<u>Good and bad particle counter use in potable water treatment.</u>

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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^o 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).

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

$$\text{where} \quad Q_{>10\mu m} = \frac{>10\mu m \ particle\ count}{>2\mu m \ particle\ count} \times 100\% \qquad (2)$$

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.

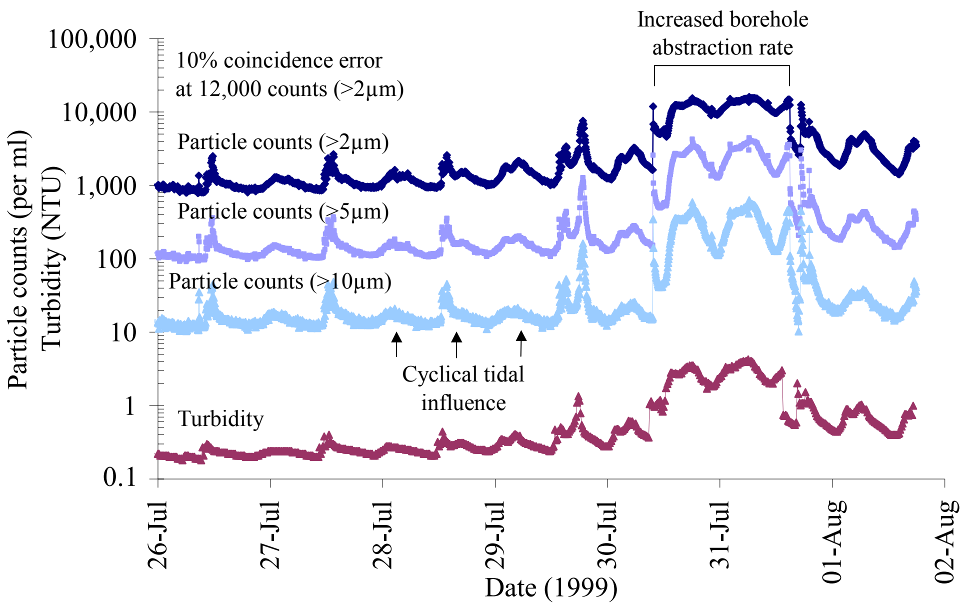

Figure 1 Works A: high turbidity groundwater (>0.2 NTU).
(This water undergoes microfiltration and chlorination before passing into supply.)

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).

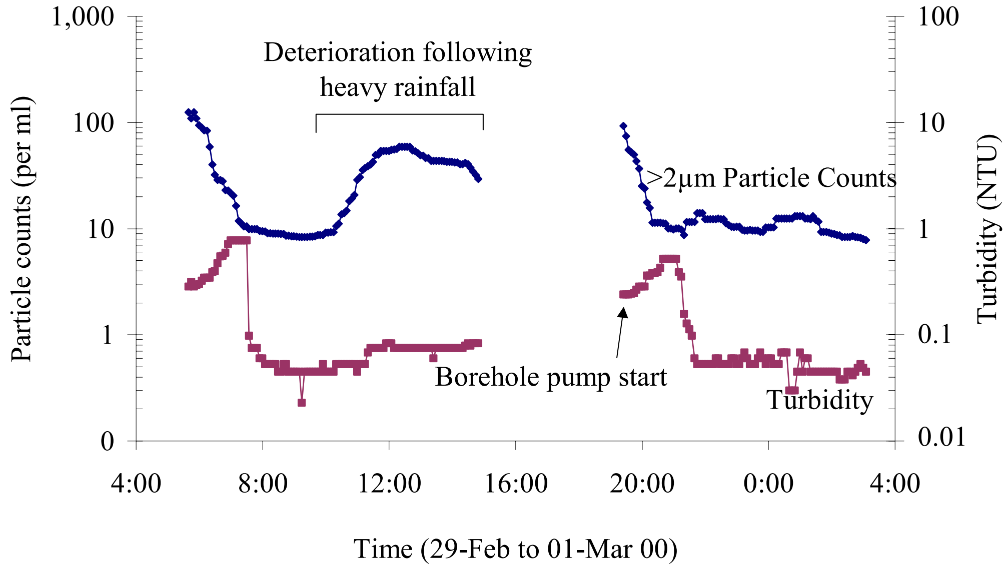

Figure 2 Works B: low turbidity groundwater (<0.1 NTU).

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.

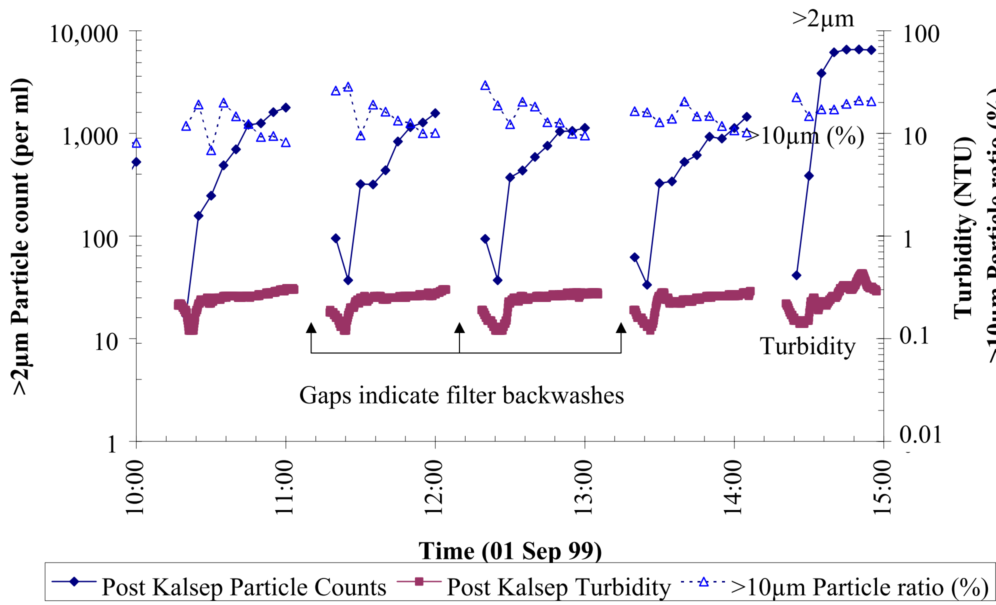

Figure 3 Works C washwater recycling: post-microfilter particle trends

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, β[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.

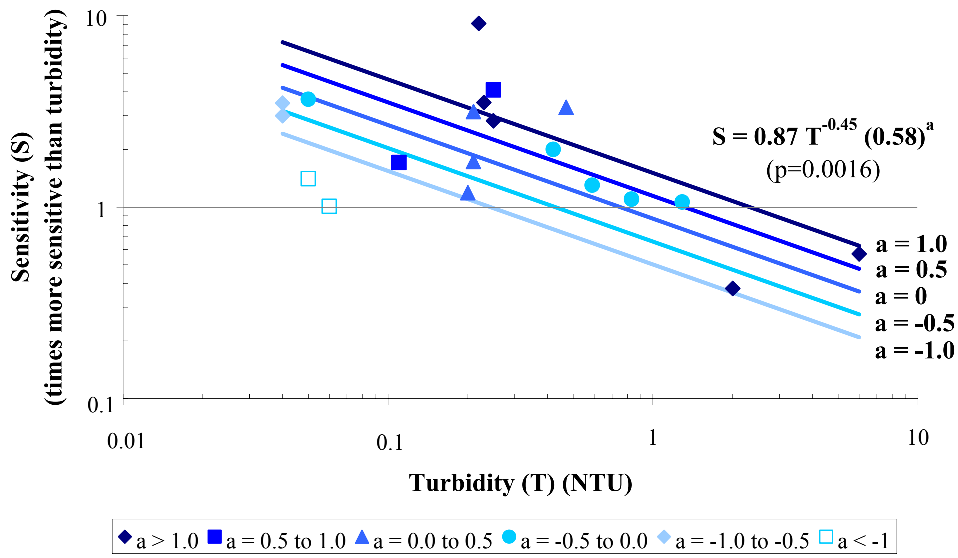

Figure 4 Particle counter sensitivity model (Experimental data)

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.

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 <u>consistently</u> 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.

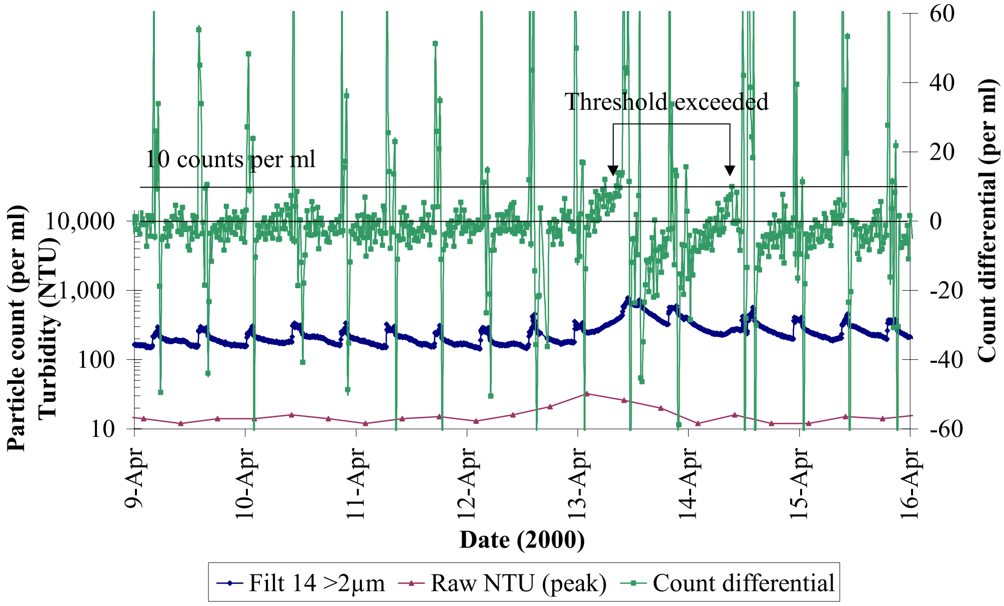

Figure 5 Works E individual RGF outlet: Particle count differential shown alongside total particle count and raw water turbidity.

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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