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Detection of Biological Suspensions Using Online Detectors in a Drinking Water Distribution System Simulator



Office of Research and Development
National Homeland Security Research Center

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United States Environmental Protection Agency
National Homeland Security Research Center
Cincinnati, OH 45268

Office of Research and Development
National Homeland Security Research Center, Water Infrastructure Protection

Table of Contents

Disclaimer ..... **vi**
Executive Summary ..... **ix**
Introduction **1**
Experimental Design **3**
Single Pass Distribution System Simulator 3
Water Quality Sensors 3
Contaminants 3
Evaluation of Water Quality Sensor Response 4
Results and Discussion **5**
Results of Sensor Response Experiments 5
Sievers® 900 On-Line Total Organic Carbon Analyzer and Hach CL17 Free Chlorine Analyzer 5
s::can Spectro::lyser™ and Hach FilterTrak™ 660 sc Laser Nephelometer 5
Real Tech Real UVT Online 9
Fluid Imaging Technologies FlowCAM® 9
JMAR Technologies BioSentry® 9
Discussion and Significance of Sensor Response Results 10
Sensor Cost Considerations 10
Conclusions and Future Work **13**
References **15**

Disclaimer

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List of Tables and Figures

Table 1: Water quality sensors 4

Table 2: Sensor response to contamination reported as absolute change (top), percent change (middle) and signal-to-noise ratio (bottom) 6

Table 3: Formulation for terrific broth and sporulation media 9

Table 4: Sensor detection and purchase data 11

Figure 1: Sensor baseline and response to contamination with *Bacillus globigii* spores at four inch pipes densities ... 7

Figure 2: Sensor baseline and response to contamination with *Escherichia coli* K-12 at four inch pipes densities 8

Figure 3: Multiple angle light scattering device response to *Escherichia coli* K-12 and *Bacillus globigii* 10

List of Acronyms

ATCC	American Type Culture Collection
CWS	Contamination Warning System
DPD	N, N-diethyl-p-phenylenediamine
GAC	Granular Activated Carbon
GCWW	Greater Cincinnati Water Works
GPM	Gallons per Minute
HSPD	Homeland Security Presidential Directive
MALS	Multiple Angle Light Scattering
MSD	Metropolitan Sewer District
NTU	Nephelometric Turbidity Unit
TOC	Total Organic Carbon
US EPA	United States Environmental Protection Agency
UV	Ultraviolet

Executive Summary

Detection of relatively low density microbial suspensions (less than 10^5 cfu/mL) was evaluated with a suite of online water quality sensors and instruments. Typically, the drinking water industry uses online sensors to measure parameters such as free chlorine, pH, and conductivity; however, in microbial suspensions below 10^5 cfu/mL, the sensors have a weak response or are ineffective. Therefore, sensors designed to detect either particulates in water or organic compounds that might accompany microbial suspensions (i.e., culture media) were evaluated for their ability to detect low density microbial suspensions.

Evaluation took place in a pilot scale drinking water distribution system simulator (DSS) with sensors attached through a slip-stream. Technologies investigated were the Fluid Imaging Technologies FlowCAM®, Hach FilterTrak™ 660 sc Laser Nephelometer, JMAR BioSentry®, Real Tech Inc., Real UVT Online and the S::CAN Spectro::lyser™.

Biological suspensions were injected into the DSS and sensor responses were compared to stable baseline values before injection. The JMAR BioSentry® detected the least dense biological suspension (600 cfu/ml) while the S::CAN Spectro::lyser™ and Hach FilterTrak™ 660 sc Laser Nephelometer performed as well as the online free chlorine and TOC analyzers ($2.5x10^4$ cfu/ml). The results were determined by selecting the biological densities that elicited an obvious visual response from the sensor. However, it should be noted that changes not obvious to the naked eye could be detected with event detection algorithms. Operation and maintenance costs of the sensors are minimal, but some have high capital costs that must be considered when weighing their detection ability.

Introduction

Detecting contamination in drinking water distribution systems has challenged water utilities for many years. Water utilities have traditionally focused on intrusion from incidents such as pipe breaks or plant malfunctions as the primary source of contamination, but in recent years utilities have also considered issues associated with intentional contamination. Contaminant-specific sensors show promise for detecting contamination, but their use is limited by factors such as cost, ease of use, commercial availability and limited acceptability by the drinking water community. Furthermore, the large number of contaminant-specific sensors needed to detect the universe of potential contaminants makes their use inefficient.

The drinking water community has explored the use of common water quality sensors to help detect contamination (Allmann et al., 2005; Byer et al., 2005; Kessler et al., 1998; King et al., 2005; Kroll et al., 2005; Magnuson et al., 2005). In response to Homeland Security Presidential Directives (HSPD) 7 and 9, the United States Environmental Protection Agency (USEPA) has undertaken research using a multifaceted contamination warning system (CWS) for drinking water distribution systems, of which online water quality monitoring is one component (USEPA, 2005a; 2006; 2007; Hall et al., 2007; Szabo et al., 2006; HSPD 7, 2003; HSPD 9, 2004). Research efforts have remained focused on commercially available online water quality sensors, since they offer the dual benefits of water quality data and potential detection of contamination.

Detecting biological suspensions at low concentrations (less than 10^5 cfu/mL) in drinking water has proven challenging. Previous research has shown that biological suspensions, injected with the growth media in which they were cultured, will affect parameters like free chlorine and total organic carbon (TOC) in chlorinated water (Hall et al., 2007; USEPA, 2007). This is due to the nutrient media reacting with and reducing free chlorine and organic carbon in the broth, which increases TOC. If biological suspensions are washed and injected without growth media, or injected into a large volume where the growth media is highly diluted, standard water quality parameters show little noticeable response.

Therefore, it is sensible to study less common sensors to determine whether they can detect biological suspensions at lower densities than standard sensors. This paper describes detection studies with a suite of specialized water quality monitors and their response to biological contamination at 1×10^2-2.5×10^4 cfu/ml. As-tested cost information is also included, which will hopefully provide perspective to any water utility or other user looking to employ the tested water quality monitors.

Experimental Design

Single Pass Distribution System Simulator

The drinking water distribution system simulator used in this study was described in Yang et al. (2008). A drinking water distribution pipe was represented using a once-through (or single pass) pipe at USEPA's Test and Evaluation (T&E) Facility in Cincinnati, Ohio. The pipe consisted of 1,200 feet of 3-inch diameter fiberglass-lined ductile iron. Experiments were conducted at 22 gallons per minute (gpm), which corresponds to an average velocity of 1 foot per second (ft/sec) in the pipe. This flow rate will produce turbulent flow (Reynolds number approximately 26,000) in the relatively smooth pipe. Although the pipe was lined with fiberglass, sections have chipped away, exposing ductile iron. These sections were heavily corroded and were more representative of an iron drinking water pipe than the lined sections. Note that English standard units, commonly used by the U.S. water utility personnel, have been used throughout this report. For example, volume is reported in U.S. gallons and velocity in feet per second (ft/s). However, in keeping with industry usage, contaminant concentrations are reported in metric units, in milligrams per liter (mg/L).

Chlorinated tap water was introduced directly from the Greater Cincinnati Water Works (GCWW) distribution system into a 750 gallon storage tank where it was fed by gravity into the 3-inch pipe system. An air gap was maintained between the GCWW system and this experimental setup to ensure that there was no back flushing of the injected contaminant. Free chorine was generally 1.0 +/- 0.1 mg/L, with temperature ranging from 10° to 30° C depending upon the season. Turbidity was 0.1 nephelometric turbity units (NTU) or less throughout the year. The water fed from the 750 gallon overhead tank provided a 10 to 12 pounds per square inch (psi) inside the pipe. Contaminant injections were performed for 20 minutes by injecting a 10 L mix of contaminant in chlorine-free granular activated carbon (GAC) filtered tap water at the rate of 0.5 L/min. Contaminant concentration in the pipe was varied by altering the amount of contaminant mixed in the 10 L volume. Control experiments were performed by injecting 10 L of the GAC filtered tap water without the contaminant at the same injection rate.

Water Quality Sensors

A suite of sensors measured water quality at 80 feet from the injection point through a slipstream. Past experimental results indicated that of the standard water quality parameters, free/total chlorine and TOC were the best at indicating contamination in chlorinated tap water (USEPA, 2006a; 2005b). Total chlorine was measured using a Hach CL17 Total Chlorine Analyzer (Hach Company, Loveland, Colo.), which uses the N, N-diethyl-p-phenylenediamine (DPD) colorimetric method (Standard Methods, 1998). TOC was measured using a Sievers® 900 On-Line Total Organic Carbon Analyzer (GE Analytical Instruments, Boulder, Colo.) The operation and maintenance of these sensors is described in Hall et al. (2007).

The following specialized water quality sensors were evaluated in this study to determine if their response was better than the standard TOC and chlorine sensors listed above:

- A laser turbidimeter, the Hach FilterTrak™ 660 sc Laser Nephelometer (Hach Company, Loveland, Colo.), was used as an enhanced turbidity monitor. It operates similarly to a standard turbidimeter, except that it employs a laser nephelometer, which yields better resolution.
- A BioSentry® Water Monitoring system (JMAR Technologies, San Diego, Calif.) represented a laser based multiple-angle light scattering (MALS) device. In addition to detecting changes in the number of particles in water, it has the ability to classify microorganisms using their unique bio-optical MALS signatures, but this information was not specifically analyzed in this study.
- Estimates of TOC and turbidity were obtained using a 100 mm s::can Spectro::lyser™ (s::can Meßtechnik GmbH, Vienna, Austria). The spectro::lyser operates using ultraviolet-visible (UV-Vis) absorption spectrometry in the 200 to 750 nm range.
- Continuous ultraviolet light transmission at UV 254 nm wavelength (UV_{254}) was made with a Real UVT Online monitor (Real Tech, Inc., Whitby, Ontario, Canada). Similarly to the spectro::lyser, changes in UV absorption by aromatics or other light absorbing compounds in the microbial suspension could be detected by this device.
- An online flow-cytometer and microscope called FlowCAM® (Fluid Imaging Technologies, Yarmouth, Maine) was used as a digital imaging microscope-based particle detector. Particles are channeled through a flow cell where they are digitally imaged and can be counted.

Contaminants

Two microorganisms were used in this study. *Escherichia coli* K-12 (ATCC 25204) (*E. coli*) was used as representative vegetative bacteria. *Bacillus globigii* (*B. globigii*) (obtained from the US Army's Dugway Proving Ground, Dugway Proving Ground, Utah) was used in spore form and was considered to be a representative spore-forming bacterium. Storage and culturing methods are described in detail in Szabo et al. (2007) and Hall et al. (2007) for *B. globigii* and *E. coli*, respectively. Wastewater (secondary effluent) was also injected and was obtained from the Cincinnati Metropolitan Sewer District (MSD) Mill Creek treatment plant.

Table 1: Water quality sensors

Trademark or Brand Name	Manufacturer's Name, City and State	Web Site
BioSentry®	JMAR Technologies, Inc., San Diego, California	http://www.jmar.com
FlowCAM®	Fluid Imaging Technologies, Yarmouth, Maine	http://www.fluidimaging.com
Hach CL17 Free Chlorine Analyzer	Hach Company, Loveland, Colorado	http://www.hach.com
Hach FilterTrak™ 660 sc Laser Nephelometer	Hach Company, Loveland, Colorado	http://www.hach.com
Real UVT Online	Real Tech, Inc., Whitby, Ontario, Canada	http://www.realtech.ca
Sievers® 900 On-Line Total Organic Carbon Analyzer	GE Analytical Instruments, Boulder, Colorado	http://www.geinstruments.com
Spectro::lyser™	scan Messtechnik GmbH, Vienna, Austria	http://www.s-can.at

Evaluation of Water Quality Sensor Response

Sensor response to contamination was evaluated by calculating the absolute and percent change from a stable baseline to the peak value recorded as the contaminant passed the sensor. Baseline values were calculated by averaging the sensor signal over a one hour period before contaminant injection, with baseline noise represented by standard deviation. Sensors were polled every minute during test runs, so 60 pre-injection data points were used for determining baseline mean and standard deviation. Contamination injections were performed in duplicate, and results are presented as the average of those duplicates (see Table 2 in the results section).

Evaluating the data by calculating the percent change yields a good system specific response of water quality parameters to contaminants. However, percent change may be different in systems that have different water quality. For example, if a contaminant injected into water with 1 mg/L free chlorine decreases the chlorine concentration to 0.9 mg/L, a 10% reduction has occured. If the same contaminant injected at the same concentration in water with 2 mg/L free chlorine consumes the same amount of free chlorine, a 5% reduction has occured. Therefore, sensor response is also characterized as a signal-to-noise ratio. The maximum absolute change (baseline to peak) recorded during injection was normalized by the baseline standard deviation. Analyzing data with the signal-to-noise approach illustrates sensor response as the magnitude of the water quality change relative to the variation in the baseline before injection.

The time period when the injected contaminant was in contact with the sensors was determined based on the flow rate and injection duration. Injections were 20 minutes long and flow velocity was 1 ft/sec, so the injection reached the 80 ft sensor station 1.3 minutes after injection and continued passing the sensors for 20 minutes. Sensor responses usually lasted longer than 20 minutes at this station due to dispersion, which elongated the contaminant plume in the pipe. Peak sensor responses were taken from the time periods when the contaminants were in contact with the sensors.

Although water quality sensors typically respond within seconds of water quality change, the Hach CL17 and Sievers® 900 On-Line Total Organic Carbon Analyzer used for this experiment run on cycles of 2.5 and 8 minutes, respectively. These instruments were polled every minute, but only returned new values at the end of their cycles. Still, new values were returned frequently enough that the changes in water quality were seen for both devices while the contaminant was passing the sampling point.

Results and Discussion

Results of Sensor Response Experiments

Table 2 summarizes the response of the standard and specialized sensors to various cell densities (or concentrations) of *E. coli* and *B. globigii*. Time series plots of some of the specialized sensor responses are presented for *B. globigii* and *E. coli* in Figures 1 and 2, respectively. These plots show the response of duplicate experiments in sequence, as well as the baseline data that precedes the injection.

Sievers® 900 On-Line Total Organic Carbon Analyzer and Hach CL17 Free Chlorine Analyzer

Total chlorine measured by the Hach CL17 decreased by 0.04 and 0.08 mg/L upon addition of *B. globigii* and *E. coli*, respectively, at $2.5x10^4$ cfu/mL. The response of the JMAR Biosentry® was much larger at this cell density, but the chlorine response is comparable to the s::can and laser turbidimeter at $2.5x10^4$ cfu/mL for both microbial suspensions. TOC measured by the Sievers® 900 changed by 0.16 and 0.41 mg/L for *B. globigii* and *E. coli*, respectively, at $2.5x10^4$ cfu/mL. The signal-to-noise ratio of 13.7 for *E. coli* at 10^3 may indicate a change, but no visual change was noticeable below this level. Sievers® 900 TOC and Hach CL17 Total Chlorine results confirm what has been reported in the past: there is a significant decrease in the response of both instruments when the cell density (or concentration) of injected microorganisms decreases below $2.5x10^4$ cfu/mL. It is important to note that the Sievers® 900 TOC and Hach CL17 Total Chlorine response occurs only when *B. globigii* and *E. coli* are injected with their respective sporulation and growth media. If these growth media were washed away or sufficiently diluted, the Hach CL17 Total Chlorine and Sievers® 900 TOC sensors show little or no response. Signal-to-noise values for the Sievers® 900 TOC analyzer are higher than the other instruments below $2.5x10^4$ cfu/mL because TOC baseline was stable during these tests.

s::can Spectro::lyser™ and Hach FilterTrak™ 660 sc Laser Nephelometer

The response for the s::can spectro::lyser's™ turbidity measurement channel is the same for each injected density and provides little indication that a contaminant is present. The percent change values are misleading since the average value of turbidity is low, but the data are noisy. When the peak during injection is compared to the mean, it appears that a large change has taken place. However, when signal-to-noise is calculated, the response is one to two, indicating that the peak is close to the standard deviation in the baseline. Figures 1 and 2 confirm that visually distinguishing a turbidity response is difficult.

Table 2: Sensor response to contamination reported as absolute change (top), percent change (middle) and signal-to-noise ratio (bottom)

Injected Agent	In-Pipe Concentration (cfu/mL)	Hach Total Chlorine (mg/L)	Sievers ®TOC (mg/L)	S::CAN TOC (mg/L)	S::CAN Turbidity (FTU)	Hach Laser nephelometer (mNTU)	JMAR Biosentry® (counts)	FlowCAM® (#/mL)	RealUVT (UVA)
E. coli **(in Terrific Broth)**	**1.0E+02**	-0.01 -1.3% -3.5	0.00 0.4% 1.0	0.01 0.5% 1.1	0.07 44% 1.4	1.7 6% 3.2	173 22% 9.4	No Data	No Data
	6.0E+02	0.00 0.0% -0.1	0.01 1.0% 5.9	0.01 0.8% 2.0	0.10 43% 2.3	2.9 12% 3.6	256 32% 17	No Data	No Data
	1.0E+03	-0.01 -0.9% -4.2	0.02 2.2% 13.7	0.01 1.1% 2.4	0.08 30% 1.8	1.7 6% 2.7	316 41% 16	446 230% 2.4	0.0003 1.7% 2.1
	2.5E+04	-0.08 -7.0% -19	0.41 36.1% 319.3	0.08 7.6% 16	0.09 65% 1.6	13 45% 21	4616 696% 263	2099 7591% 84	0.0002 1.4% 1.5
B. globigii **(in sporulation media)**	**1.0E+02**	-0.01 -0.5% -1.5	0.01 0.9% 1.2	0.00 0.2% 0.4	0.10 86% 2.3	1.1 4.1% 2.0	86 12% 5.9	No Data	No Data
	6.0E+02	-0.01 -0.8% -2.3	0.01 0.7% 1.2	0.01 0.5% 1.0	0.06 43% 1.5	0.9 3.3% 2.9	75 10% 5.6	No Data	No Data
	1.0E+03	0.00 0.1% 0.1	0.01 1.1% 2.1	0.01 0.6% 1.2	0.08 63% 1.4	1.1 4.1% 1.9	123 17% 10.4	1.7 120% 1.6	0.0003 1.6% 1.9
	2.5E+04	-0.04 2.9% -9.6	0.16 14.8% 42.0	0.03 2.6% 5.9	0.08 64% 1.7	7.6 27% 13.9	1706 255% 153	5.8 388% 5.6	0.0004 2.4% 2.4
Wastewater (Secondary Effluent)	**10 L (0.026 v/v)**	-0.13 -11% -32	0.07 6.4% 36.3	0.07 6% 12	0.15 239% 3.1	34 116% 47	3356 538% 249	4079 1158% 9.5	0.0028 25.4% 13.2
Control Blank (DI Water)	**0**	0.01 1.5% 3.6	0.01 1.9% 0.9	0.04 4.4% 17	0.09 15% 2.3	1.5 6.6% 3.3	29 3.8% 1.7	1907 4496% 40	0.0002 1.0% 1.4

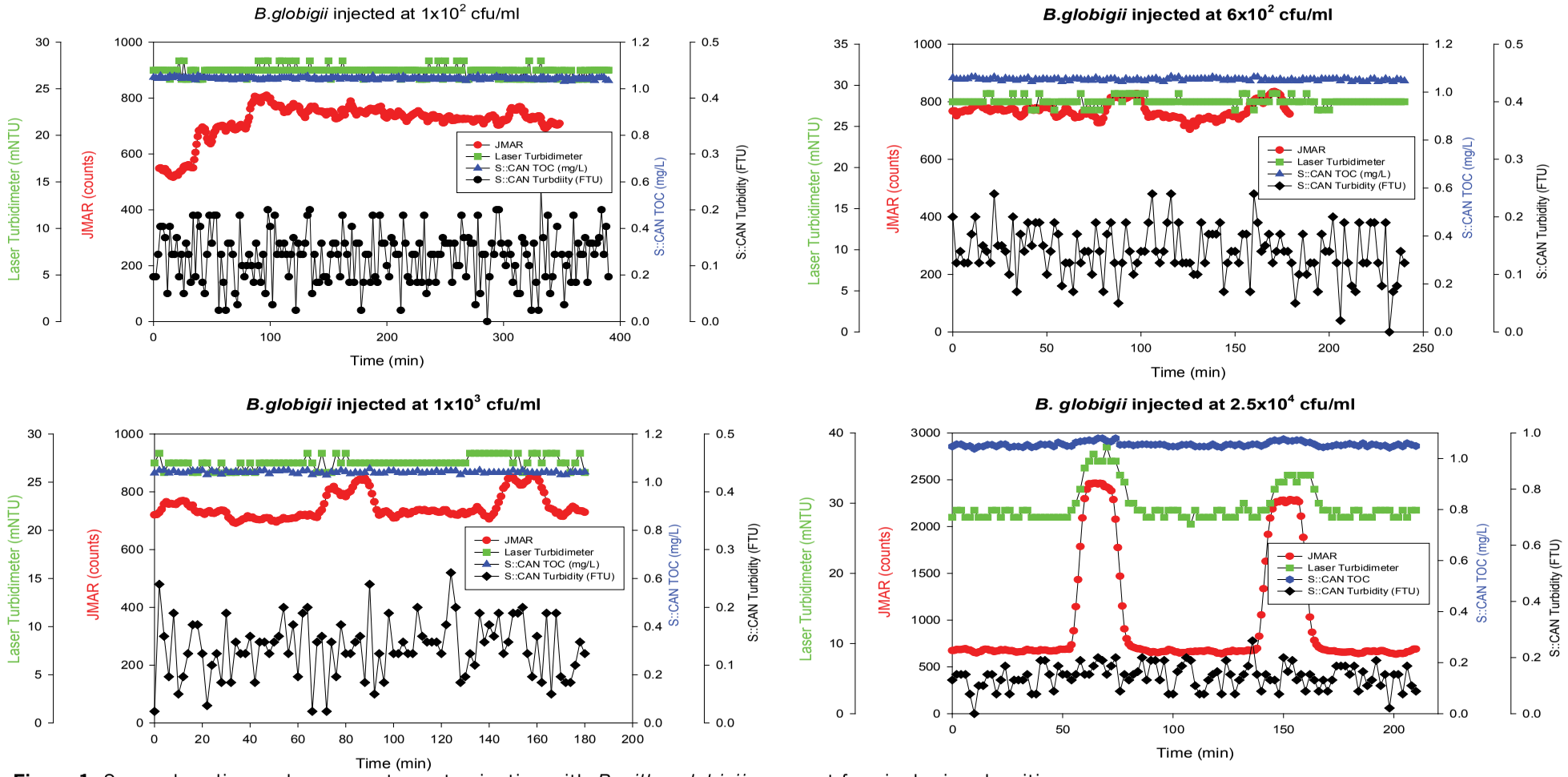


Figure 1: Sensor baseline and response to contamination with *Bacillus globigii* spores at four inch pipe densities

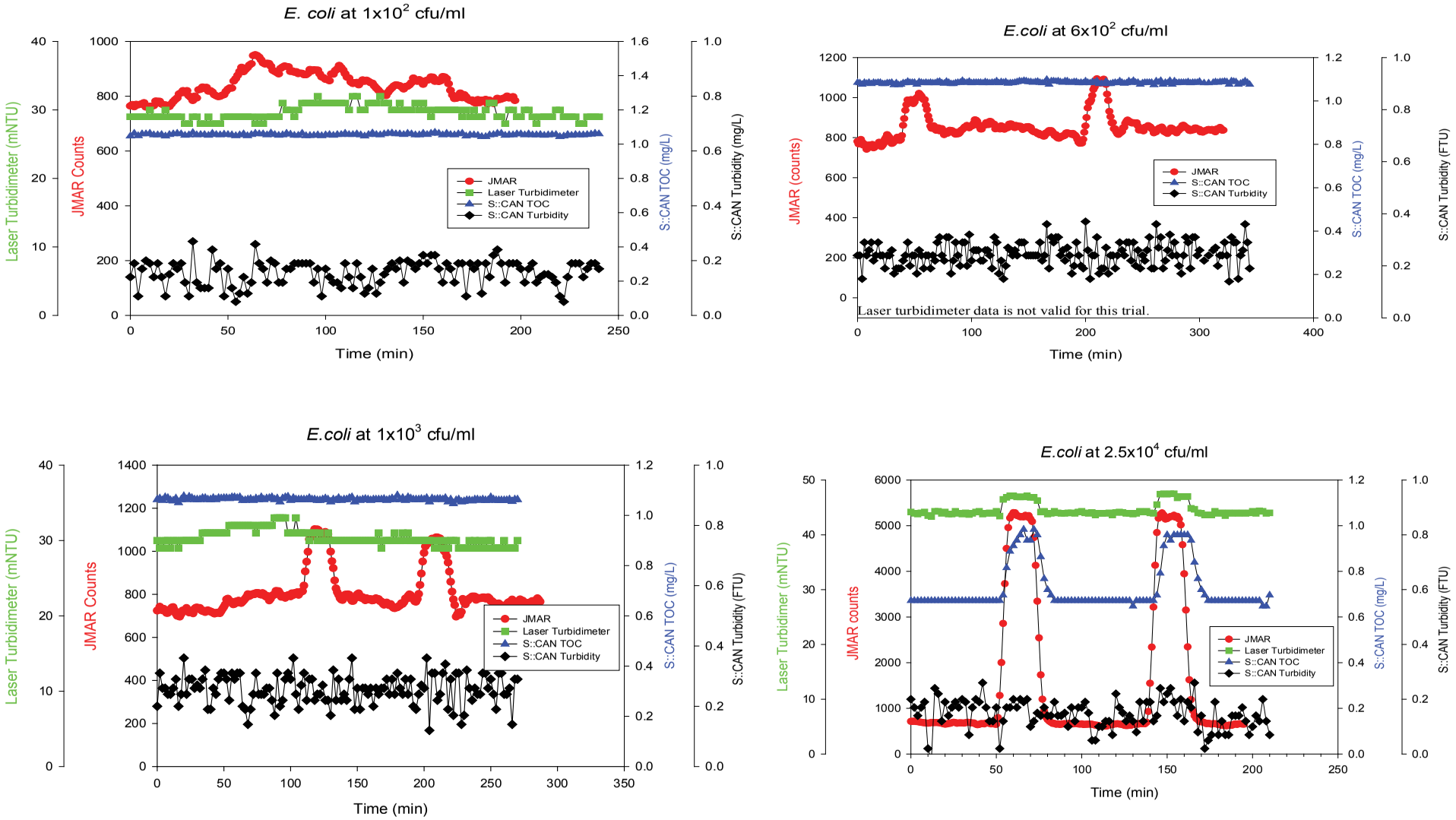


Figure 2: Sensor baseline and response to contamination with *Escherichia coli* K-12 at four inch pipe densities

Table 3: Formulation for terrific broth and sporulation media

Terrific Broth (per liter of water)	Sporulation Media (per liter of water)
Pancreatic Digest of Casein…12 g Yeast Extract…24 g Dipotassium Phosphate…9.4 g Monopotassium Phosphate…2.2 g	Nutrient Broth…8 g Manganese Sulfate…40 mg Calcium Chloride…100 mg

s::can spectro::lyser™ TOC yielded a response for *E. coli* at $2.5x10^4$ cfu/mL and a weak response for *B. globigii* at the same cell density. This is not surprising, since the s::can spectro::lyser™ detection principle is based on absorption of UV and visible light. Table 3 shows that the media in which the *E. coli* were cultured (Terrific Broth) is much more enriched in sugars and amino acids compared to the sporulation media in which the *B. globigii* spores were suspended. The higher concentration of compounds that absorb/emit light will lead to a greater response. The Hach FilterTrak™ 660 sc Laser Nephelometer responded in similar manner to the s::can spectro::lyser™ TOC, with a peak emerging during injection at the $2.5x10^4$ cfu/mL density for *E. coli* and *B. globigii*.

Real Tech Real UVT Online

The Real UVT measures percent transmission (i.e., the light that is not absorbed) of UV light at 254 nm, so it was hoped that either light absorbing functional groups on the cells or the nutrient broth injected with the cells would elicit a change. The Real UVT showed little response to either *E. coli*, *B. globigii* or the control injection. This is likely due to either the functional groups in the nutrient broth or on the microorganism not absorbing light at 254 nm, or the functional groups were not concentrated enough. The wastewater injection caused a noticeable 25% (S/N 13.4) change from the baseline.

Fluid Imaging Technologies FlowCAM®

FlowCAM® response to the biological agents and secondary effluent was similar to the responses of an online turbidity sensor: percent changes were large, but signal-to-noise ratio was low due to high baseline variation. However, unlike the responses of a turbidity sensor, large baseline changes were sporadic and not always explainable. Large variability in the baseline made changes difficult to detect. The exception was the *B. globigii* injection at $2.5x10^4$ cfu/mL, where the signal-to-noise ratio of 84 indicated a large, discernable change.

A good example of the FlowCAM® baseline variation is the control blank data where GAC filtered tap water elicited a change larger than some of the contaminants injections. The control blank should not cause a change larger than a contaminant injection. In later experiments, it was observed that touching or bumping the instrument during testing resulted in a spike in counts, which were likely due to the release of accumulated particles in the instrument plumbing. Also, flow to the optics for this device is controlled by a peristaltic pump, and this flow varied widely depending on how the length of the tubing in the pump. If flow is cut off from the optics, no detection will take place. Flow that is too fast might force particles through the flow cell too quickly to be counted. These instrument design/operational limitations could have led to the changes recorded during the control blank injection. The changes recorded by the FlowCAM® were likely real. Attributing changes to a contaminant – or other random event – proved difficult. Finally, images of the bacteria taken by the FlowCAM® were visible merely as small "dots." The highest available resolution of the 20X objective was not enough to visualize the *B. globigii* or *E. coli*.

JMAR Technologies BioSentry®

Of the tested devices, the multiple angle light scattering device (JMAR Biosentry®) performed best, with an obvious response at $6x10^2$ cfu/mL for *E. coli* and *B. globigii*. A change was not visible at the 1×10^2 cfu/mL level due to the noise in the baseline. Figure 3 shows the change in counts from baseline plotted against the increasing density of both biological agents. The output from the BioSentry® is in "unknown counts," or the number of particles that the machine is counting. At any concentration, the response is larger for *E. coli* compared to *B. globigii* since the vegetative cells are larger and easier to detect than the spores.

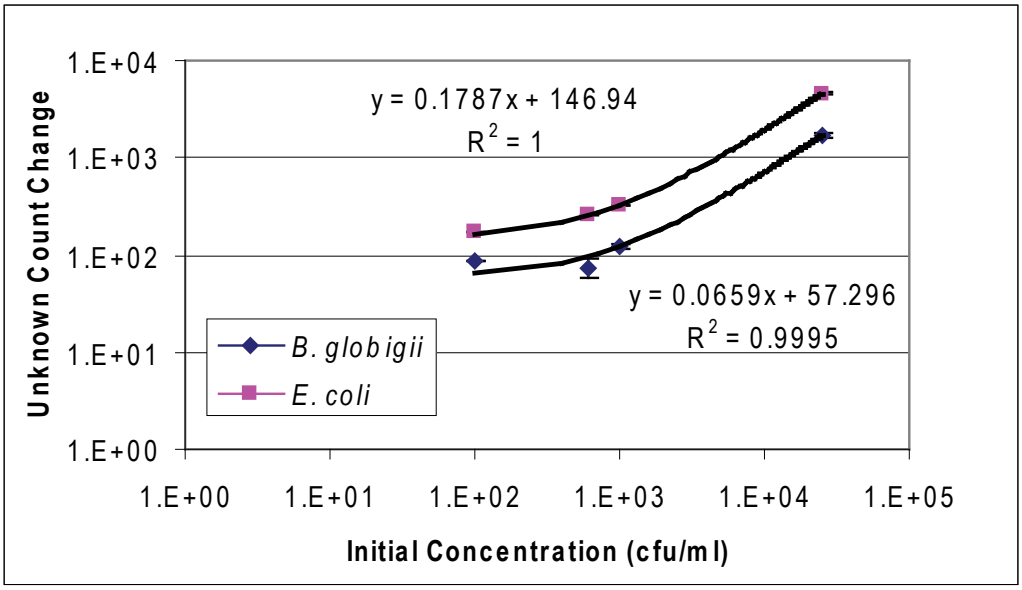


Figure 3: Multiple angle light scattering device response to *Escherichia coli* K-12 and *Bacillus globigii*

Discussion and Significance of Sensor Response Results

B. globigii and *E. coli* were visibly detected at $2.5x10^4$ cfu/mL by all of the sensors tested. At the 1,000 and 600 cfu/mL cell densities, the Biosentry® provided the only visually significant response. None of the sensors provided any significant visual response at the 100 cfu/mL cell density. It should also be noted that 10 L of secondary effluent triggered an easily detectable response from each sensor used in this study due to the fact that it contains large particles and has a relatively high organic content compared to tap water. This is particularly interesting when considering that wastewater cross connections in drinking water distribution systems may be detected by standard and specialized sensors since raw effluent would presumably be more concentrated in solids, organics and nutrients.

The sensor response results have been presented as what can be visually detected as a change from a baseline. Visual changes can be useful when manually evaluating sensor data, but whether someone can discern a change depends on the variability of the baseline data. The experimental conditions in this study were ideal since baseline variation was minimal, but variability can increase in the field. Therefore, event detection algorithms should be considered for use in conjunction with standard or specialized water quality sensors to lower detection levels (McKenna et al., 2008). Although the human eye may not be able to discern a change from baseline data, an event detection algorithm may detect it. However, the data provides a glimpse of the water quality changes that could be caused by biological contamination. Even if an event detection algorithm indicates an unusual change, the data that caused the alarm will likely be manually examined.

Finally, adding a specialized sensor could benefit a chloraminated drinking water system. Inactivation of microorganisms will be slower in chloraminated water, especially *Bacillus* spores, so the results presented for chlorinated water should transfer to chloraminated systems. Furthermore, including devices like the s::can spectro::lyser™ or Sievers® 900 will add TOC as an online monitoring parameter in an online water quality monitoring station. This is especially important for chloraminated systems since total chlorine is not as effective at responding to contamination in chlorinated water as in chlorinated water (Szabo et al., 2008).

Sensor Cost Considerations

Table 4 lists the costs of each piece of equipment. The cost of the JMAR BioSentry® unit used in these tests was $46,215. Should there be a particularly sensitive point in a utility's distribution system the BioSentry® may be an effective tool for detecting low level biological contamination. However, should a utility wish to deploy more units, they may look to standard online sensors that cost less, but cannot detect biological suspensions as low as the BioSentry®. If biological contamination is a concern to a water utility, then this tradeoff between detection and cost must be considered.

Table 4: Sensor detection and purchase data

Sensor	Density at which sensor responded (cfu/mL)	Approximate Purchase Price (year 2007 $)
JMAR BioSentry®	$2.5x10^4$, $1x10^3$, $6x10^2$	50,000
s::can spectro::lyser™ TOC	$2.5x10^4$	25,000
Spectro::lyser™ turbidity	$2.5x10^4$	
Hach FilterTrak™ 660 sc Laser Nephelometer	$2.5x10^4$	5,000
RealTech Real UVT	–	5,000
FlowCAM®	$2.5x10^4$	35,000
Sievers® 900 On-Line Total Organic Carbon Analyzer	$2.5x10^4$	25,000
Hach CL17 Total Chlorine Analyzer	$2.5x10^4$	5,000

Conclusions and Future Work

The data from the studies indicate that some specialized sensors can detect biological suspensions at lower densities in drinking water than standard online water quality sensors. The JMAR BioSentry®, which uses multiple angle light scattering (MALS), detected the lowest concentration (600 cfu/mL), while the s::can spectro::lyser™ TOC and Hach FilterTrak™ 660 sc Laser Nephelometer performed as well as the Hach CL17 Total Chlorine Analyzer and Sievers® 900 On-Line Total Organic Carbon Analyzer. An important component to any future work would be using an event detection algorithm in concert with the online water quality sensors. Even though an obvious visual change did not occur at low levels of contamination (100 to1,000 cfu/mL) for all sensors, there may be a subtle change that an algorithm could detect that the human eye cannot. This is especially important if a specific water quality parameter is "noisy" at the location it is being monitored. Other conclusions are as follows:

- The operational and maintenance costs of all the specialized optical devices tested were favorable. There are no reagents to buy and replace and no major maintenance issues were observed during the testing.
- As with all online turbidity and particle counting sensor equipment, control of bubble formation is needed to prevent false alarms.
- There is a wide range of capital costs for the equipment tested. This is good news for potential consumers of this equipment, since multiple sensors of varying cost can be used together to create a more comprehensive detection network. Furthermore, it is anticipated that the cost of the multiple angle light scatter device can be reduced as larger market demand is generated and cost efficiencies are identified.
- The lower detection capability of the more expensive equipment should be weighed against the higher cost of the equipment. For example, one expensive device with lower detection capability could be deployed to a sensitive area while multiple less expensive devices could be more widely distributed.

Finally, although some of these devices did not respond to injections of microbial suspension, it should be noted that the manufacturers might not have designed them for detection of low density biological suspensions. Results from this study should not be used to evaluate the detection capabilities of these devices when used in other scenarios or for their intended purpose.

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