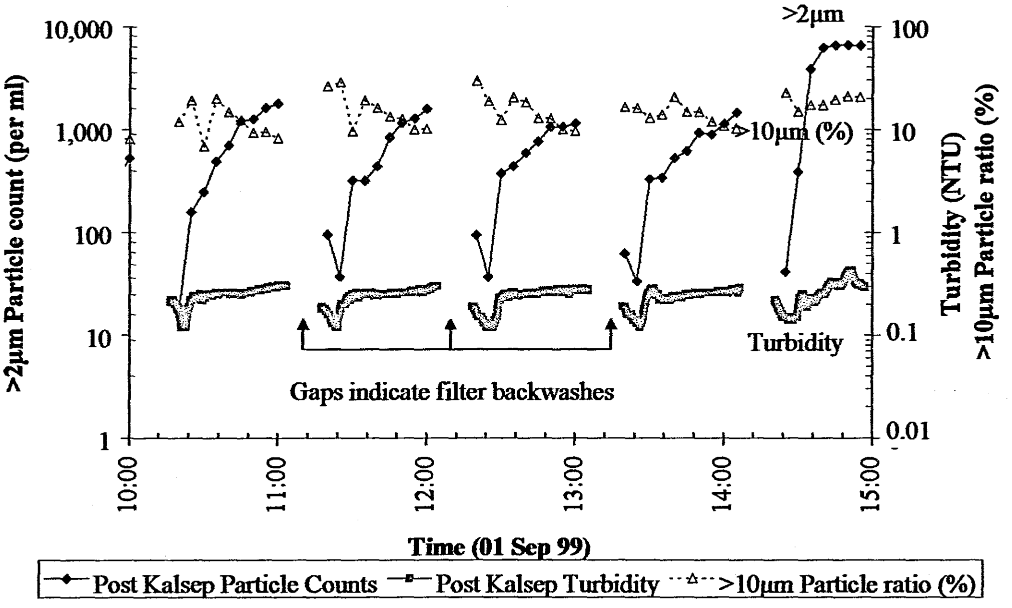

Figure 3 *Works C washwater recycling: post-microfilter particle trends*

Monitoring for changes in particle size distribution

Multichannel particle counters can also be beneficial in identifying anomalies in particle size distribution as well as count. Rather than looking obliquely at two or more differently sized particle counts, particle size is arguably best observed using a statistic such as inverse power coefficient, $\beta^{6,17}$ or, as used here, the >10µm particle ratio defined previously. In most cases, only small fluctuations were seen in particle size distribution. At one works, diurnal variations in particle size (not shown) were attributed to algae. Although, these were interesting from a 'research' point of view, they were of little operational value. However, particle sizing did yield some more significant benefits as shown in the following two examples.

The relationship between particle size distribution and particle volume

Particle sizing was used to compare representative samples taken from the two washwater recycling plants monitored (Table 2). Both processes were similar, the only difference being that a polyelectrolyte was added before clarification at Works C but not at Works D. On inspecting the turbidity and total particle counts entering and leaving the Kalsep microfilters it appears that Works C produces the cleanest recycled effluent. However, by considering the >10µm size range and the estimated particle volumes, the Works D plant performs better overall. This shows that particle size distribution is an important consideration when assessing filter performance. Ideally, when comparing samples in this way, some representation of particle size should be made (e.g. the >10µm particle ratio) in addition to the total count.

Table 2 *Samples taken from 2 washwater recycling processes*

	Works C	**Works D**
Polyelectrolye added?	Yes	No
Clarifier	Lamellar	Settle Tank
Microfilter	Kalsep AX200	Kalsep AX200
Pre Kalsep Turbidity (NTU)	10	8.9
Post Kalsep Turbidity (NTU)	0.38	2.9
Post Kalsep >2µm per ml.	6,568	11,391
Post Kalsep >5µm per ml.	2,262	3,054
Post Kalsep >10µm per ml.	1,374	716
Post Kalsep >10µm (% of total)	20.9 (a=1.3)	6.3 (a=0.8)
Post Kalsep Particle vol. (µm^3 per ml)*	2.46×10^7	1.76×10^7

* estimated

Particle monitor sensitivity model

Size distribution information was also useful in deriving a sensitivity model to compare particle counter and turbidimeter sensitivity when used on 'real' water samples. A more detailed account of this work is to be published separately[29]. Where particle monitor trends showed a deterioration or improvement in water quality, a comparison has been made between the size of change in turbidity readings and corresponding particle counts. For example, if a change in turbidity readings from 0.05 to 0.10 NTU (two-fold increase) coincided with a change in particle counts from 10 to 100 counts per ml (ten-fold increase), then in this instance, particle counters were five times more sensitive.

Figure 4 shows that particle counter sensitivity can be correlated against (a) baseline turbidity values (low readings) and (b) mean particle size distribution, characterised here by a. Although this model is 'observational' in origin, several inferences can be made from it.

(a) Particle counters tend to be more sensitive at low turbidities and can therefore be used to fine-tune treatment processes.
(b) A small change in turbidity can represent a large increase in particle number.
(c) Particle counters are not always more sensitive at low turbidities; this will depend on a sample's particle size distribution.
(d) Particle counters may be especially sensitive to changes in water containing a high proportion of large (>10μm) particles.
(e) The model can be used to assess the benefit of using particle counters at a works.
(f) It also provides a way of analysing anomalous particle count and turbidity data.
(g) Finally, it can be used to compare the sensitivity of different types of particle monitor.

A different model (to be published separately[29]), built from literature data revealed a similar pattern. Particle index monitors[30] (photometric dispersion analysers) gave a very similar response to particle counters at lower turbidities suggesting that these instruments may have potential as a cheap alternative to particle counters.

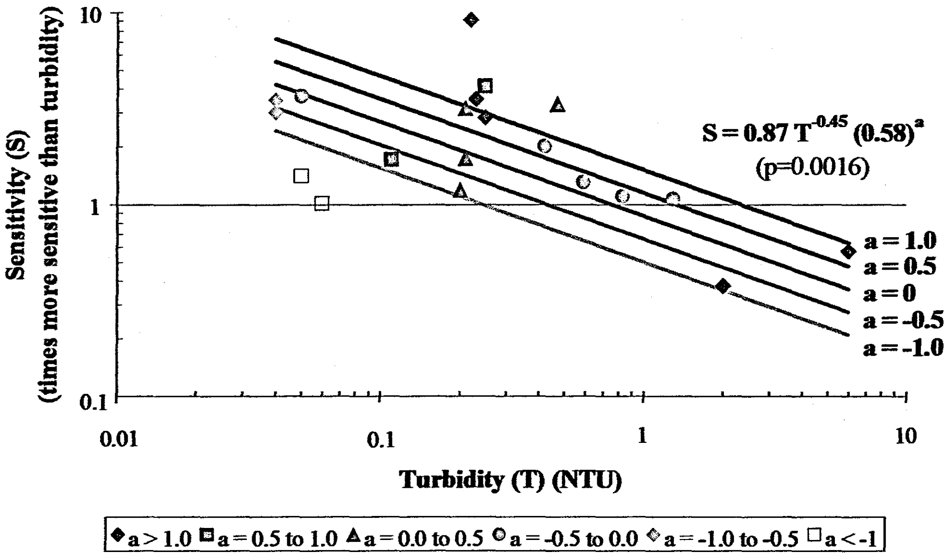

Figure 4 *Particle counter sensitivity model (Experimental data)*

DISCUSSION

Where to use particle counters

Counters used in the 'wrong' places will tend to produce a large amount of superfluous information. This justifies the need for caution when investing in this technology. However, as shown here, and by other authors, particle counters do have some potential benefits especially in fine-tuning processes at low turbidities (<0.1 NTU). In general, particle counters appear to be best used on high quality filtered water and groundwater samples although the exact level of sensitivity gained at lower turbidities will vary depend upon the particle size distribution of the sample. This can be assessed on a site-specific basis using the sensitivity model.

In terms of monitoring higher turbidity samples such as raw, dosed and clarified water, indications are that any successful applications, if they exist at all, will be limited to particle sizing (not studied). Exceptions to this may include samples containing a particle size distribution strongly biased towards larger particles, such as in the washwater example presented earlier, although the permanent installation of particle counters to continually monitor such samples is not advised unless provisions can be made against sensor blocking.

How to use particle counters

Particle counters are arguably best used as a non-regulatory process optimisation and research tool. For example they can be used for filter backwash and start-up optimisation[31], to investigate suspected filter breakthrough[17,23-25], to fine-tune coagulant dosing during stable raw water conditions[32], to check membrane filter integrity[22] etc. In these instances, permanently installed counters can be considered although portable instruments might be more cost-effective. Indeed the case for permanently installed counters on combined and/or individual filter outlets, for example, is still relatively unproven.

Currently in the UK particle counters are generally not used in on-line process control. This function is, for the most part, ably performed by turbidimeters. These are reasonably sensitive around and above 0.1 NTU and arguably are more important as far as detecting larger deteriorations in water quality, which may be more significant in terms of *Cryptosporidium* risk. For example, the largest problem in water treatment is controlling coagulant dose under rapidly changing raw water conditions[33,34]. On these occasions, turbidity may rise substantially above 0.1 NTU where particle counters would seem to be of diminishing value.

As mentioned previously, the Bouchier[3] Recommendation 5.4.4 recommends on large treatment works that, '*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 some suitably representative level.*' It is evident from the sensitivity model that below 0.1 NTU, a small change in turbidity e.g. from 0.05 to 0.06 NTU, for example, can still represent a large increase in particle numbers. A water company might therefore consider using particle counters to control processes that consistently produce very low turbidity water such as membrane or certain rapid gravity filter plants.

What parameters to use

This study corroborates previous work[6,11,14-16] which shows a high degree of similarity between different particle sizes. This can lead to a 'data overload' situation where valuable information can be overlooked. To minimise the number of particle trends, this study suggests that, where particle counters are being used, it would seem sensible to focus attention on three key parameters.

(a) A single particle count statistic such as a total count (>1μm or >2μm) to monitor changes in particle number.

(b) A particle size distribution statistic such as the >10μm particle ratio to identify changes in particle size distribution.

(c) These parameters are best viewed alongside turbidity readings. Particle counters and turbidimeters both see particles differently and so a more detailed picture is given when the information is trended together. For a deeper analysis, the sensitivity model can be used to compare the data.

This approach is very much trend-based: a particle 'counting' parameter for changes in particle number and a particle 'sizing' parameter for changes in particle size. It does not attach special significance to absolute particle figures nor does it presuppose a high level of particle counter accuracy and resolution.

Count differentials

In addition to monitoring particle counts and size, another potentially useful statistic is the particle count differential[35], which can detect sudden increases in particle count readings, e.g. taken at 15 minute intervals (Equation 3).

$$Differential = (>2\mu m Particle\ count)_{t=0} - (>2\mu m Particle\ count)_{t=-15} \qquad (3)$$

Count differentials are fairly resistant to calibration differences between individual sensors and are in keeping with the idea that particle counters should be used as a 'trend parameter'. They should not be confused with differential counts i.e. those measured over discrete size ranges, 2-3μm, 5-10μm etc.

One possible strategy would be to control a works on turbidity (as recommended by Bouchier[3]) but have local alarms set up to trigger when a certain increase in treated water particle counts is detected. In this way, treatment operators could be made aware of and investigate significant changes in water quality even at very low turbidity. In the example shown (Figure 5), an alarm triggered by a count differential of more than 10 counts per ml in successive fifteen minute readings picked up (a) each filter backwash (Enelco filter design) and (b) deterioration during periods of high raw turbidity when coagulation is perceived to have been sub-optimal. Further work is required to see how this alarm system would work in practice. An alternate system based on turbidity differentials could also be considered.

Further work

As the next part of its research, Southern Water is installing particle counters to monitor treated water (combined RGF outlet) at all eight of its surface water treatment works. Initially, these will be used for process optimisation and evaluation purposes only. This project is being undertaken in conjunction with the installation of automatic coagulant control systems at these works. The Company will continue to use portable particle counters in other process optimisation and evaluation work.

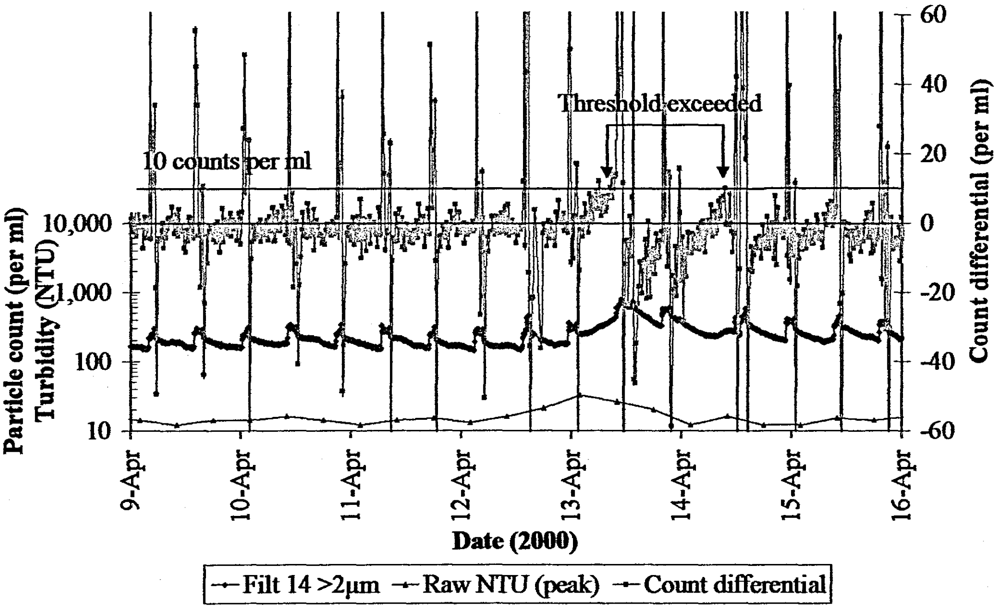

Figure 5 *Works E individual RGF outlet: Particle count differential shown alongside total particle count and raw water turbidity.*

CONCLUSIONS

Particle counters have been successfully used in three areas, utilising (a) their high sensitivity at low turbidities (below 0.1 NTU), (b) their high sensitivity to changes associated with larger particle sizes, and (c) their ability to detect anomalies in particle size distribution.

These results suggest that particle counters are generally best used as a fine-tuning instrument on very low turbidity samples (<0.1 NTU). In these instances, permanently installed counters can be considered although portable instruments might be more cost-effective. For processes that consistently produce very low turbidity water, there may be some value in using particle counters in process control. An alarm system based on particle count differentials could be used for this.

Where multichannel particle counters are being used, there may also be some value in looking at particle size distribution alongside particle counts and turbidity. This is best achieved by using a particle size statistic such as the >10μm particle ratio. The size distribution of particles in water samples, as defined by this particle ratio, has a significant effect on monitor sensitivity and can affect the suitability of using particle counters at some works. This can be assessed using the sensitivity model described. The model can be also used to compare the sensitivity of different particle monitors. There is limited evidence, for example, to suggest that particle index monitors are as sensitive as particle counters below 0.1 NTU.

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