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An analysis of particle monitor sensitivity in potable water treatment

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ABSTRACT

The sensitivity of particle counters, relative to conventional turbidimeters, is shown to follow an inverse power relationship with turbidity. It is argued that particle counters are best used as fine-tuning instruments below 0.1 NTU turbidity.

A sample's particle size distribution is also shown to influence monitor sensitivity. The model provided can be used to assess the value of using particle counters at a treatment works. It can also be used to compare the sensitivity of different particle monitors as well as anomalous particle monitor readings.

Key words | particle counting, particle index, turbidity, water quality, water treatment

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INTRODUCTION

Studies have shown that reducing particulate matter in treated water samples can reduce the number of *Cryptosporidium* oocysts in drinking water (LeChevallier & 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 & Lewis 1995; Hunt 1993, 1995; 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, 1995). 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 0.01 μm upwards (Hunt 1993), they respond optimally to particles in the submicron (<1 μm) size range as shown by latex bead experiments (Gregory 1994). Most particle counters, on the other hand, count supermicron particles (>1 μm). Particle index monitors are especially sensitive to very large (>20 μm) particles (Kirby *et al*. 1998).

Despite these differences, however, when monitoring 'real' water samples, a strong degree of correlation is often

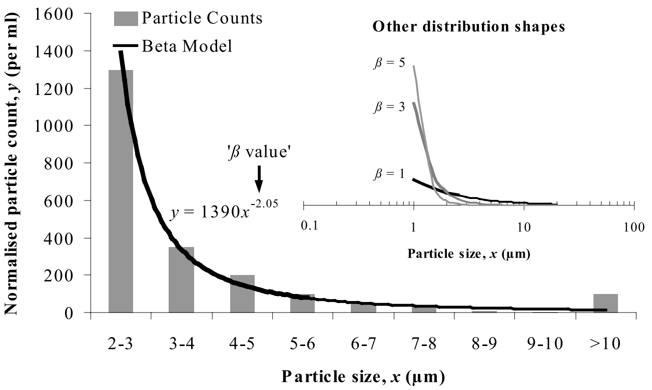

Figure 1 | Typical size distribution of particles in water.

seen between different particle counts and turbidity trends (Hargesheimer *et al.* 1992; Hargesheimer & 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; Kavanaugh *et al.* 1980; Ginn *et al.* 1992; Hargesheimer *et al.* 1992), described by an inverse power relationship (Figure 1, Equation 1), and to vary in similar proportions across all size ranges. The similarity between particle counts 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.

$$\textit{Particle size distribution},\ N_i = A x_i^{-\beta} \qquad (1)$$

where 'normalised' count,

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

x_i = particle size, midpoint of channel i (µm),
A and β are 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 & Trussell (1978), Hargesheimer *et al.* (1992) and Hargesheimer & 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.* (1993), an increase in filtered water turbidity from 0.08 to 0.10 NTU was mirrored by an increase in particle count from 82 to 101 per ml (>1 µm) 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, 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.

METHODS

Sensitivity modelling

The data analysed in this study have 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

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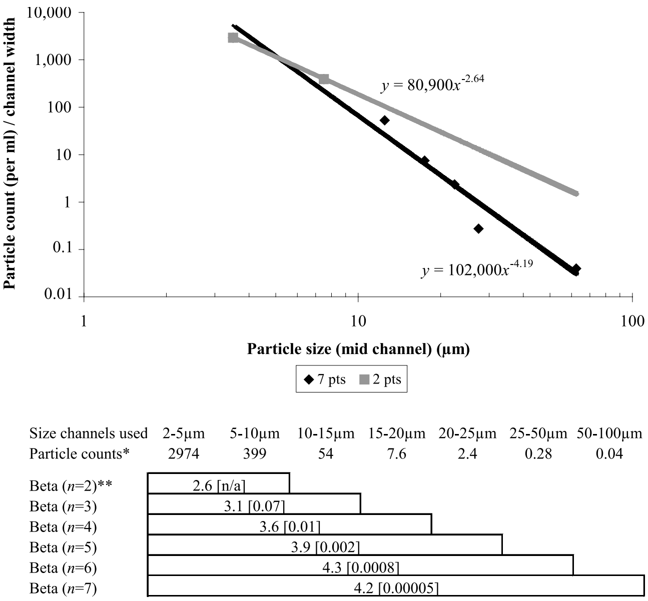

Figure 2 | Beta estimates calculated using different size channels (light obscuration sensor, surface water sample, data taken from Hargesheimer & Lewis 1995). *Normalised particle count (i.e. divided through by channel width). **n=number of indicated size channels used to calculate beta. The significance level [P] associated with each β calculation is shown in square brackets.

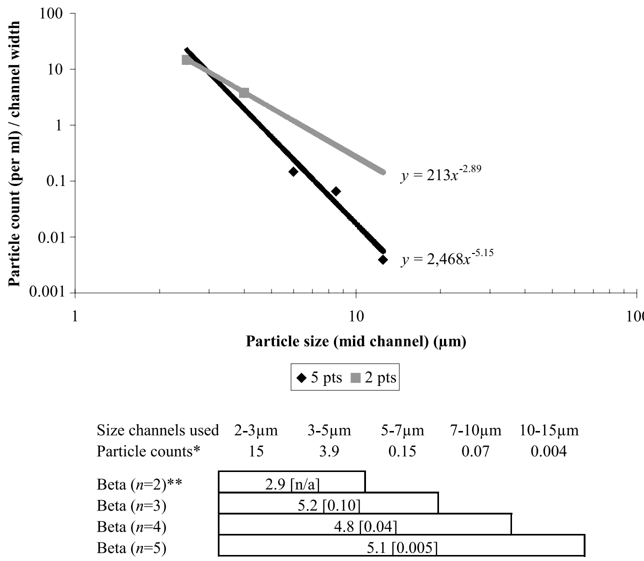

Figure 3 | Beta estimates calculated using different size channels (light obscuration sensor, filtered groundwater sample). *Normalised particle count (i.e. divided through by channel width). **n=number of indicated size channels used to calculate beta. The significance level [P] associated with each β calculation is shown in square brackets.

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:

$$S_{\mathrm{pc}} = \frac{\Delta_{\mathrm{pc}}}{\Delta_{\mathrm{ntu}}},\ S_{\mathrm{pi}} = \frac{\Delta_{\mathrm{pi}}}{\Delta_{\mathrm{ntu}}} \qquad (2)$$

$$\text{where } \Delta_{\mathrm{monitor}} = \frac{\text{high monitor reading}}{\text{low monitor reading}} \qquad (3)$$

'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 $\Delta_{\mathrm{ntu}} = 1.7$. At the same time, particle counts (>1 µm) increased from around 2 to 1000 per ml, giving $\Delta_{\mathrm{pc}} = 500$. Dividing Δ_{pc} by Δ_{ntu}, gave $S_{\mathrm{pc}} = 300$ 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 $S = 500$, for example 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.

Experimental data

The experimental data have been extracted from five 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).

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

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Table 1(a) | 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) Figs 9,11	Post membrane	Damaged fibres	Met-One 250/211 (FALS, > 1 μm)	0.02	1.00	50.0	1	10,000	10,000	200
Saunders *et al.* (1999) Figs 1.8	Post RGF	Filter breakthrough	Not specified	0.025	0.026	1.0	20	125	6.3	6.0
Pizzi & 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) Figs 9,11	Post membrane	Damaged fibres	Met-One 250/211 (FALS, > 1 μm)	0.03	0.50	16.7	2	10,000	5,000	300
Adham *et al.* (1995) Figs 9,11	Post membrane	Damaged fibres	Met-One 250/211 (FALS, > 1 μm)	0.03	0.50	16.7	5	5,000	1,000	60
Jacangelo *et al.* (1991) Fig. 7	Post membrane	Damaged fibres	Met-One 210/211 FALS, > 2 μm)	0.04	0.06	1.5	2	1,000	500	333
Chipps *et al.* (1995) Table 3	Post RGF	Lower pre-ozone dose	Unspecified LO counter	0.04	0.05	1.3	400	4,200	11	8
Hargesheimer *et al.* (1992) Fig. 8.15	Post RGF	Filter ripening	HRLD-150 sensor (LO, > 1 μm)	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, > 1 μm)	0.07	1.3	18.6	750	12,000	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 (> 2.5 μm)	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, > 1 μm)	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, > 0.7 μm)	0.08	0.12	1.5	600	2,100	3.5	2.3
Goldgrabe *et al.* (1993) Table 3	Post filter	Filter acclimatisation	Hiac Royco 9064/HRLD-150 (LO, > 1 μm)	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, > 1 μm)	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 & Manz (1991) Fig. 2	Post RGF	Filter breakthrough	Hiac Royco 4100/346-BCL (FALS)	0.10	0.30	3.0	100	3,000	30	10
Lewis & Manz (1991) Fig. 2	Post RGF	Filter breakthrough	Hiac Royco 4100/346-BCL (FALS)	0.10	0.45	4.5	300	8,000	27	5.9
Hall & Croll (1997) Fig. 1	Post RGF	Filter breakthrough	Hiac Versacount	0.1	0.5	5.0	100	2,500	25	5.0

Table 1(a) | Continued

Reference*	**Sample**	**Reason for change**	**Particle counter/sensor**	NTU_{low}	NTU_{high}	Δ_{ntu}	PSC_{low}	PSC_{high}	Δ_{psc}	S_{psc}
Keay (1995) Fig. 3	Post RGF	Filter breakthrough	Unspecified electrical resistance counter	0.10	0.25	2.5	50	550	11	4.4
Tate & Trussell (1978) Fig. 7	Post RGF	Poly dose change	Hiac Model 320	0.11	0.36	3.3	5	105	21	6.4
Beard & Tanaka (1977) Fig. 2	Post RGF	Filter ripening	Hiac PC-320/Not specified (> 2.5 μm)	0.11	0.2	1.8	16	100	6.3	3.5
Hall & Croll (1997) Table 4	Post RGF	Filter ripening	Hiac Versacount	0.15	0.2	1.3	1,500	4,300	2.9	2.2
Kavanaugh *et al.* (1980) Fig. 10	Post RGF	Filter breakthrough	Hiac Model 320	0.18	0.36	2.0	20	1,000	50	25
Hall & Croll (1997) Table 4	Post RGF	Filter ripening	Hiac Versacount	0.2	0.4	2.0	7,100	15,000	2.1	1.1
Wilson & Morse (1999) Fig. 5	Post RGF	Filter ripening	PMS Liquilaz E20	0.20	0.36	1.8	130	680	5.2	2.9
Tate & 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 & 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.* (1998) Fig. 3	Post RGF	Misc. samples	PMS Liquilaz E20	0.3	1.2	4.0	600	5,300	8.8	2.2
Hamilton *et al.* (2000) Fig. 8	Groundwater	Tidal influence	PMS Liquilaz E20	0.36	0.69	1.9	1,385	3,886	2.8	1.5
Hargesheimer & Lewis (1995) Fig. 6.1	Surface water	Misc. samples	PMS Liquilaz E20	0.6	7.4	12.3	7,800	30,000	3.8	0.3

Table 1(b) | 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) Figs 10–11	Post membrane	Damaged fibres	Chemtrac PM3500	0.02	1.00	50.0	5	10,000	2,000	40
Adham *et al.* (1995) Figs 10–11	Post membrane	Damaged fibres	Chemtrac PM3500	0.03	0.50	16.7	1	9,000	9,000	540
Adham *et al.* (1995) Figs 10–11	Post membrane	Damaged fibres	Chemtrac PM3500	0.03	0.50	16.7	10	1,000	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.
RGF=rapid gravity filter; LO=light obscuration; FALS=forward angle light scatter.

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 2 & 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 two or more size channels are used. The difference is especially apparent in Figure 2 data with a 'knee' clearly visible around the 10 μm gradation. Interestingly, in latex bead experiments, Van Gelder *et al.* (1999) observed that, compared with electrical resistance particle counters, light obscuration instruments tended to underestimate the number of particles in the 2–5 μm size range. Whether these observations are linked is unclear.

Figure 2 shows that the inclusion in the calculations of particle counts above 20 μm 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 2, a point of relative equilibrium is reached when using 4 size channels; in Figure 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: 2–3 μm, 3–5 μm, 5–10 μm, and 10–20 μm.

Particle ratios

Because of the discrepancies seen when calculating β, an alternative size distribution parameter was also used, namely the proportion of 'large' particles (>10 μm) in a sample expressed as a percentage of the total count, denoted here by $Q_{>10\,\mu m}$ (Equation 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).

$$Q_{>10\mu m} = \frac{>10\mu m \text{ particle count}}{>2\mu m \text{ particle count}} \times 100\% \quad (4)$$

$$a = log_{10}(Q_{>10\,\mu m}) \quad (5)$$

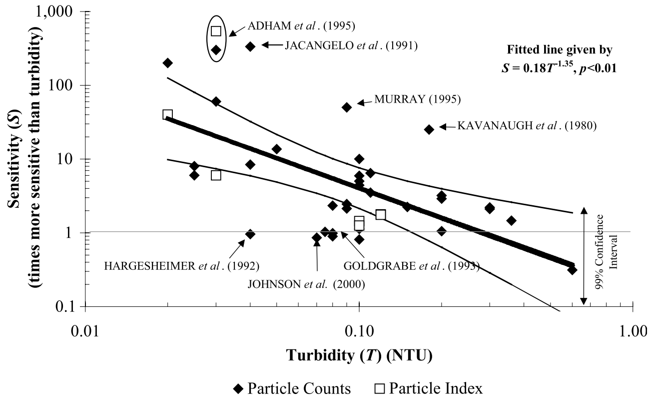

Figure 4 | Particle monitor sensitivity model (literature data).

RESULTS

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 1a & 1b), a strong inverse power relationship between particle monitor sensitivity (S) and turbidity (T) was apparent (Figure 4), given by:

$$S = 0.18T^{-1.35},\ p<0.01 \quad (6)$$

which 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 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 has been 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 fall outside the 99% confidence interval shown in Figure 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.

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 2) were used. As can be seen in Figure 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.

$$S_{pc}=3.71T^{-0.50}(0.66)^{\beta},\ p<0.01 \quad (7)$$

Alternate model using particle ratio

Because of discrepancies surrounding the calculation of beta, an alternate model was also built. This used the >10 μm particle ratio (a) defined previously. As can be seen in Figure 6, a similar pattern was seen linking particle counter sensitivity with turbidity and particle size.

$$S_{pc}=0.87T^{-0.49}(0.58)^{-a},\ p<0.01 \quad (8)$$

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.

DISCUSSION

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 (Works A) 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 for 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.

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 ($\beta<3$).

Table 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}	a**	Diff**	β**	Diff**
A	Groundwater	Rainfall 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
B	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
C	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
D***	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
E	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

*>2 μm counts per ml.
***a* 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 the Discussion section.

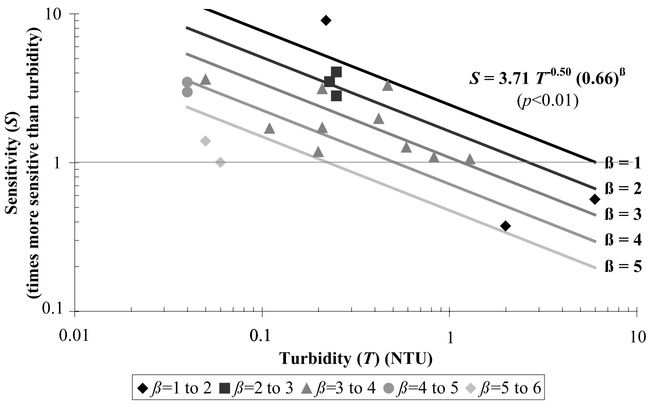

Figure 5 | Particle counter sensitivity model with β (experimental data).

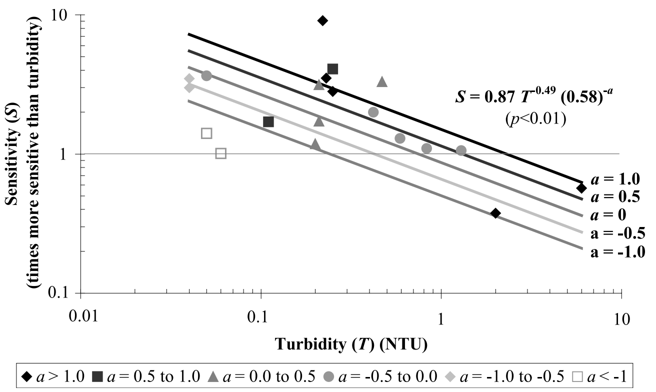

Figure 6 | Particle counter sensitivity model with particle ratio (experimental data).

This has several implications. First, where there is an anticipated shift increase or decrease in particle size, the sensitivity of particle counters (>2 μm) 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 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 (Works D). Here, a blend of filter washwater and clarifier sludge is dosed with polyelectrolyte and 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.

CONCLUSIONS

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.

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