Dynamic Particle Analysis; A New Technology For Optimizing Particle Removal In A Water Treatment Plant

Ian Douglas*, City of Ottawa

Dave Thomas, Brightwell Technologies Inc., Ottawa

Jim Guthmann, City of Ottawa

Sean Russell, Brightwell Technologies Inc., Ottawa

Sue Springthorpe, University of Ottawa, Ottawa

ABSTRACT

The primary objective of the Coag/Floc/Sed/Filtration process is to remove suspended particles and their associated pathogens. Water Treatment Plants (WTP's) must continually adapt treatment techniques to cope with both changing source water and variations in plant operating conditions in order to optimize particle removal efficiency. It is important to understand changes in particle populations (concentration, size, and general nature) throughout the treatment process during normal operation as well as during transient conditions such as seasonal changes, process upsets, and sub-optimal treatment conditions.

A new particle characterization technology called Dynamic Particle Analysis (or DPA) provides a tool for studying WTP process dynamics. DPA makes use of digital microscopy, image analysis, and a fluid handling system to count, size, and image particle populations in flowing liquids. Primary advantages of this technique include speed, sensitivity, and accurate detection of high particle concentrations (>10^6 per mL) permitting application throughout all stages of the WTP. Additionally, DPA technology provides new insights into process-related particle structure by virtue of the particle images made available.

This study summarizes experimental results from applying DPA to characterize full-scale WTP streams during normal process conditions. Particle characterization was carried out at each stage of the treatment process including raw water influent, mixing chambers, settling basin effluent, dual-media filter effluent, chlorine contact basin, and plant effluent. Results were correlated and compared to data from online turbidity meters and online particle counters. In addition, filter effluent changes throughout a typical filter hydraulic step-change (10ML/day to 20ML/day) were analyzed.

It was found the DPA unit detected three to five times more particles/ml relative to the online Particle Counters over the same size measurement range. When used to evaluate the filter effluent response to the step increase in flow rate, the DPA reported a transient increase from 309 to 1355 particles/ml (particles >5µm increased from 10 to 26) while the turbidity readings reported a very small change of only 0.02 NTU before stabilizing. It was also found that through application upon the raw water, mixing chamber samples, and settled water, the DPA technology was able to provide visibility into the dynamics of particle formation and removal throughout the coagulation/flocculation/sedimentation process and provide useful data that may be used to evaluate and ultimately predict particle removal efficiency under various loading and operational conditions.

Future work will involve applying DPA to study treatment plant particle removal as influenced by seasonal effects such as water temperature and raw water microbial constituents, and Pilot-scale exploration of process impairments such as non-optimal coagulant dose, pH, and polymer dose. Additionally, filter effectiveness throughout a typical filter cycle including filter ripening phase, performance throughout operational phase, early breakthrough and late breakthrough phases will be investigated.

INTRODUCTION

Britannia Water Purification Plant

The City of Ottawa supplies an average of 360 ML/d of drinking water to 785,000 customers from two treatment plants: Lemieux Island Water Purification Plant (c.1931) and the Britannia W.P.P. (c.1961). Both plants use an identical water treatment process and have undergone significant expansion and modernization over the years. Using the Ottawa River as the raw water source, the treatment process consists of the following steps:

- Physical screening
- Low-Lift pumping
- Coagulation (alum & sulphuric acid)
- Hydraulic flocculation (using activated silica)
- Sedimentation (conventional and plate settling)
- Dual-media filtration
- Primary disinfection (sodium hypochlorite)
- pH/alkalinity adjustment (sodium hydroxide & carbon dioxide)
- Secondary disinfection (chloramine)
- Fluoridation
- High-Lift pumping and storage

All treatment, pumping, and storage systems are continuously controlled by a dedicated SCADA control system and monitored by licensed plant operators 24 hours per day. Each plant uses 35 on-line analyzers to monitor the effectiveness of the treatment process at each stage of operations.

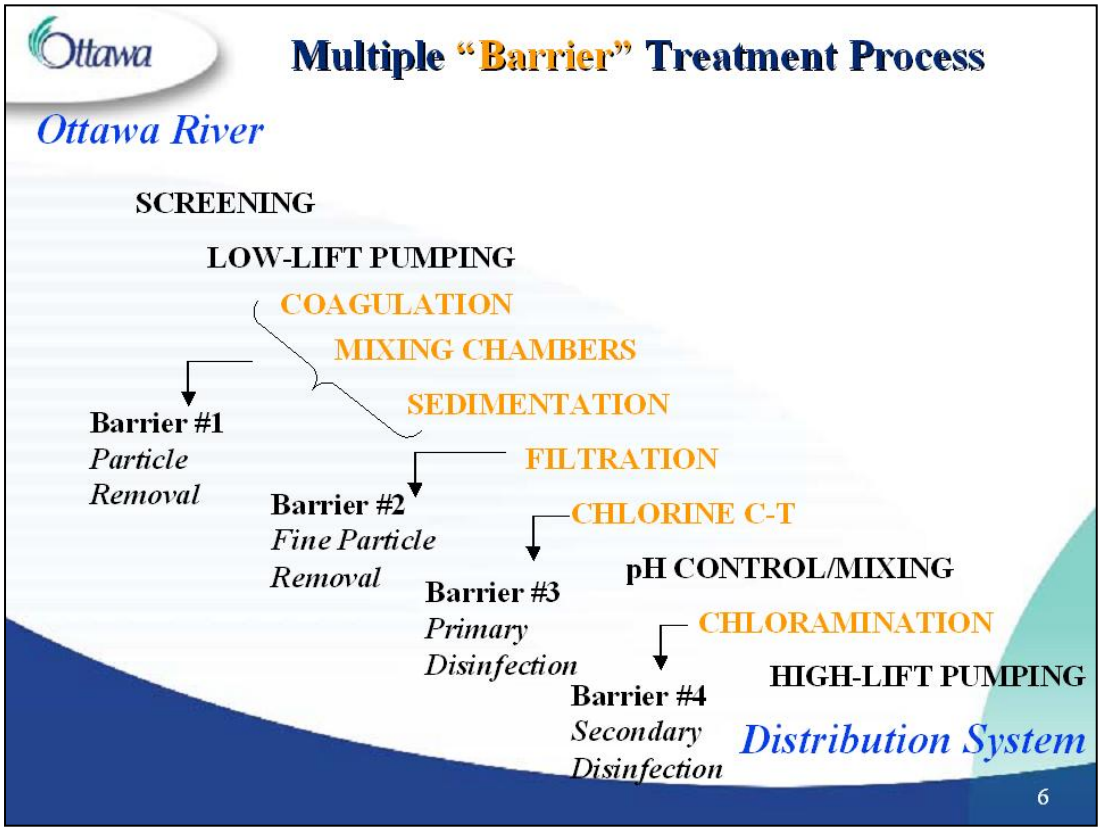


Figure 1: Britannia Water Purification Plant Process

Dynamic Particle Analysis (DPA) Technology

Dynamic Particle Analysis (DPA) is a new imaging-based particle characterization technology designed to rapidly measure the size and concentration of suspended particles within water, and provide images of these particles for additional information regarding particle shape and structure. The technology (produced by *Brightwell Technologies Inc.*) supports measurement of particles ranging in size from 2 to 1000µm at concentrations from 0 to 10^6 particles/ml, and resolution of 0.25µm.

The principle of operation of Dynamic Particle Analysis (DPA) technology is shown in Figure 2. The sample is drawn via peristaltic pumps through a sheathed micro-fluidic flow cell. A section of the flowing liquid is illuminated by a pulsed high intensity light source. During each pulse, a magnified image of this section is formed on the camera's pixel array. The software interface identifies particles by processing individual pixel values. The data from these pixels is used to calculate particle size and trigger storage of particle images meeting user-specified criteria. The optical system's field-of-view and the physical geometry of the sample flow cell define the sampling volume and permit the particle concentration to be calculated. Providing a particle has adequate contrast for an image to be detected, the DPA is insensitive to particle material, shape, or surface properties and is therefore ideally suited for measurement of heterogeneous particle populations typical of water samples. Unlike light obscuration or light scattering techniques, no assumptions regarding particle properties are required, and calibration against particle size standards is not necessary.

Approximately three frames per second are analyzed in real time, while one per second is displayed on the system monitor in grayscale (or black and white) providing instant visual feedback on the nature of the sample's particle population and confirmation of the particle size distribution data. The software permits storage of all pixel data in frames containing particle images meeting specified size criteria. Target particles are automatically identified using color-coding for further examination and post-processing. The DPA also supports image acquisition at higher magnifications with increased resolution.

The instrument model used for this research was the DPA4100. The size range (determined by flow cell geometry and optical configuration) was 2-400µm, and the display resolution was selected to be 1.0µm. Particles as small as 1µm will be detected by the system in this configuration, and are included in the total concentration reported by the DPA. Under this configuration, a complete analysis (size, concentration, and image storage) of 1ml takes approximately five minutes.

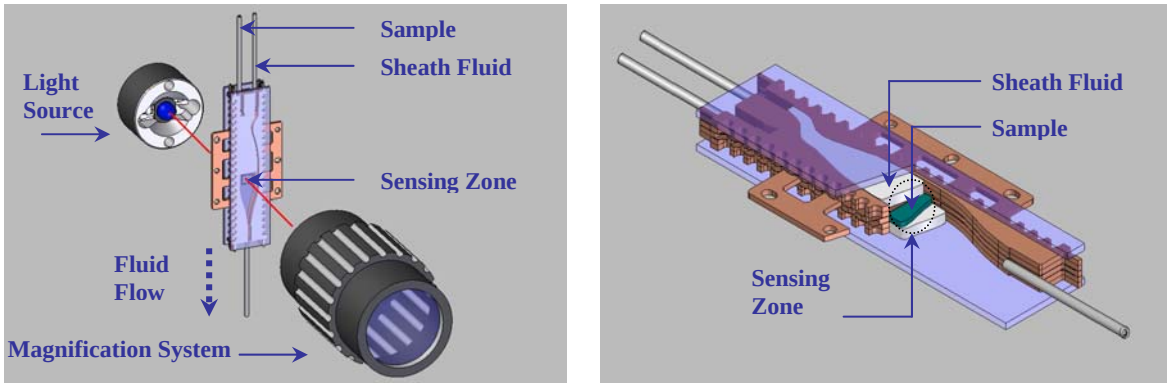


Figure 2: Principle of Operation

SAMPLE HANDLING

All samples were collected from their source using 300ml, single use, pre-cleaned PET bottles certified to conform to MISA standards. The samples were then transported to the Brightwell Technologies facility for refrigerated storage (4ºC) and subsequent analysis. The cleanliness of the sample bottles was estimated by selecting one as representative and filling with particle-free water (filtered to 0.2µm), then analyzing with the DPA4100. Particle concentrations >2µm were found to be lower than 10 particles/ml.

Prior to analyzing each individual sample, system cleanliness was ensured by first analyzing filtered water introduced into the system glassware. In all cases, the concentration of particles >2µm was found to be less than 25 particles/ml (typically less than 15 particles/ml). After system cleanliness was demonstrated, the filtered water was removed from the sample introduction glassware, the sample was tumbled 10 times, rolled 10 times and then approx 150ml (or half) of the sample was poured into the system glassware. The glassware was then placed upon a magnetic stir plate where the RPM was kept constant throughout the duration of the testing.

PARTICLE CHARACTERIZATION THROUGH THE TREATMENT PROCESS

In order to evaluate the water purification plant particle removal performance, representative samples from each stage of the treatment process were collected and analyzed with the DPA4100, effectively providing a 'snapshot' of the particle population characteristics at a specific point in time. Additionally, turbidity and online particle counters (PC) data was considered wherever possible. Samples acquired included the Raw Water Influent, Mixing Chamber #1, Mixing Chamber #2, Mixing Chamber #3, Settling Basin #1 Effluent, Filter #3 Effluent, Chlorine Contact Basin, and the Plant Effluent. In each case, 3ml of the sample was analyzed using the DPA4100. In order to evaluate the changes of the coagulation/flocculation bulk 'interstitial' fluid throughout the mixing process, the samples taken from the Mixing Chambers were permitted to settle for 48 hours after acquisition, prior to drawing approximately 125ml from the top 70 % (by volume) of the sample container.

Data regarding the plant operating conditions were recorded as follows:

Sample Acquisition Date	16-Aug-04	Ammonia Dose	0.32 mg/L
Sample Test Date(s)	17-18-Aug-04	Secondary Cl_2 Dose	1.35 mg/L
Plant Flow Rate	134 ML/day	Secondary Cl_2 Residual	1.60 mg/L
Alum Dose	40.0 mg/L	Fluoride Residual	0.75 mg/L
Sulphuric Acid Dose	0.0 mg/L	Raw Water pH	7.30
Silica Dose	1.0 mg/L	Coagulation pH	5.91
Primary Chlorine Dose	1.2 mg/L	Plant Effluent pH	9.20
NaOH Dose	15.7 mg/L	Filter Sampled	#3 of 18
CO_2 Dose	0.0 mg/L	Plant Effluent Turbidity	0.10 NTU

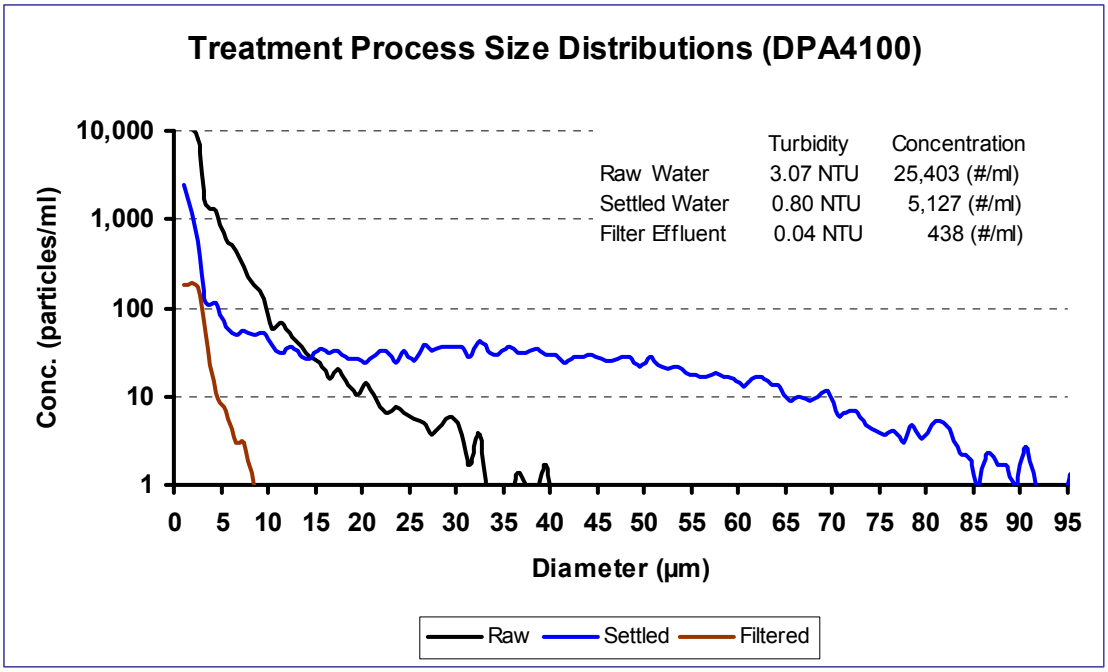


Figure 3: Treatment Process Size Distributions (DPA4100)

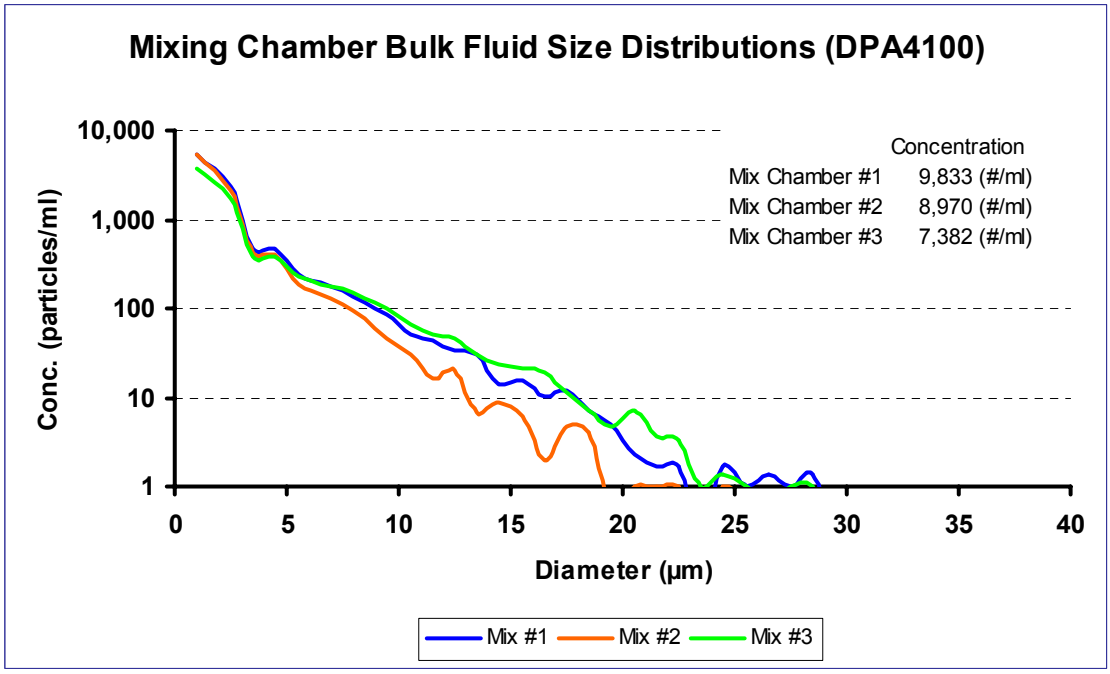


Figure 4: Mixing Chamber Size Distributions (DPA4100)

Note: only the bulk 'interstitial' fluid at the top of the Mixing Chamber samples was analyzed after the samples had settled for 48hrs, therefore the presence of larger more dense particles would not be included as they would have settled out.

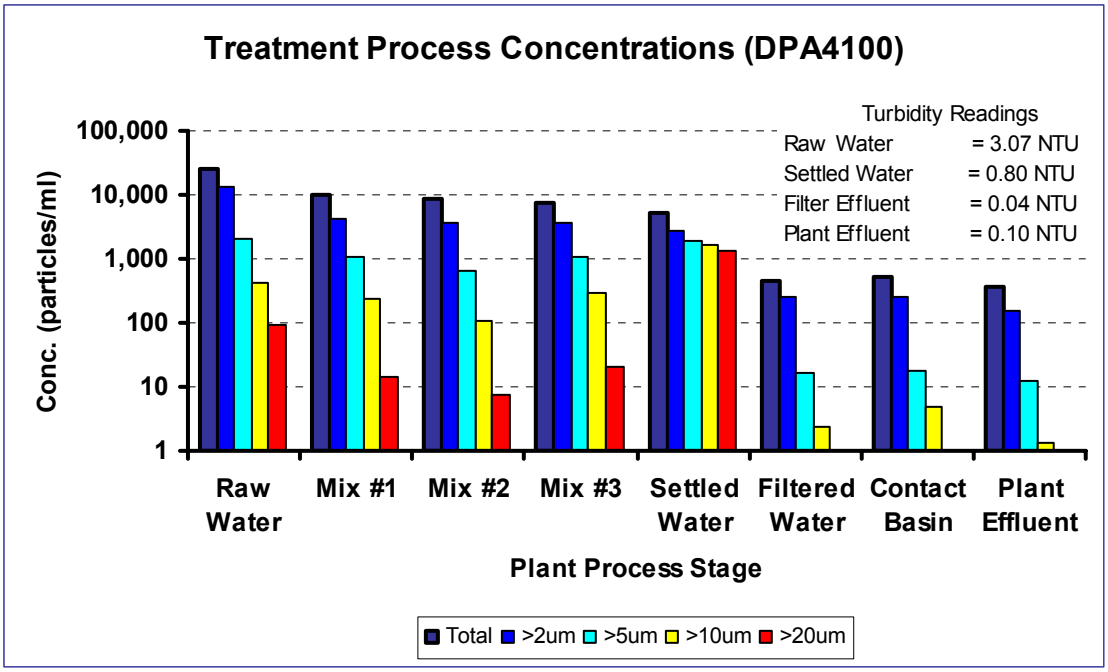
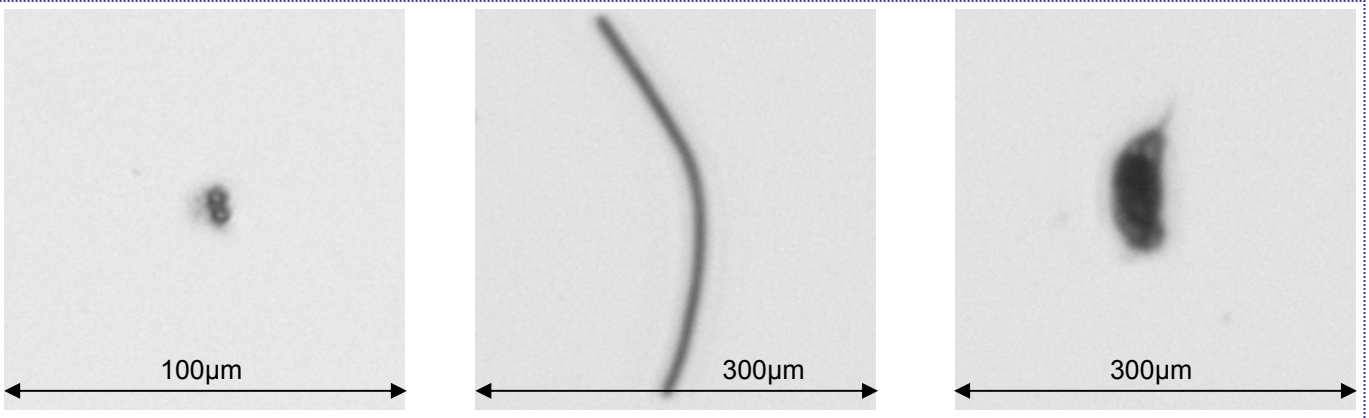


Figure 5: Treatment Process Particle Concentrations (DPA4100)

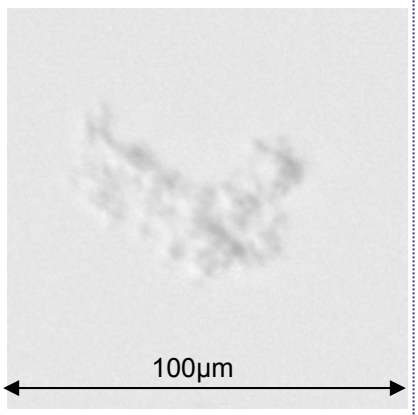
Process Stage	Raw Water	Mix #1	Mix # 2	Mix #3	Settled Water	Filtered Water	Contact Basin	Plant Effluent	Particle Removal (Raw→Filtered)
Turbidity	3.07	-	-	-	0.80	0.04	-	0.10	98.70%
Online Particle Counter Concentrations (particles/ml)									
>2µm	5,345	-	-	-	-	70	-	-	98.70%
>5µm	936	-	-	-	-	8	-	-	99.18%
>10µm	97.0	-	-	-	-	0.8	-	-	99.20%
>20µm	5.3	-	-	-	-	0.3	-	-	93.56%
DPA4100 Concentrations (particles/ml)									
Total	25,403	9,833	8,970	7,382	5,127	438	535	359	98.27%
>2µm	13,063	4,323	3,638	3,642	2,701	252	264	158	98.07%
>5µm	2,032	1,047	669	1,108	1,900	17	18	13	99.18%
>10µm	411	238	106	297	1,630	2	2	1	99.43%
>20µm	90	15	7	21	1,318	1	1	1	99.26%

Table 1: Treatment Process Concentration Comparison (DPA4100 vs. Particle Counter)

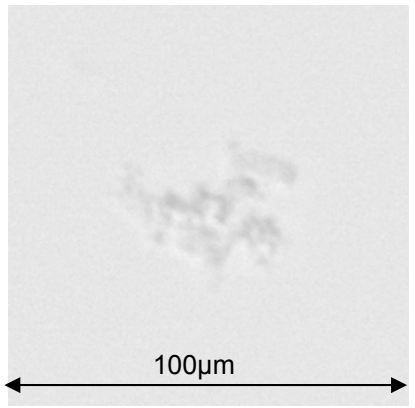
Representative Images Stored by the DPA4100:



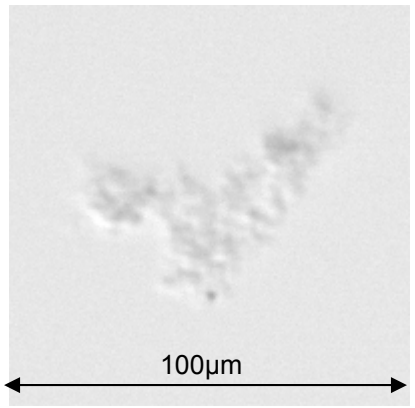
Raw Water



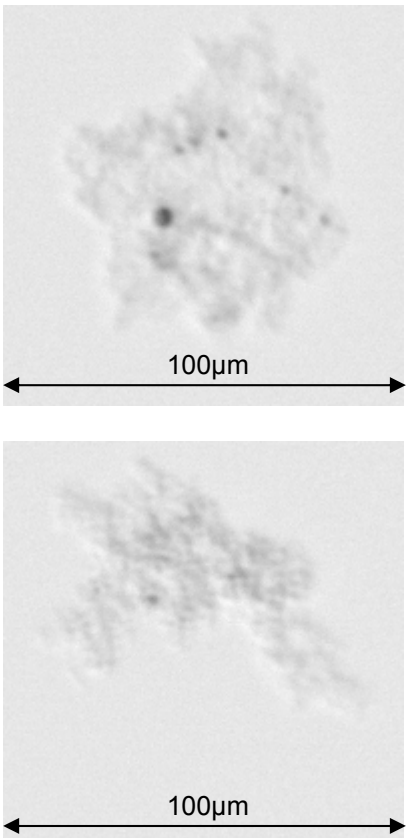
Mixing Chamber #1

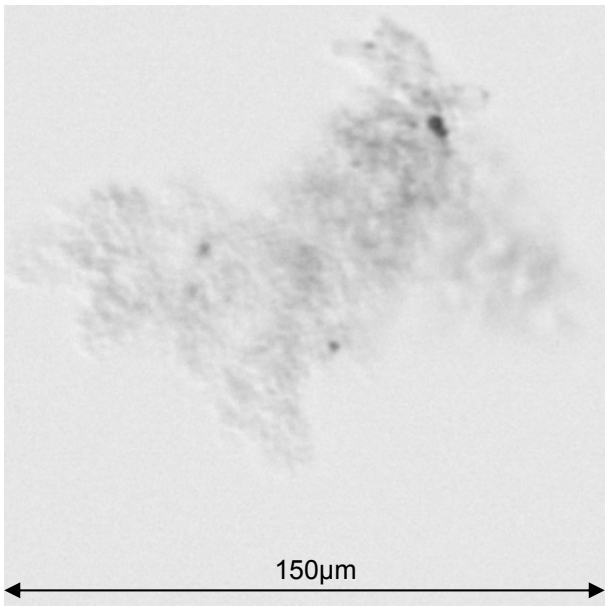


Mixing Chamber #2

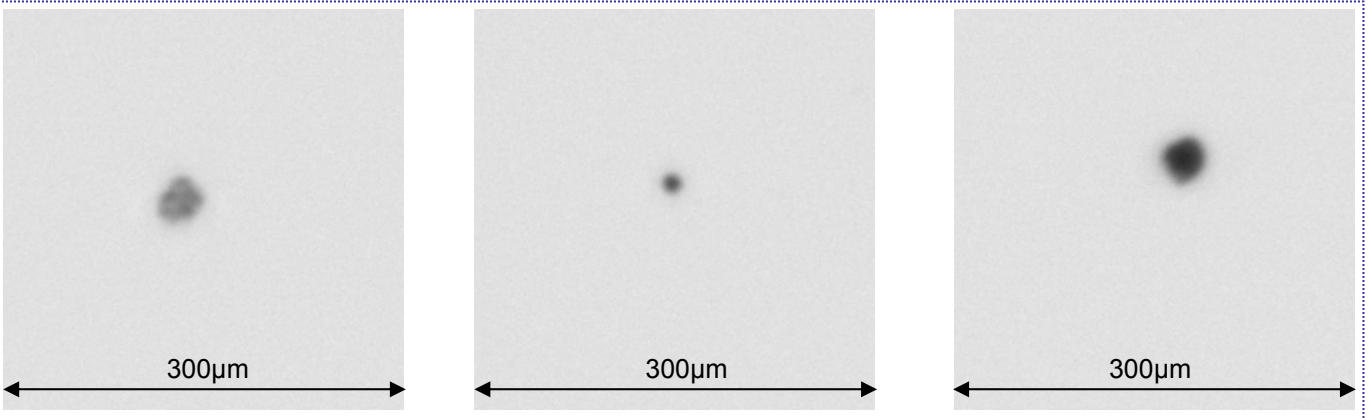


Mixing Chamber #3

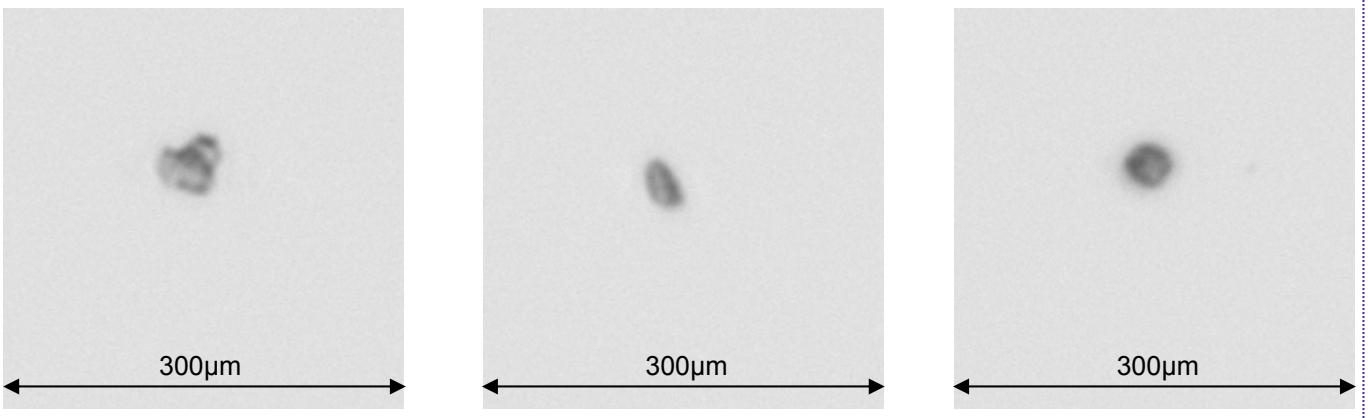




Settled Water



Chlorine Contact Basin



Plant Effluent

FILTER RESPONSE TO STEP FLOW INCREASE

In order to characterize the particle removal as a function of sudden changes to the filter flow rates, samples from two different filters at specific time intervals immediately following an abrupt flow rate change from ~10ML/day to 20ML/day were collected and analyzed with the DPA4100. In each case, 3ml of sample was analyzed. The filters chosen as representative were Filter #14 and Filter #3 (of 18). Both filters are dual media (sand and anthracite). Both filters demonstrated very comparable data, therefore only data from Filter 3 is presented within this report. Comparisons to Turbidity readings and online Particle Counters were made where possible.

Data regarding the plant operating conditions were recorded as follows:

Filter #3 Samples:	
Sample Acquisition Date	16-Aug-04
Sample Test Date	20-23-Aug-04
Plant Flow Rate	134.60 ML/day
Plant Effluent Turbidity	0.09 NTU
Silica Dose	1.0 mg/L
Alum Dose	36.0 mg/L
Coagulation pH	5.91
Filter Run Hours	20 hrs
Actual Flow Rate Change	7.1-20 ML/day

Filter #14 Samples:	
Sample Acquisition Date	9-Aug-04
Sample Test Date	11-12-Aug-04
Plant Flow Rate	210 ML/day
Plant Effluent Turbidity	0.09 NTU
Silica Dose	1.0 mg/L
Alum Dose	36.0 mg/L
Coagulation pH	9.19
Filter Run Hours	37 hrs
Actual Flow Rate Change	11.5-20 ML/day

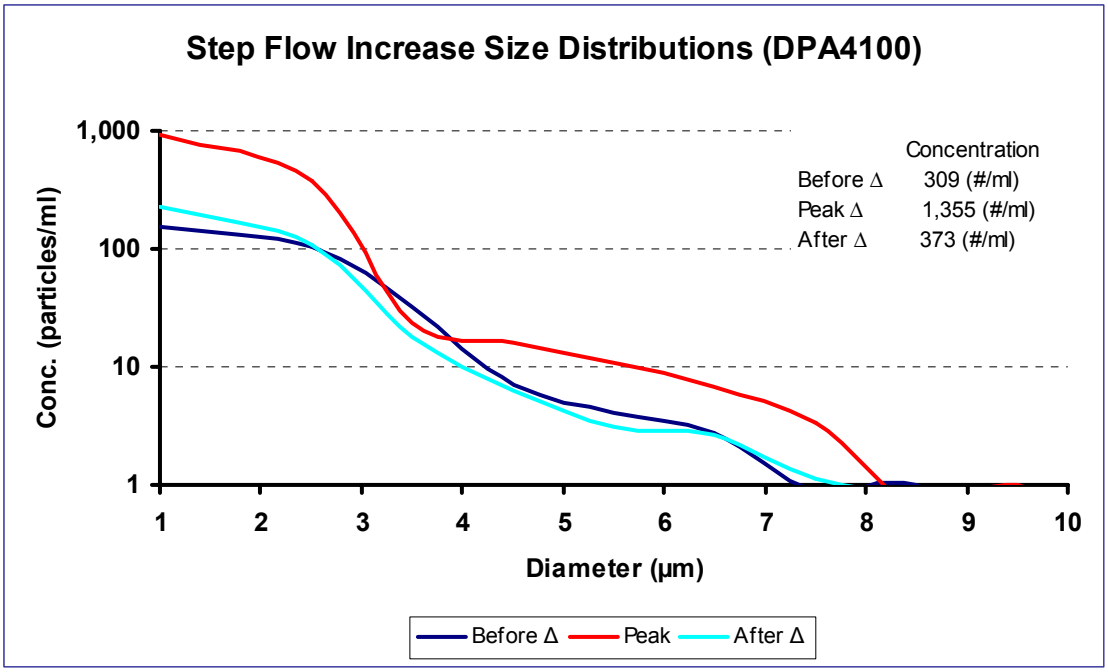


Figure 6: Step Flow Increase Size Distributions (DPA4100)

Note: 'Before Δ' was calculated by taking the average of the first three readings (0 min, 1 min, and 2 min), the 'Peak' represents the maximum concentration measured within each category, and 'After Δ' represents the average of the last three readings (20, 25, and 30 minutes after the change in flow rates).

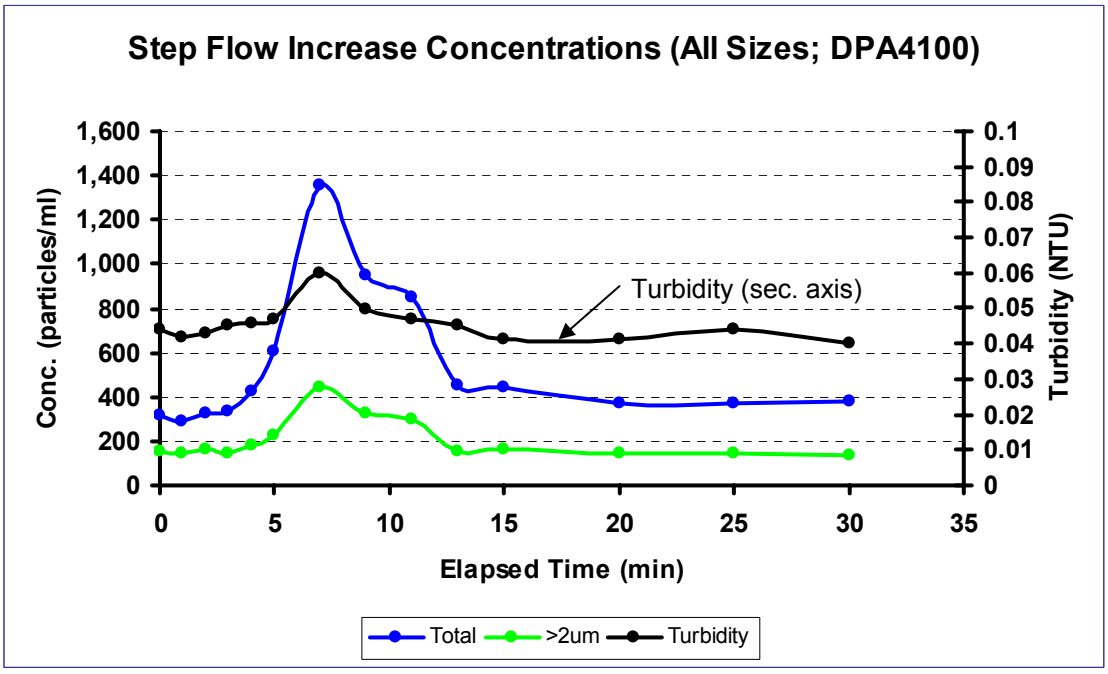


Figure 7: Step Flow Increase Concentration (All Sizes; DPA4100)

Note: Time zero represents the point in time immediately prior to changing the filter flow rate from ~10ML/day to 20ML/day.

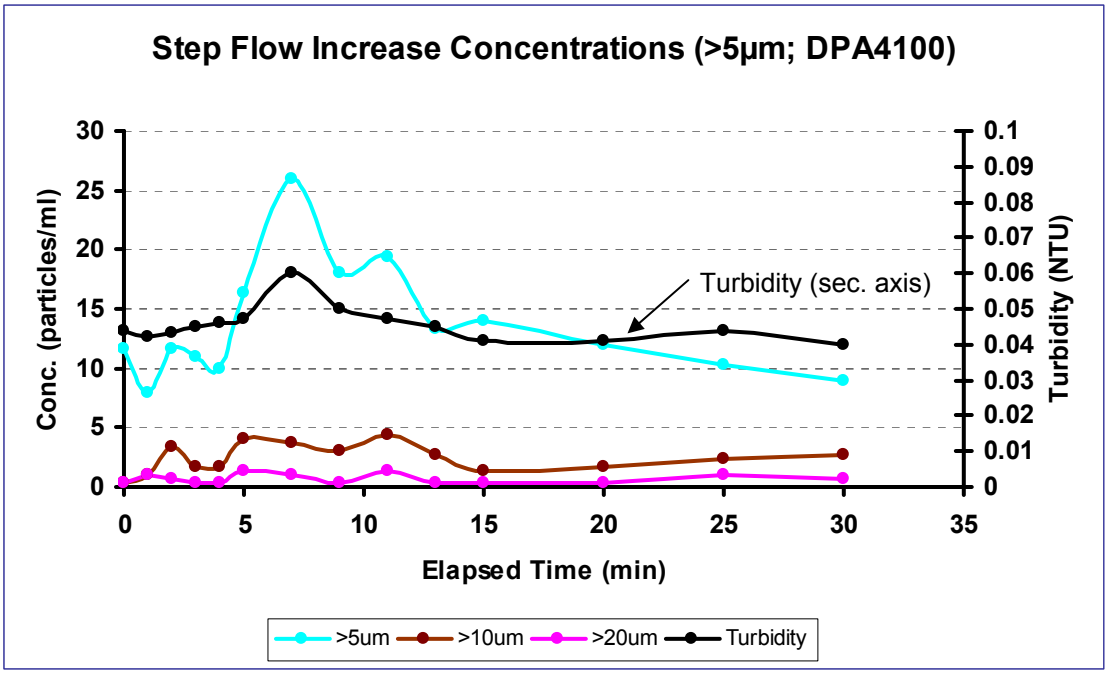


Figure 8: Step Flow Increase Concentration (>5µm; DPA4100)

Elapsed Time	0 min	1 min	2 min	3 min	4 min	5 min	7 min
Turbidity	0.044	0.042	0.043	0.045	0.046	0.047	0.060
Total	315	287	325	337	424	609	1355
>2µm	152	146	164	145	185	229	441
>5µm	12	8	12	11	10	16	26
>10µm	0	1	3	2	2	4	4
>20µm	0	1	1	0	0	1	1

Elapsed Time	9 min	11 min	13 min	15 min	20 min	25 min	30 min
Turbidity	0.050	0.047	0.045	0.041	0.041	0.044	0.040
Total	951	851	453	373	373	369	376
>2µm	324	295	157	148	148	141	139
>5µm	18	19	13	12	12	10	9
>10µm	3	4	3	2	2	2	3
>20µm	0	1	0	0	0	1	1

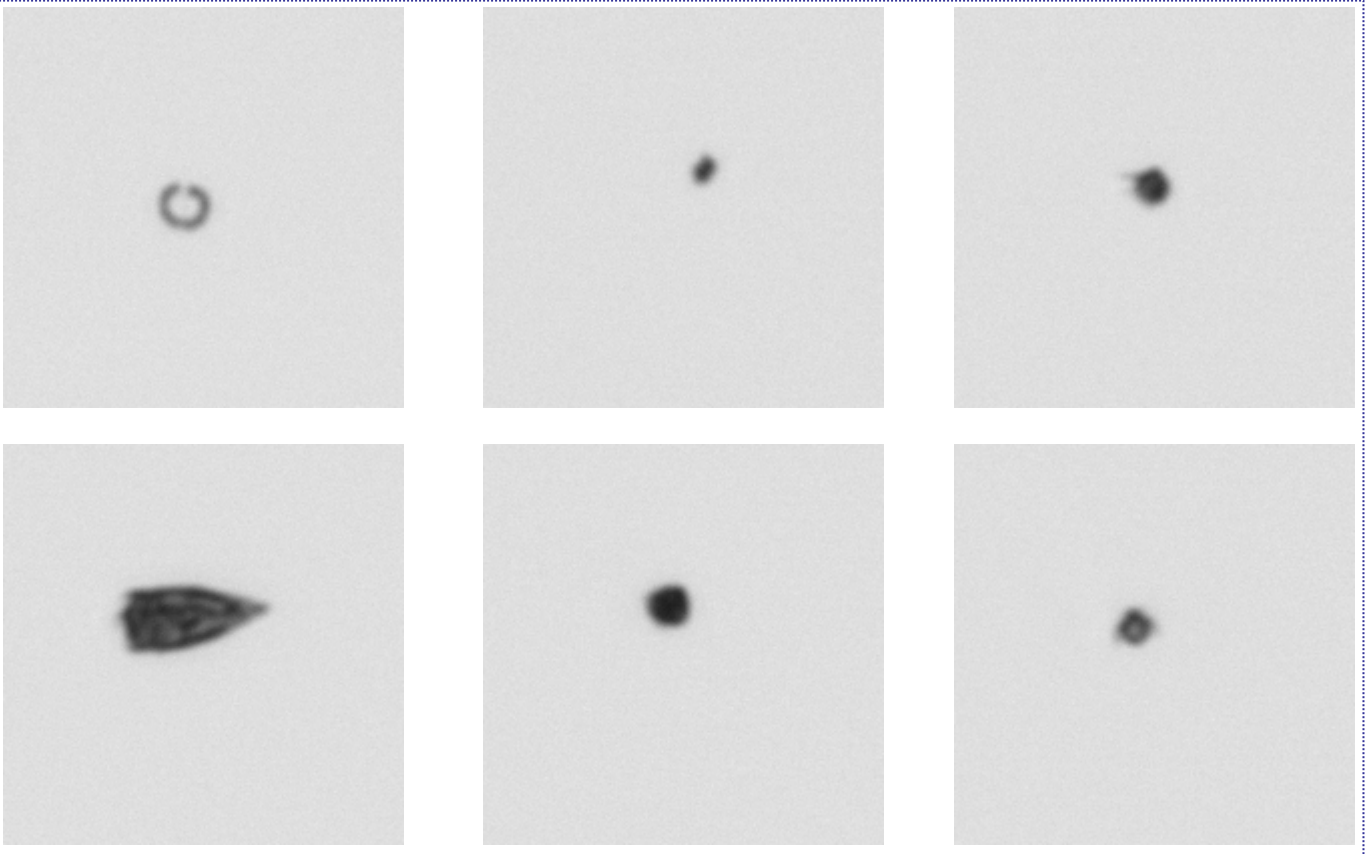
Table 2: DPA4100 Particle Count and Turbidity Response to Flow Increase

Measurement	Before Δ	Peak	After Δ	% Inc.	% Δ
Turbidity	0.04	0.06	0.04	40%	-3%
Online Particle Counter Concentrations (Particles/ml)					
>2µm	65	93.03	48.06	43%	-26%
>5µm	6.6	10.63	5.4	61%	-18%
>10µm	0.9	1.55	0.58	72%	-36%
>20µm	0.3	0.63	0.16	110%	-47%
DPA4100 Concentrations (Particles/ml)					
Total	309	1355	373	339%	21%
>2µm	154	441	143	186%	-7%
>5µm	10	26	10	149%	0%
>10µm	1.56	4.33	2.22	179%	43%
>20µm	0.67	1.33	0.67	100%	0%

Table 3: Step Flow Increase DPA4100 vs. Particle Counter

Note: The '% Inc.' represents the percent increase in particle count ('Peak' relative to 'Before Δ'), and the '% Δ' represents the net change after the transient effects have subsided. In the case of the Particle Counters, average values prior to and post flow rate change were taken from the plant SCADA system, as well as the maximum concentration measured.

Representative Images Stored During the Step Flow Increase:



DPA 4100 Images Stored During the Period of Peak Particle Counts

Plant Characterization Observations

1. The overall particle removal measured by the DPA4100 was 98.07% when comparing all particle concentrations in the Raw Water relative to particle concentrations in the Filtered Water, as compared to 98.70% with the online Particle Counters. The drop in turbidity was 98.70%.
2. The most dramatic reduction in concentration occurred when comparing the Raw Water particle concentrations to the first stage of coagulation/flocculation (Mixing Chamber #1), when the particles >2µm dropped from 13,063 particles/ml to 4,323 particles/ml (67% reduction).
3. The size distribution behaved as predicted during progression through the Mixing Chambers in the sense that the concentration of smaller particles dropped (5510 to 3740 particles/ml <2µm) while the concentration of larger particles grew (particles >5µm within Mixing Chamber #3 grew relative to Mixing Chamber #2 from 669 to 1108 particles/ml). (Note: only the bulk 'interstitial' fluid at the top of the Mixing Chamber samples was analyzed after the samples had settled for 48hrs, therefore larger more dense particles would not have been included in the analysis as they would have settled out.)
4. The nature of the Settled Water was dramatically different relative to that of the Raw Water in terms of the presence of significantly greater number of larger particles (15 times more particles >20µm).
5. The DPA4100 was able to detect a significant quantity of particles <2µm (e.g. 12,340 of the 25,403/ml in raw water), representing a significant number of particles not reported by the on-line particle counters in use.

Filter Flow Increase Observations

1. Upon changing the filter flow rates from ~10 to 20 ML/day flow rates (within normal operating practice), particle concentrations >2µm increased from 154 to 441 particles/ml (average change of 186%). When including particles <2µm detected by the DPA4100, the concentrations increased from 309 to 1355 (339%).
2. The peak response in terms of particle shedding took place between 5 and 10 minutes after the change to the flow rates was initiated, with concentrations returning to 'normal' 15-20 minutes after the change was initiated.
3. Both large and small particle concentrations reacted to the flow rate change (the concentration of particles >5µm increased by a factor of 2.5 before stabilizing to pre-flow rate change concentrations).
4. A very small change in turbidity (0.02 NTU) was observed during the abrupt increase in particles in the filter effluent.
5. A very small change in online particle counter readings (65 to 93.03 particles/ml, or an increase of 43%) was observed during the abrupt increase in particles in the filter effluent.
6. Similar results were observed upon testing two additional sample sets from Filter #14.

CONCLUSIONS

The DPA4100 has proven to provide a more sensitive detection of suspended particles within water relative to online Particle Counters and Turbidity Meters, offering additional insights into the dynamics of particle formation and removal during the coagulation/flocculation and sedimentation treatment process steps. Additionally, the DPA technology has been found to be an effective tool for studying the impact of hydraulic changes within the system on particle removal efficiency and filter shedding behavior. In conjunction with turbidity meters and online particle counters, the DPA technology possess the potential to act as an highly sensitive measure of water quality, as well as a predictive tool for determining plant particle removal behavior under various loading and operational conditions.

Further study is required at the Britannia WPP, and the next steps involve exploring the biological nature of the filter given a recent elimination of the pre-filter chlorination step from the treatment process, and exploring the impact of different plant flow rates (including start from a full stop) as it relates to the coagulation/flocculation/sedimentation process given the hydraulic design of the mixing chambers. Other areas of interest include establishing a correlation between the characteristics of the Settled Water size distribution and filter behavior (backwash frequency, ripening period, particle log reduction…) and determining the sensitivity this distribution to variables such as silica dose, alum dose, and water chemistry.

ACKNOWLEDGEMENTS

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