Measuring particles in drinking water transportation systems with particle counters

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ABSTRACT

Particles within distribution systems can deposit and resuspend causing problems with discolouration of drinking water. In two Amsterdam drinking water distribution networks the use of particle counters to monitor the particle quantity is investigated. Particle counters were found to be far superior to turbidimeters, as the greater amount of qualitative and quantitative data obtained by particle counters allowed determination of particle size distributions and residence times. Although the treatment processes of the two systems studied were fairly comparable, a large difference in particle size and number of particles in the two systems was found. Particle counters have proven to be a valuable tool in understanding processes in a distribution system.

Key words | drinking water, online monitoring, particles, particle counting, transportation system

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INTRODUCTION

Distribution systems are complex systems. In general, they have a length of several tens to hundreds of kilometres with varying diameters and materials in a multi looped network. The distribution systems are hidden underneath the ground and no accurate data on actual flow rates, residence times and water quality in the systems are generally available. Research on water quality within the distribution system is mostly restricted to the analysis of samples prescribed by legislation. Broader scoped research is rarely being undertaken due to the high cost and the limited application of the resultant case-specific information. In addition, any full scale trials are high risk due to the possible negative impact on water quality in the distribution system, which may result in customer complaints (Eisnor & Gagnon 2003). On-line information about the water quality in distribution systems is important; as it can provide an understanding of the processes eventually resulting in water quality deterioration at the customers tap, compared to the water leaving

the treatment plant. If on-line monitoring is performed it is generally restricted to relatively simple parameters such as turbidity, pH, conductivity, temperature and sometimes flow rate measurements (van de Hoven & Vreeburg 1992). However, especially turbidity is not sensitive enough for the high quality, low particulate drinking water distribution systems.

A large proportion of customer complaints stem from the occurrence of discoloured water in drinking water distribution systems. Discolouration is associated with loose deposits or particulate material in networks (Gauthier *et al.* 1996; Boxall *et al.* 2001; Carriere *et al.* 2005), which can originate from different sources. Particle counters provide detail on the size and the number of particles in water. In the last decade on-line particle counters have become available for applications in drinking water treatment. Well known examples of the use of particle counters are detection of fibre breakage of membranes (Glucina *et al.*

1997) and evaluation of treatment efficiency (O'Leary *et al.* 2003). Particle counters have also been applied in a study to relate turbidity, particle counts and bacteriological quality within water distribution lines (McCoy & Olson 1986). It was concluded that, although there was a direct positive relationship between turbidity and particle counts across different distribution systems, no direct relationship was seen within a distribution system due to the variability of measurements. In another study multiple on-line particle counters were used to evaluate the effect of changes in velocity in a pilot distribution system (Maier 1999). Sharp increases in total number of particles (factor 100) were found when the flow increased. The peaks propagate, almost intact, through the test rig system.

Recently, Dutch water companies have commissioned an ambitious research programme in pursuit of an impeccable water quality, called Q21 (van Dijk & van der Kooij 2005). The programme includes, among others, studies on the prevention of water quality deterioration in the distribution network. Part of the wider Q21 study is looking at tools for understanding the processes resulting in water quality deterioration in the distribution system. The aim of this particular study is to obtain on-line information about the quantity of particulate material in drinking water distribution systems. Furthermore, a comparison of the particulate material at different locations in the distribution system and between different distribution systems will be made. Experiments have been done in two different distribution networks of the Amsterdam Water Supply. In both networks multiple turbidimeters and particle counters have been used, simultaneously, to observe changes in particle size distribution.

MATERIAL AND METHODS

Characteristics of the Amsterdam water supply system

For the city of Amsterdam drinking water is produced at two locations; Leiduin and Weesperkarspel (Figure 1). Both treatment plants feed distribution systems with different characteristics. The Leiduin system is a low pressure transportation system delivering water to distribution reservoirs close to the city. The changes in flow rates in

this system are gradual. The Weesperkarspel system is a combined transportation and reticulation system without distribution reservoirs. As a result larger variations in flow rate occur.

Drinking water from the Leiduin treatment plant has undergone a number of treatment steps. The source water from the river Rhine is pre-treated by flocculation with iron chloride, settling in open basins and rapid sand filtration. Then the pre-treated water is transported over 60 km to a dune area where it is infiltrated. After a residence time in the dunes of at least 60 days the water is abstracted via wells and canals and transported in an open system to the Leiduin treatment plant. At the Leiduin treatment plant the water is aerated, rapid sand filtered, ozonated, softened, activated carbon filtered and finally slow sand filtered. Caustic soda is used for the softening. Drinking water from the Weesperkarspel treatment plant has undergone a similar multi-barrier treatment. A mixture of canal water and seepage water is first coagulated with iron chloride, stored for about 3 months in a reservoir and afterwards treated by rapid sand filtration, ozonation, softening, activated carbon filtration and slow sand filtration. The distributed water of both treatment locations has a very good quality (see Table 1). The biological stability due to the low AOC value should be highlighted, as a result of the final slow sand filtration.

From the Leiduin treatment plant several transport lines deliver the drinking water to the western side of the city of Amsterdam (Figure 2). Most water goes through the Haarlemmermeer intersection, where a relatively small flow is diverted through a booster station to the Schiphol airport. Afterwards, the main splits into two lines: Amstelveenseweg North and Amstelveenseweg South before reaching the Amstelveenseweg storage reservoir. The North-line is somewhat shorter than the South-line and has part of its supply diverted to the distribution system at the booster station at Osdorp. The transport mains that are monitored are made of concrete and cement mortar lined steel and the total distance between Leiduin and Amstelveenseweg is about 23 km. Sampling of particles and turbidity at all locations took place directly from the transportation mains.

Drinking water leaving the Weesperkarspel treatment system is directly fed in a combined transportation and reticulation system. At Diemen and Zeeburg standard water
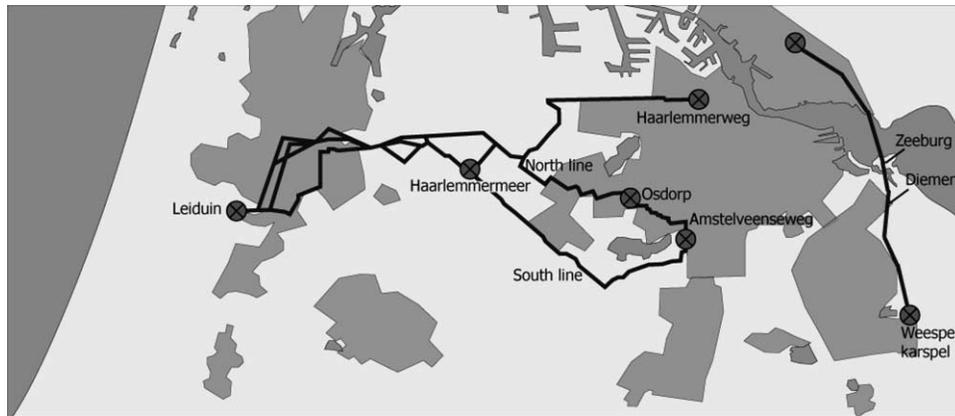
Figure 1 | Map of the sampling sites used in the study. Leiduin is the treatment plant location. Sampling also occurred at the pumping stations of Haarlemmermeer, Amstelveenseweg North and Amstelveenseweg South. Weesperkarspel is the other treatment location. Sampling also occurred at Diemen and Zeeburg.

quality measuring units are available. In these units the pH, conductivity, temperature and flow rate are logged. An extra sampling point was made in these units for the particle counters. The transport mains in the Weesperkarspel system are made of cement lined cast iron and the total distance between Weesperkarspel and Zeeburg is about 9 km.

Sampling strategy

To compare the changes in particle load over time, two to three turbidimeters and particle counters were deployed simultaneously at the different sampling sites. In the first measuring period they were used in the Leiduin system at

Table 1 | Water quality parameters treatment plants Leiduin and Weesperkarspel (2003–2004)

| Parameter	Unit	Leiduin			Weesperkarspel		
		Min	Average	Max	Min	Average	Max
Turbidity	NTU	<0.1	0.12	0.36	0.09	0.12	0.18
pH	–	7.96	8.37	8.69	7.57	8.05	8.47
SI	–	0.3	0.48	0.7	0.29	0.43	0.51
DOC	mg/l	0.9	1.1	1.4	3.1	3.4	3.9
AOC	μg/l	4.2	13	30	–	18.5	–
Iron	mg/l	<0.01	<0.01	0.13	<0.01	<0.01	<0.01
Silicon	mg/l	n.a.	n.a.	n.a.	0.02	0.24	0.45
Manganese	mg/l	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Aluminium	μg/l	<3	3.7	4	–	2.5	–
Magnesium	mg/l	8.8	9.9	10.9	6.3	6.6	6.9
Calcium	mg/l	39	43	47	48	52	52
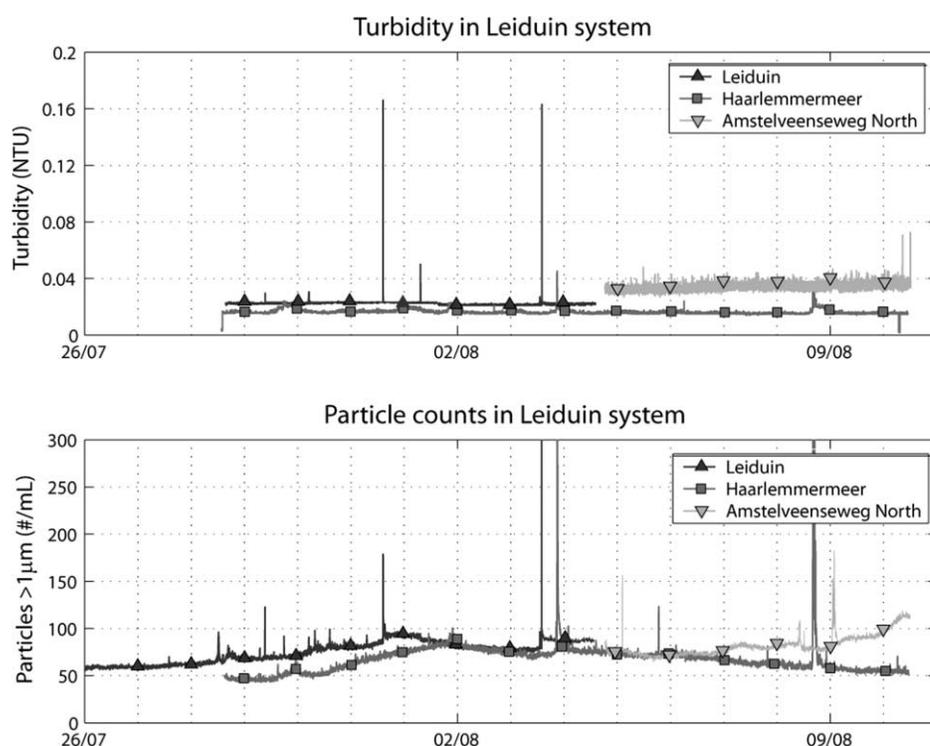
Figure 2 | On-line turbidity measurements and total particle counts in the Leiduin transportation system.

the Leiduin treatment plant and Haarlemmermeer for one week. Then the particle counter at Leiduin was moved to Amstelveenseweg North measuring on the North-line for one week while measuring continued at Haarlemmermeer. In the second measurement period three particle counters were operated simultaneously in the Weesperkarspel systems for one week.

Analytical methods

Turbidimeters

The turbidimeters used in the Leiduin system were identical Sigrist KT65 turbidimeters. The measuring principle is based on scattering at an angle of 90° of white light. The turbidimeter was able to measure on four ranges. In this research only the lower range of 0 to 2 NTU was used. The resolution of the turbidity measurements was 1% of the maximum of the range. The turbidity was logged every minute. Before the experiments both turbidimeters were calibrated. The turbidimeters in the Weesperkarspel system were identical Hach 1720C turbidimeters. The turbidity measurements are based on a light

scattering technique at 90° from the incident beam. The turbidity was logged every 10 minutes.

Particle counters

Two of the particle counters used were Met One PCX units with 32 channels of one μm band widths ranging from 1 - >31 μm. The third particle counter used was also a Met One PCX only with a one μm measuring band width in the range of 2 - >31 μm. The measuring technique is based on light blocking by laser-diode based particle counting sensors. The particle counters were calibrated at the same time and run simultaneously in the laboratory and at the Leiduin location to compare the magnitude of the signal from each unit. Results were in good agreement showing peaks at the same time and having less than 10% difference in total particle counts, on average.

Data representation

Particle counters provide a large number of data. This data needs to be processed and evaluated before it can be represented (Ceronio & Haarhoff 2005). In this paper, the

results of particle counts will be represented in terms of total number of particles or in specific size range counts. Furthermore, the particle volume concentration will be used. This calculated particle volume concentration is based on spherical particles with a geometrical average diameter of each size range (Ceronio & Haarhoff 2005). As the measurement of particle counting in distribution systems is still quite new the full strength of this measuring method is not fully exploited and is still in development.

RESULTS

Turbidity and particle counting Leiduin system

As can be seen from Figure 2, top graph, the turbidity in the Leiduin transportation system is low at all sampling locations. The average turbidity is below 0.04 NTU. The turbidity at Leiduin is very stable, almost a flat line is observed except for a few spikes caused by switching between transportation pumps in order to have an even number of running hours per pump. The turbidity at Haarlemmermeer is slightly lower than at Leiduin and shows some variability. This is not a meaningful difference because these values are at the lower limit of the measuring range. The turbidity at Amstelveenseweg North shows some small fluctuations but is still stable.

The total number of particles larger than $1\,\mu m$ in the Leiduin system are given in Figure 2, bottom graph. As can be seen by comparing both graphs of Figure 2 generally the turbidity and particle counts have similar trends. However, the particle counters are more sensitive at detecting fluctuations in the water quality as more peaks are detected than by the turbidimeters.

The particle counting data allows a more detailed look at the differences in particle size ranges at the different locations, as measurements are done in 31 ranges of $1\,\mu m$ diameter. In Figure 3 the number of particles in the Leiduin system in the size ranges $1\text{--}3\,\mu m$ and $>31\,\mu m$ are depicted. These size ranges have been chosen to compare the smallest and largest measurable particles. From this figure it becomes clear that at the treatment plant in Leiduin mostly small particles are present, while large particles are not observed (flat lining at 0 particles/ml in the bottom left graph of Figure 3). In fact there were even no particles

larger than $10\,\mu m$ present. At Haarlemmermeer the number of small particles is slightly lower than the number of particles leaving the treatment plant at Leiduin. A different trend is observed with respect to the large particles, as more large particles are observed at Haarlemmermeer, compared to Leiduin. At Amstelveenseweg North, the number of small particles is still in the same range as Leiduin, whereas the number of large particles has increased dramatically.

Turbidity and particle counting Weesperkarspel system

In Figure 4 the turbidity and the total number of particles $> 2\,\mu m$ are depicted for the Weesperkarspel system. To standardize the data range for all locations in the Weesperkarspel system the $1\text{--}2\,\mu m$ range was excluded. In Figure 5, further details of the size ranges of the particles are given. The turbidity in this combined transportation and reticulation system was also reasonably constant. All values of the turbidity were below 0.07 NTU, however, more variation in the turbidity is observed in this system compared to the Leiduin system. The particle count data also confirms the variation and shows a greater number of particles over all measuring ranges than in the Leiduin system. At Weesperkarspel a greater overall number and size of particles were present than at the other sampling locations.

Residence time evaluation

The residence time between two points in a distribution system network can be determined using continuous water quality measurements (van de Hoven & Vreeburg 1992). The necessary variations in water quality should be significant as is hardly the case in both the Leiduin and Weesperkarspel systems. The measurement of particle counts in the Leiduin transport system, however, made it possible to track disturbances of particles from the treatment plant to pumping stations and distribution reservoirs farther downstream. The turbidimeters were not sensitive enough for this application due to the low variation in the turbidity reading. In Figure 6, the total number of particles $>1\,\mu m$ for the pipeline Leiduin – Haarlemmermeer is given. The peak in particle counts at Leiduin on August 3rd is seen 7 hours later at sampling location Haarlemmermeer. This peak can also be observed in the turbidity (see Figure 2), although the
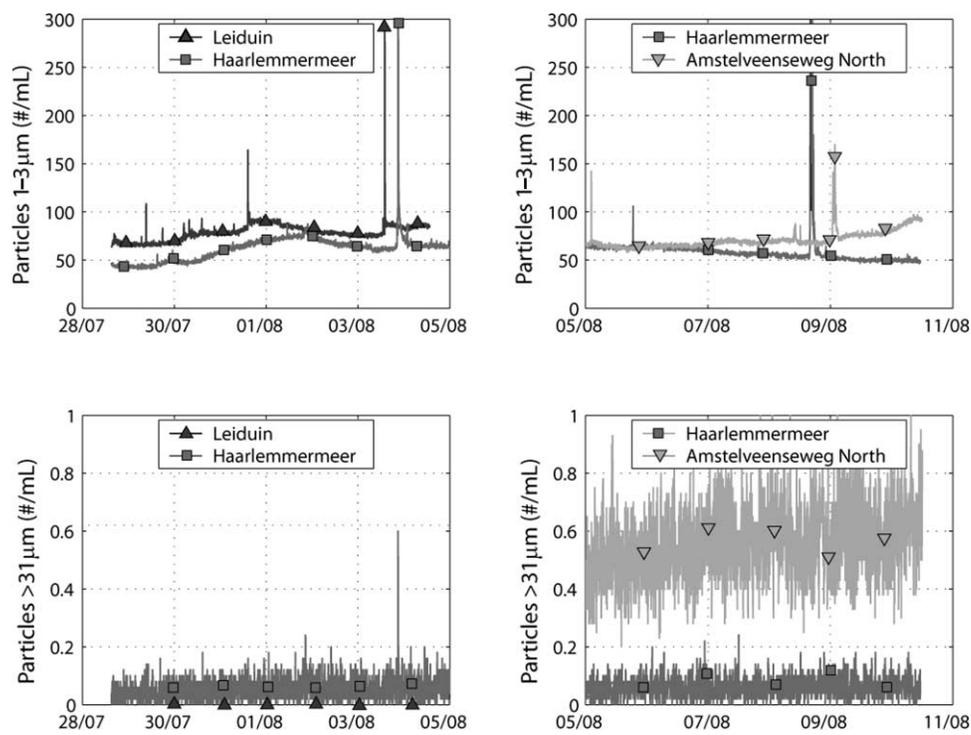
Figure 3 | Particles in the 1–3 μm range and >31 μm in the Leiduin transport system. Left figures compare the particle numbers at Leiduin and Haarlemmermeer, right figures compare the particle numbers at Haarlemmermeer and Amstelveenseweg North.
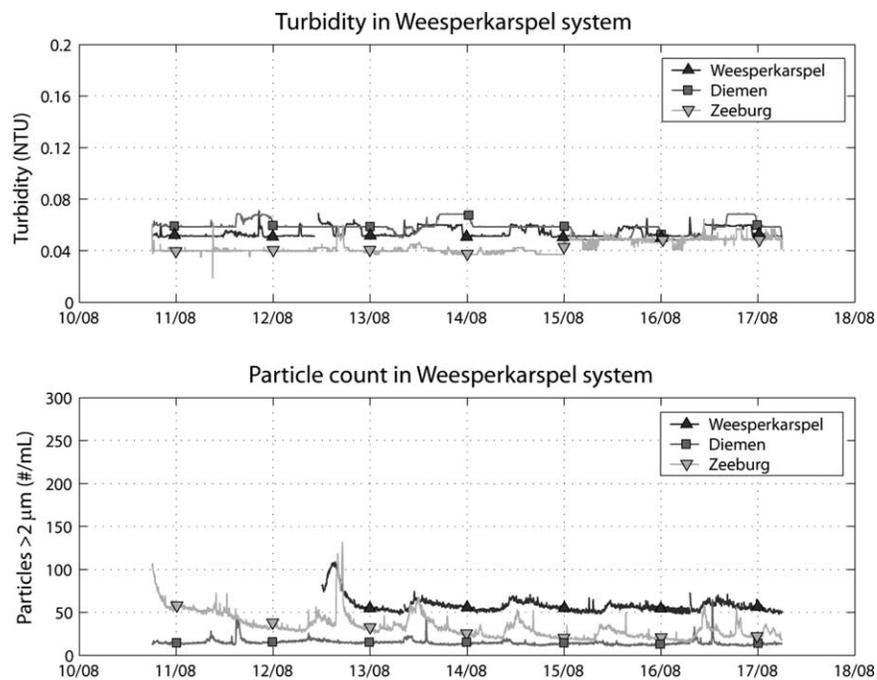

Figure 4 | On-line turbidity measurements and total particle counts >2 μm in the Weesperkarspel transportation system.
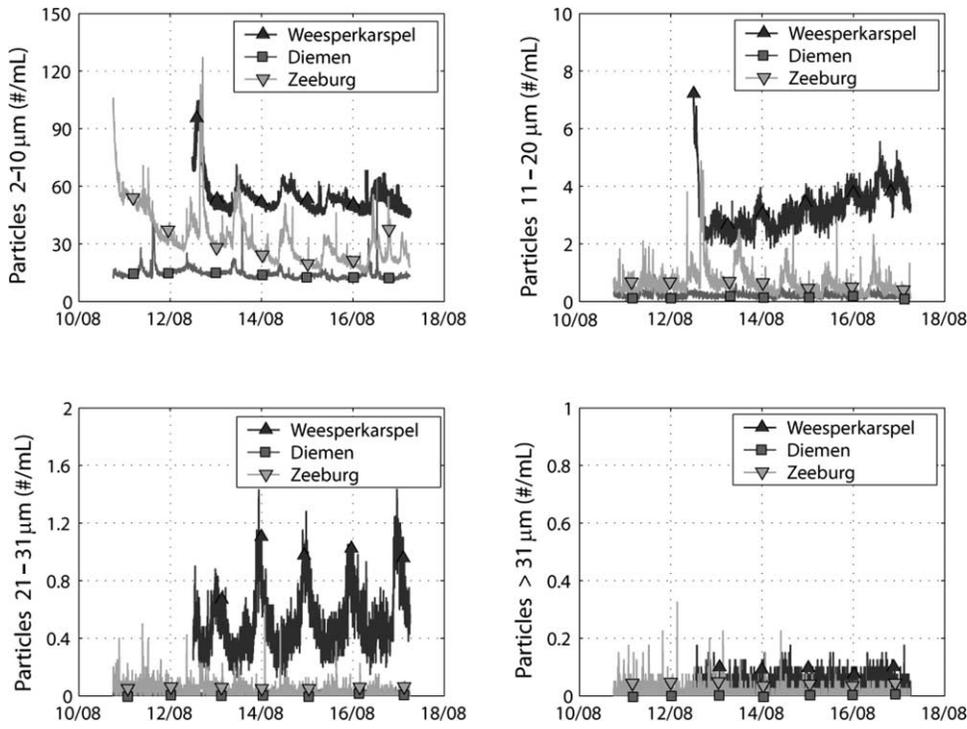
Figure 5 | Particles in the size range 2–10, 11–20, 21–31 and >31 μm in the Weesperkarspel distribution system.

peak at Haarlemmermeer is already very low. Also a peak of particles in the Haarlemmermeer – Amstelveenseweg North pipeline can be clearly observed and the time lag between these peaks is 9.5 hours. This peak is only very faintly visible in the turbidity (Figure 2) and hardly significant to conclusively determine the residence time. The residence times are in accordance with the calculated residence times based on flow rate, pipe diameter and distance between sampling locations. The residence time in the Weesperkarspel system could not be determined

because no clearly visible peaks in the particle numbers were observed during the measuring period.

DISCUSSION

Relationship between turbidity and particle counts

From the results shown in Figures 2 and 4 it follows that the turbidity measurements and the particle counts both showed a stable and good water quality over time. The measured
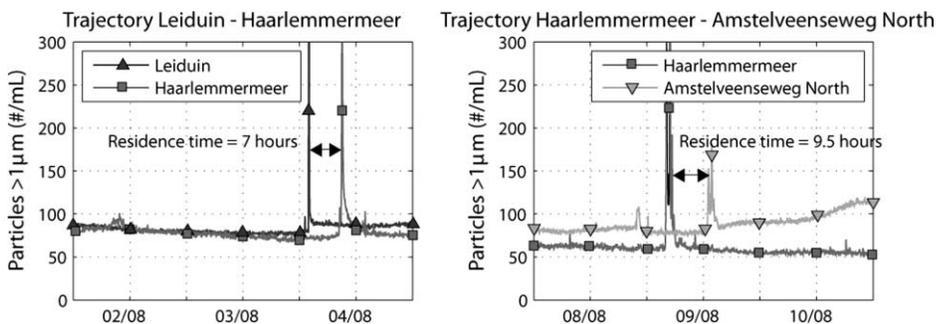

Figure 6 | Determination of residence time based on particle counting.

turbidity in the transportation systems was on average 0.05 NTU. The small variation of turbidity at Amstelveenseweg North compared to Leiduin may be an indication that some transport of particles takes place in the Leiduin distribution system. The consequent lower value at Zeeburg compared to Weesperkarspel is too small and within the measuring accuracy of the turbidimeters to use for drawing conclusions on a possible transport of sediment in the Weesperkarspel system. A correlation between turbidity and particle counts is not possible to make from this study because of the lack of variability in turbidity compared to particle counts. This conclusion is in correspondence with an earlier study (McCoy & Olson 1986) where no correlation between turbidity and particle counts within different distribution systems was found. However, this conclusion was based on the high variability in measurements.

Change of particle sizes in the distribution systems

By examining the different particle size ranges some interesting observations can be made. In Figure 3 the differences in particle size between small particles (1–3 μm) and large particles (>31 μm) in the Leiduin system is given. At the

Leiduin treatment plant only small particles were present and no large particles. Farther downstream in the transportation system the number of small particles was almost equal to the number at the treatment plant, while the number of large particles increased. Obviously during the transport of water from the treatment plant to the distribution reservoirs close to the city centre more large particles are formed. This is mainly due to a combination of post-treatment flocculation, corrosion of cementous pipes, resuspension of 'old' sediment and biological growth (Verberk *et al.* 2006). In the Weesperkarspel distribution system a different observation is made (Figure 5). It appears that deposition and resuspension are probably the dominant process. At the treatment plant more and larger particles are present than further along in the distribution system. This indicates that there is settling of particulate material in the system. At Zeeburg there are more particles than at Diemen, indicating a possible resuspension of previously deposited particles.

Comparison of particles across systems

To better compare the particle loading across different systems, the data was converted to total particle volume
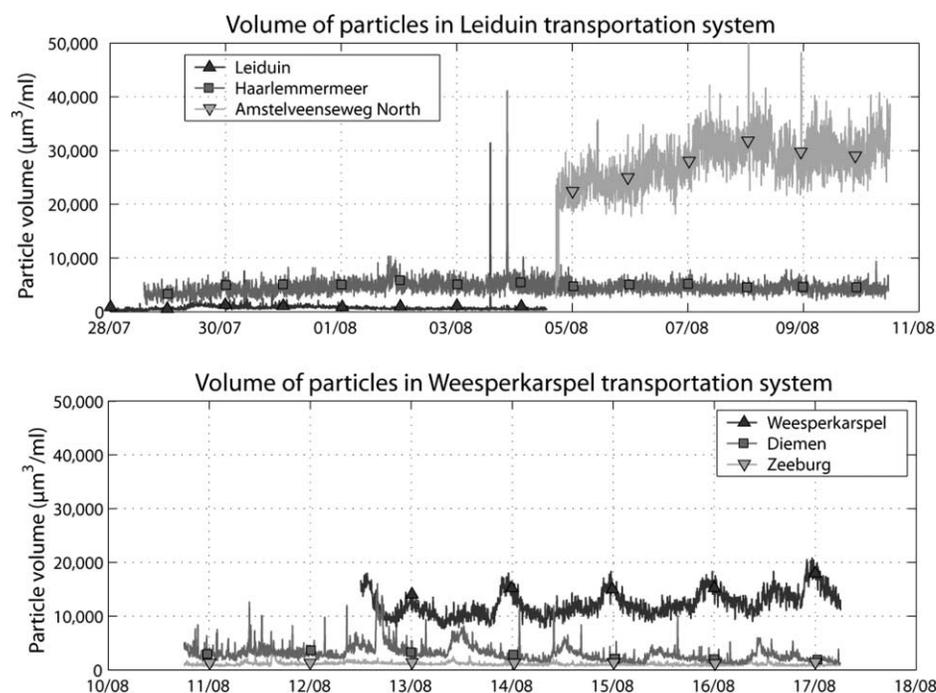

Figure 7 | Calculated particle volume concentration at the different measuring locations in Leiduin and Weesperkarspel system.
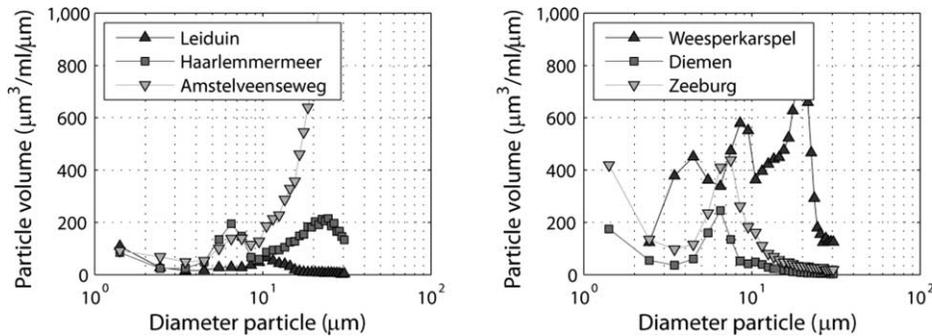
Figure 8 | Relative contribution of different size ranges to total particle volume concentration.

Table 2 | Total particle concentration of both distribution systems

Location	Calculated Particle Volume (μm^3/ml)	Location	Calculated Particle Volume (μm^3/ml)
Leiduin	714	Weesperkarspel	12,413[*]
Haarlemmermeer	4,575	Diemen	1,275
Amstelveenseweg South	28,097	Zeeburg	3,481

[*]Only size range 2– > 31 μm measured.

concentration (Figure 7) and the relative contribution of size ranges to the total volume (Figure 8). A clear increase in the particle volume concentration in the Leiduin system is observed (Table 2). The average particle volume concentration is almost 40 times larger at Amstelveenseweg North than at Leiduin during the measuring period. This indicates a production of particles in this system.

In the Weesperkarspel system, between Weesperkarspel and Diemen, a decrease in particle volume concentration is observed indicating deposition of particulate material. Between Diemen and Zeeburg an increase in particle volume concentration is observed, possibly caused by the reversing flows in the transportation system distribution system at Zeeburg overnight.

It is clear from the total particle volume concentrations that although the water quality leaving the treatment plants in Weesperkarspel and Leiduin (see Table 1) is fairly similar, the sediment load of the distribution system in Weesperkarspel is much higher than the sediment load at Leiduin. The particle volume concentrations leaving the treatment plants were 12,000 and 700 μm^3/ml respectively;

a difference of about a factor 20. The particles coming from the Weesperkarspel treatment plant are larger and deposit in the early part of the transportation system. Post-treatment flocculation and corrosion processes and possibly biological growth are less important factors in the Weesperkarspel system although the latter is contradicted by the higher level of DOC in the Weesperkarspel water. In further research the reasons for these differences in outgoing particle volume concentrations will be investigated.

Figure 8 shows which size range has the largest contribution to the total particle volume concentration. For the Leiduin system the larger particles contribute most to the particle concentration, while in the Weesperkarspel system the contribution of several particles size ranges is important.

CONCLUSION

The results of the study show that on-line measurement of particles in distribution systems gives additional quantitative information to turbidity measurements on the water

quality in distribution systems. By using multiple particle counters simultaneously at different locations in the distribution network it is possible to observe changes in particle size, number and volume concentrations. This information can then be used to relate changes in particle numbers to processes, like deposition and resuspension of loose material. Furthermore, it is possible to compare the sediment loading of separate distribution systems and relate the differences between systems to the preceding treatment processes and the hydraulic conditions in the network. Another observation is that residence times in networks can better be determined using particle count measurements, compared to only turbidity measurements. While total particle number and turbidity generally followed a similar pattern it was found that the particle counters were more sensitive to changes in water quality.

It was not possible to find a correlation between turbidity and particle counts because of the low variability in both parameters.

Particle counters generate huge amounts of data. Because the use of particle counters in distribution systems is new, the full potential of this monitoring technique is currently not fully realized. Further and additional research needs to be done to make optimal use of the particle counters. If used in combination with particle capturing methods such as time-integrated sampling devices a better understanding of the processes resulting in water quality deterioration can be obtained.

Specifically for the Amsterdam water supply system, the following conclusions can be made:

- In the Leiduin system there are mainly small particles present directly after treatment. During transportation the number, size and volume of particles increase dramatically. An increase in the particle volume concentration of up to a factor of 40 was measured.
- In the Weesperkarspel system after treatment a high number of large particles are observed. In the combined transportation and reticulation system the number of large particles decreases as a result of deposition. A decrease in particle volume concentration of a factor of 4 was observed.
- Comparison between the two transportation systems shows that the particle volume concentration in the Weesperkarspel system is much higher than in the Leiduin system, despite similar treatment trains.

The particle volume concentrations leaving the treatment plants were 12,000 and 700 μm^3/ml respectively.

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