On-Line Water Quality Monitoring for Distribution System Operational Improvements And Security

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Continuous monitoring of distribution system water quality was rarely conducted prior to the United States terrorist attacks of 2001. Following that event, and the completion and review of risk assessments for all public water systems (PWS) serving greater than 3,300 population, the distribution system was identified as the most vulnerable area of attack.

In response to Homeland Security Presidential Directive 9, which required the U.S. Environmental Protection Agency (EPA) to develop a process for utilities to improve their water distribution system protection, distribution system water quality monitoring pilot projects were conducted, funded through the EPA Water Security Division Water Security (WS) initiative. As a result, continuous monitoring systems are in operation in Cincinnati, Dallas, New York, Philadelphia, and San Francisco. Independent from the WS initiative program, some PWS and U.S. government agencies have been developing similar programs. Benefits of these systems include improvement of water treatment processes, increased efficiency of water utility operations, more assured quality of water delivered to consumers, and increased protection of public health.

Benefits of Distribution System Monitoring

Benefits from continuous distribution system on-line water quality monitoring (OWQM) may be categorized as operational enhancements, regulatory compliance, and contamination warning.

Operational enhancements include continuous indication of water quality in the distribution system, beyond that which is possible through routine regulatory sampling. Early indication may be provided of unusually low residual chlorine levels, impending nitrification (elevated ammonia), turbidity excursions caused by main breaks, and other unusual water quality changes. This monitoring is achieved through measurement of several water quality parameters that water utilities are already familiar with (e.g., chlorine residual) and other parameters, which are relatively new to this application; for example, total organic carbon (TOC).

Warning of intentional or unintentional contamination in the distribution system is somewhat more complex. Specialized analyzers are available, including gas chromatographs, which may detect specific contaminants, and toxicity monitors of many types that can provide a general warning of contamination. Due to the large number of potential contaminants, rather than attempting to specifically identify a contaminant, it is more practical to monitor for an indication of contamination through changes in many of the same water quality parameters, or surrogates, that are used for operational benefits monitoring.

Regulatory compliance benefits of OWQM include improving the ability to maintain chlorine residual as part of the Total Coliform Rule (TCR) and maintaining proper pH control to avoid potential violations of the Lead and Copper Rule.

Beyond monitoring for operational and contamination purposes, utilities should consider OWQM as part of the distribution system optimization program of the Partnership for Safe Water, which is a voluntary effort that includes EPA, the American Water Works Association (AWWA) and several other drinking water organizations, and more than 200 water utilities throughout the United States. The goal of the organization is to provide a new measure of safety to millions of Americans by implementing prevention programs where legislation or regulation does not exist. The preventative measures are focused on optimizing treatment plant performance and distribution system operation.

Selection of Water Quality Parameters

The water utility that is embarking on the design of distribution monitoring must first decide which water quality parameters to monitor. Parameters that are typically included in OWQM systems include:

- TOC
- Residual chlorine
- Conductivity
- pH
- Turbidity

These are of interest to utilities from a distribution system, operational, and regulatory perspective and provide critical information, including:

- *TOC* – Elevated turbidity excursions can be associated with a breakthrough at the water treatment plant or scouring and release of biofilm within the distribution system.
- *Residual Chlorine* – Identifies sudden loss in residual which could promote biofilm growth and potential violation of the TCR.
- *Conductivity* – This measurement provides an easy method to identify mixing or different water sources, which can have a significant impact on many industrial operations.
- *pH* – Controlled for disinfection and corrosion control. The formation of some disinfection byproducts is pH-dependent.
- *Turbidity* – Provides warning of a system disruption created by a surge or reversal in flow that scours the pipeline. This could be caused by a pipeline break, hydrant knockover, or other problems that will impact chlorine residual and customer satisfaction.

Utilities that use chloramines for disinfection also measure for ammonia, nitrates, and dissolved organic carbon (DOC) to pro-

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vide early warning of nitrification in the distribution system. The first water quality indicator of nitrification will be the increase of ammonia, which will occur before nitrites and nitrates begin to increase.

The myriad of potential contaminants have been classified among twelve categories by EPA (EPA, 2005). Laboratory testing has concluded that three of these water quality parameters (TOC, residual chlorine, and conductivity) respond to the presence of contaminants from 10 of the 12 categories, as shown in Figure 1. By using these three parameters, along with operational monitoring, broad contaminant coverage is also provided with a minimum of instrumentation. The relative change in quality of water with either chlorine or chloramines has been investigated by EPA and the pilot cities, and can serve as general guidance for evaluating a water quality anomaly.

Most OWQM systems include monitoring for absorbance of ultraviolet (UV) light. The UV analyzers that operate by measurement of absorption at the single 254 nanometer (nm) wavelength are generically referred to as UV-254 analyzers; instruments, which operate through analysis of a broad spectrum from 200-720 nm and are referred to as spectral analyzers.

The UV absorbance has been shown to be strongly correlated to TOC content (Dilling). The UV-254 analyzers measure absorbance at the 254 nm wavelength, since this is the radiation emitted by a common mercury-based UV source lamp. The absorbance of UV light by TOC or other contaminants contained within the water sample is reported as a percent of the uninhibited lamp intensity, ranging from 0-100 percent.

Spectral analyzers utilize a xenon lamp to produce a light source across UV and visible light wavelengths from 200-720 nm. Measurement of absorbance at 254 discrete wavelengths across this range enables construction of an absorbance, or spectral curve (Figure 2). Due to the substantially greater information provided by spectral analysis, the broadband spectrum enables measurement of TOC based on calculation of numerous UV/visible light wavelengths, which are associated with this parameter. Similarly, turbidity is also calculated based on analysis of numerous wavelengths. Subtraction of the turbidity component enables derived measurement of nitrate and DOC. Other parameters, not typically included in OWQM analysis, also may be derived from broad spectral absorbance of UV and visible light.

Not all sources of TOC are revealed by UV/visible light absorbance, but a large enough percentage are detected so that these technologies are generally accepted for the OWQM application. This limitation of correlated or spectral indication of TOC must be considered when selecting OWQM parameters.

Selection of Water Quality Analyzers

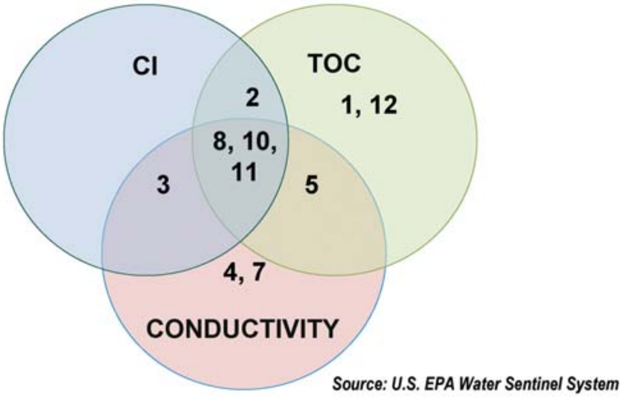
Once water quality parameters to be used for OWQM monitoring are selected, specific instruments to be used for this purpose must be selected. All utilities are under pressure to minimize capital and operating costs, so this consideration factors into analyzer selection. Addition of OWQM monitoring must be done without unnecessarily adding to the existing responsibilities of utility technicians, and this also impacts the selection of OWQM analyzers. One way to do this is to select sensors and analyzers that are reliable and inexpensive to operate, and require only infrequent direct attention or maintenance.

Chlorine Analyzer: The two most common methods for on-line chlorine analysis are amperometric and colorimetric detection. The colorimetric method requires use of chemical reagents to produce the reaction that is measured and used to quantify chlorine content. Reagent reservoir levels must be regularly monitored and refilled by maintenance personnel. Additionally, reagents used for colorimetric tests have been found to degrade in environments that exceed 105 degrees and significantly impact the quality of the analysis.

Amperometric sensors measure changes in electric current or potential and operate without use of chemical reagents. For monitoring residual chlorine by OWQM systems, these sensors reduce maintenance costs and activities, and reduce operational risks from depletion of reagent reservoirs between service visits. Therefore, amperometric technologies are most frequently used.

TOC Analyzers: Traditional TOC analyzers involve multiple electrochemical reactions for operation. Phosphoric acid is used for pH reduction and inorganic carbon removal, followed by oxidation of organic carbon to CO_2 by sodium or ammonium persulfate and heat or UV light. At least one manufacturer uses boron-doped electrodes to generate oxidation radicals in place of the persulfate solution.

The CO_2 is directly detected by a nondispersive infrared (NDIR) detector, or converted to carbonic acid and measured by conductance. Operation requires periodic re-



Source: U.S. EPA Water Sentinel System

Figure 1. TOC, Chlorine, and Conductivity are the Three Primary Water Quality Parameters Used for Distribution System Contamination Monitoring.

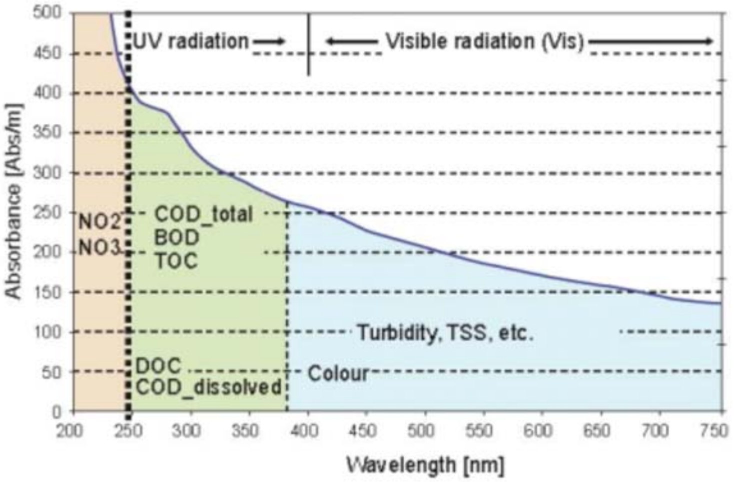


Figure 2. UV/Visible Absorbance Spectrum Enables Calculation and Derivation of Numerous Water Quality Parameters.

plenishment of acid and, if used, persulfate reagents. The UV lamp, when used, is also a replacement part.

Prefiltration of the analyzer sample stream is frequently required to prevent plugging of the microtubing, which is included in the analyzer's internal construction. In some waters with a substantial level of inorganic carbon, additional filters that remove this carbon component must be included at the inlet to the analyzer. These filtering systems are generally available from the analyzer manufacturer, but constitute a maintenance activity and cost, which varies depending upon the particular nature of the sample stream.

The TOC analyzers are mechanically and highly complex, and require substantial technical training and experience to ensure proper operation over extended periods (Hall & Szabo, 2009). While analyzers that are mechanically less intricate are now commercially available, they remain complex in operation.

UV Analyzers: When UV254 analysis is used for an OWQM system, the absorbance measurement alone may be used as a general indication of water quality. Due to the potential difficulties involved with operating and maintaining TOC analyzers, UV analyzers are sometimes used to provide a TOC measurement or indication, depending on the particular technology selected.

Several factors must be considered when selecting a UV absorbance analyzer for use in OWQM systems. Some UV254 analyzers apply a correlation coefficient to the 254 nm absorbance reading to generate a TOC measurement. However, the accuracy of the correlation is dependent upon the stability of the correlation. For systems where the source water is subject to change, the correlation may change, and without adjustment to the programmed coefficient, the TOC measurement may be inaccurate. The TOC correlation to UV254 absorbance is also impacted by the turbidity of the sample stream. Some UV254 analyzers include automated turbidity compensation, others do not.

Spectral analyzers calculate TOC and turbidity measurement from the UV and visible light absorption measurements that make up the spectral curve. Turbidity readings from these analyzers are applied to the TOC calculation to achieve a turbidity-compensated TOC measurement. These analyzers can also derive nitrate, DOC, and other water quality parameters. Specific water contaminants, for example, ricin (van den Broeke, 2009)), can be calculated based on their specific absorbance spectrum, similar to the method used for TOC determination.

The EPA studies have found that UV-visible light absorbance-based TOC readings will not detect all TOC compounds, but they do detect a large enough portion of potential TOC contaminants that these instruments are valid for contamination monitoring (Water Security Initiative: Interim Guidance on Planning for Contamination Warning System Deployment, 2007). Similarly, TOC readings by these instruments are suitable for distribution system water quality indication because drinking water TOC is typically made up of humic and fulvic acids, which are very accurately detected by UV absorption.

Absorbance-based UV and TOC measurements have the potential to be affected by deposition of mineral content on optical surfaces. This will impact absorbance readings and is highly dependent on the water being tested. Optically-based analyzers frequently include automated cleaning systems, ranging from periodic flushing with various solutions to mechanical wipers or brushes, or continuous operation of ultrasonic wave generators. Each of these has been found to be of varying effectiveness.

Some UV-based optical analyzers include automated compensation for variation of the UV lamp output over time. This is considered to be an essential function since the lamp output is known to decrease over time, requiring periodic lamp replacement.

Ammonia Analyzers: Ammonia sensors may be reagent- or nonreagent-based operations. For OWQM systems, reagentless technologies that use ion-selective electrodes are preferred to assist in minimizing maintenance activities and costs.

The ammonia measurement should include pH compensation, which may be integral to the ammonia sensor, or a separate pH sensor with signal input to the ammonia analyzer. The pH signal can also be separately used for the OWQM pH measurement. Ammonia sensors may also include potassium compensation, because elevated potassium levels will interfere with low-level ammonia measurements, such as those close to the sensor detection limit where OWQM systems typically operate. The potassium signal is not an OWQM parameter and is not separately reported by the OWQM system.

Conductivity, pH, Turbidity: These sensors operate based on standard, proven electrochemical and optical technologies, which water utilities have deployed for many years in water treatment plants and other facilities. Specific analyzers to be used in an OWQM station should be those that the user has found to be reliable in service and to provide accurate readings with minimal maintenance requirements. For these parameters, use of a utility's standard sensors is usually acceptable.

Prioritization of Installation Locations

Selection of installation locations for OWQM stations involves important considerations to reduce cost and provide an environment conducive to long-term and successful operations.

Monitoring stations are typically installed at the discharge of each water treatment plant or wholesale connection interties to indicate baseline conditions entering the distribution system for comparison with downstream measurements. These stations also indicate results of changes to the treatment process, and warn of conditions in the treatment process that may otherwise go undetected. Some OWQM process measurements may already be made at the water treatment plant (WTP), and these existing measurements can be used for OWQM purposes. When adding other OWQM parameters that are not already monitored at the WTP, some utilities use installation of OWQM stations as an opportunity to upgrade older instruments or to convert to reagentless technologies for savings of labor and maintenance costs.

The OWQM stations are frequently installed at the discharge of distribution system reservoirs and chlorine boosting pump stations. Measurement may be upstream of chlorine addition to provide a measure of the quality of the water in the reservoir and of that further upstream. The OWQM station could alternately be installed downstream of chlorine addition at the booster station to provide a baseline measurement for comparison to OWQM stations further downstream.

Other OWQM stations are installed at critical nodes in the distribution system, and different approaches may be taken in selecting these locations. Distribution system managers generally have a good understanding of operation of the piping network, and can often identify the nodes of interest based on working experience. A more scientific approach to OWQM siting is frequently conducted through the use of the Threat Ensemble Vulnerability Analysis and Sensor Placement Optimization Tool (TEVA-SPOT) software (Berry, 2008). This analytical package, developed by EPA, Sandia Laboratories, and others, analyzes a distribution system network and identifies critical nodes that will represent water quality impacting the largest number of consumers. The TEVA-SPOT

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analysis results often validate the operational understanding expressed by distribution system managers, but also frequently identify nodes otherwise not understood to be critical, or recommend subtle location changes compared to the managers recommendations.

The analysis enables prioritization of a selected number of OWQM stations to meet the budget available for a project, and identify stations to be added as a monitoring system expands over a period of years.

Requirements for Data Communication and Analysis

Several products are available for analysis of OWQM data and alarming of unusual conditions. The most common software event detection systems (EDS) are commercially available through s::can, Whitewater, and Hach. Also available is the Sandia National Laboratories freeware system CANARY, which was developed as part of the WS initiative. Each EDS has strengths and weaknesses associated with their performance under distribution system operations. Additional information can be obtained through the EPA Water Security Division.

The OWQM alarms are generally based on more than simple alarm setpoints for parameter measurements. Typically, the alarms or alerts are associated with *pattern alarms*, where multiple parameters change in a manner that is atypical of their normal relationship. As an example, if TOC increased, it would also be expected that DOC would increase in a proportional manner. When a utility has implemented enhanced coagulation, the TOC-to-DOC relationship changed and created an alert at the water quality monitoring stations. Broadband UV-Vis systems also produce a *spectral alarm*, which is initiated if the normal spectral fingerprint displays an unusual shift.

Figure 3. Typical Enclosed-Type OWQM Station. When Installed in Secure Indoor Locations, Open-Type Wall-Mount Stations are Often Used.

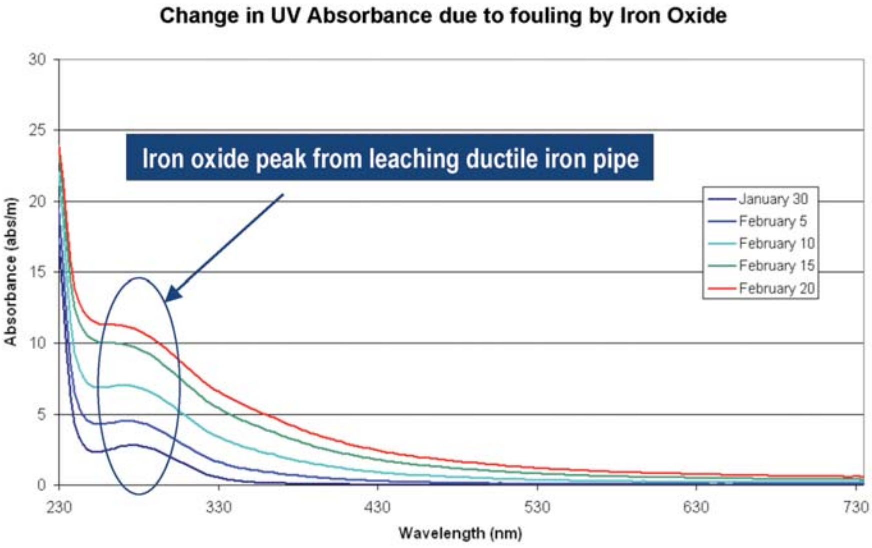

Figure 4. On-Line Water Quality Monitoring Ultraviolet Absorbance Spectrum Enables Identification of Distribution System Accelerated Corrosion.

The OWQM data is collected more frequently than typical SCADA monitoring data, and therefore OWQM data usually cannot be communicated over traditional low-bandwidth SCADA networks. Additionally, spectral data cannot be communicated over the typical SCADA data collection network, so separate communication pathways must be established for this. Many utilities therefore include all OWQM data on the alternate path and keep monitoring and maintenance of this information separate from operational SCADA data, although there is no requirement to maintain this separation. If T-1 or optical connections to the central monitoring facility are available, these pathways may be used, but typically the OWQM measurements are still transmitted as a separate data stream from SCADA parameters.

Water quality analysis is conducted local to the OWQM station, and measured values and alarms are communicated to a central historian and display. There is typically a long-term database for storage and retrieval of data and a short-term cache for short-term (30-day) trending.

For OWQM stations at water utility locations, the data may be communicated over a virtual private network (VPN) setup on the existing utility network, if available. For locations that do not have access to the utility's network, data are frequently communicated over commercial digital radio or cable service connections.

Fabricated On-Line Water Quality Monitoring Stations

Installed OWQM stations take several forms, depending on the parameters and analyzers that are selected for use. For outdoor installation, they are generally fabricated in enclosed cabinets for protection and security (Figure 3). Since water flows inside the cabinet with an open drain, ventilation of the cabinet is required to dissipate moisture that may accumulate. In hot southern climates, temperatures inside the enclosed cabinets are also of concern, so ventilation is also necessary, and shade from direct solar illumination is recommended. High internal temperatures can also impact the stability of chemical reagents, so reagentless analyzers are also preferred for this reason.

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Many of these issues may be avoided by installing OWQM stations indoors. For secure indoor locations owned and controlled by the utility, the station may be configured as a nonenclosed wall mount panel or open-frame system. Heat and moisture are usually no longer an issue, but the potential for tampering or vandalism of equipment may be more of a concern. Indoor locations that are not owned by the utility, such as at fire departments, police stations, hospitals, or other host facilities, should be configured as enclosed cabinets that will still require ventilation to remove humidity. But, indoor locations avoid the OWQM environmental impacts of excessive heat or cold, and also make it easier for utility technicians to conduct routine calibration and service. However, indoor installation at any facility requires that access be available on a short-notice basis to retrieve automatically collected water samples in the event potential contamination is detected. Continuous access is a priority for locating OWQM stations that hold contamination monitoring as a mission of critical consideration. For those that are focused only on operational benefits, quick access is less of a siting priority.

Operational Benefits

The most important aspect of OWQM systems are the benefits of assured and improved water quality provided to the consumer. Such monitoring may provide recommendations for adjustment of the water treatment process and feedback of the results of treatment process changes. The OWQM stations can provide early warning of water main breaks, low- or high-chlorine conditions, nitrification, and other conditions, and thereby not only improve operations, but also save considerable costs to the utility.

When the EDS identifies an anomaly in a data stream, an alert is sent to the centralized distribution system monitoring dashboard, which allows the operator to spatially correlate information from the other data streams (consumer complaints, enhanced security alarms, public health alerts) in real time. Operations staff can rapidly and independently query each alert to evaluate trends and relate the anomalies to explainable events that may be occurring in the water distribution system (e.g., a pipeline break). During this operational evaluation, it is possible that the cause of the alerts cannot be explained by known activities. When this occurs, the utility will proceed with a tiered response, such as a consequence management plan, which becomes increasingly aggressive as more information related to a potential contamination event is received.

The ability to rapidly convert very large data streams into actionable information and provide the consolidated alert information on a user-friendly dashboard significantly decreases a utility's response time. The ability to identify trends and nuances in the data supports operational benefits not previously available. Examples of collected data associated with distribution system events are presented.

Corrosion Detection and Control: Figure 4 shows a plot of spectral absorbance that indicated a peak characteristic of iron oxide. Plots of the data in five-day increments showed the size of the peak was rapidly increasing. This was ultimately identified as accumulating deposition of iron on the analyzer optics caused by aggressive water unexpectedly leaching from ductile iron pipe. Identifying the problem early and implementing corrective actions saved the utility an estimated $20 million in early replacement costs.

Granular Activate Carbon (GAC) Replacement Optimization: In Figure 5, DOC and TOC plots were used to optimize GAC filter performance. In this case, the utility developed correlations between total trihalomethanes (TTHM) production and effluent DOC for use in determining when to change the GAC and maintain system compliance. By revising the GAC replacement schedule from a prescribed frequency to one based on 50 percent TTHM levels, the utility reduced the annual replacement costs by $100,000 at each treatment plant.

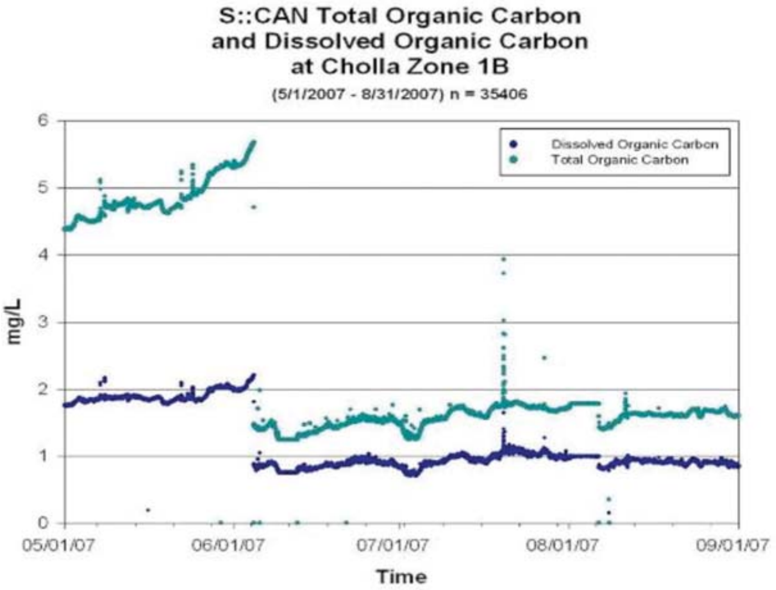

Figure 5. On-Line Water Quality Monitoring DOC and TOC Plots Used to Optimize Treatment Plant Maintenance Activities.

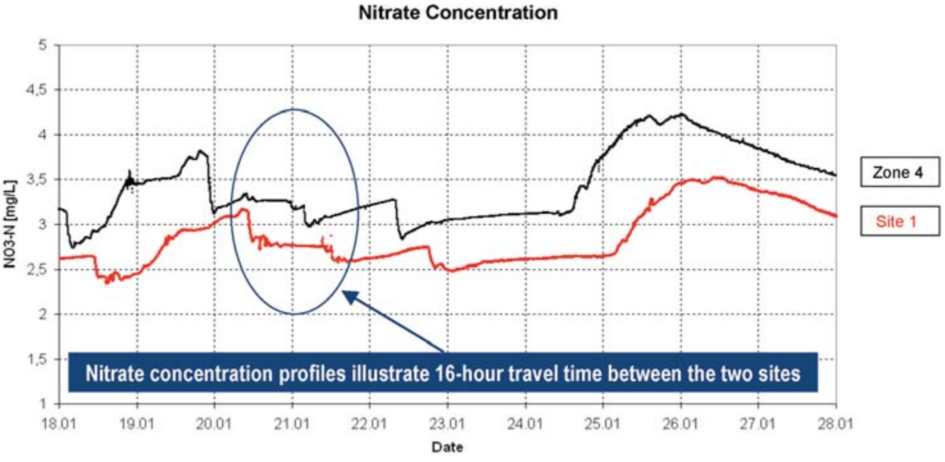

Figure 6. On-Line Water Quality Monitoring Data Enables Comparison of Nitrate Profiles and Hydraulic Model Verification.

Water Age Tracking: Figure 6 shows an example of how OWQM data can be used to track water age. In this case, nitrate profiles were compared over time to determine travel time between sites. The data was validated through the utility's calibrated model and similar readings from other distribution system locations have been used to verify their hydraulic model.

Water Quality Monitoring and Process Control: Figure 7 shows an example of how spectral absorbance changes indicated failure of treatment plant controls early enough for the problem to be resolved before major damage occurred. In this case, the failure allowed spent brine solution to flow into the distribution system reservoir. The immediate result was a spectral change associated with the highly colored brine solution blocking the UV transmittance and creating a spectral alarm and notification. The graph on the left indicates normal absorbance (blue trace at bottom, behind, and coincident with green trace). Over a period of several minutes, the absorbance increased, with maximum disruption indicated by the orange and purple marks indicating high absorbance of 30 – 50 percent for 3 min. After 13 min from start of the event, the condition was resolved, the brine solution had passed the monitoring station, and the absorbance spectrum returned to normal (green trace at bottom, coincident with the pre-event absorbance).

The right graph shows conditions the next day at a monitoring station in the distribution system. The contaminant is shown to be considerably diluted, with the maximum absorption reduced to 30-40 percent and spread over 7 min. The event is seen to take a total of four hours to pass the station from start of the event to return to normal water quality.

Water Quality Concern Source Identification: A military base using water from the local utility often had reports of water quality problems that couldn't be readily attributed to a known cause. Monitoring of the water inlet to the base identified changes in the water supply, as shown in Figure 8. Precise determination of when water quality changed helped establish a link to source water operations. The water provider occasionally changed the source of the water and where it entered the distribution system, with the result of heavy scouring in the pipe, directly impacting water quality on the base. Once the problem was understood, base personnel worked with the retail water provider so they would understand the impact associated with flow reversals. The water provider

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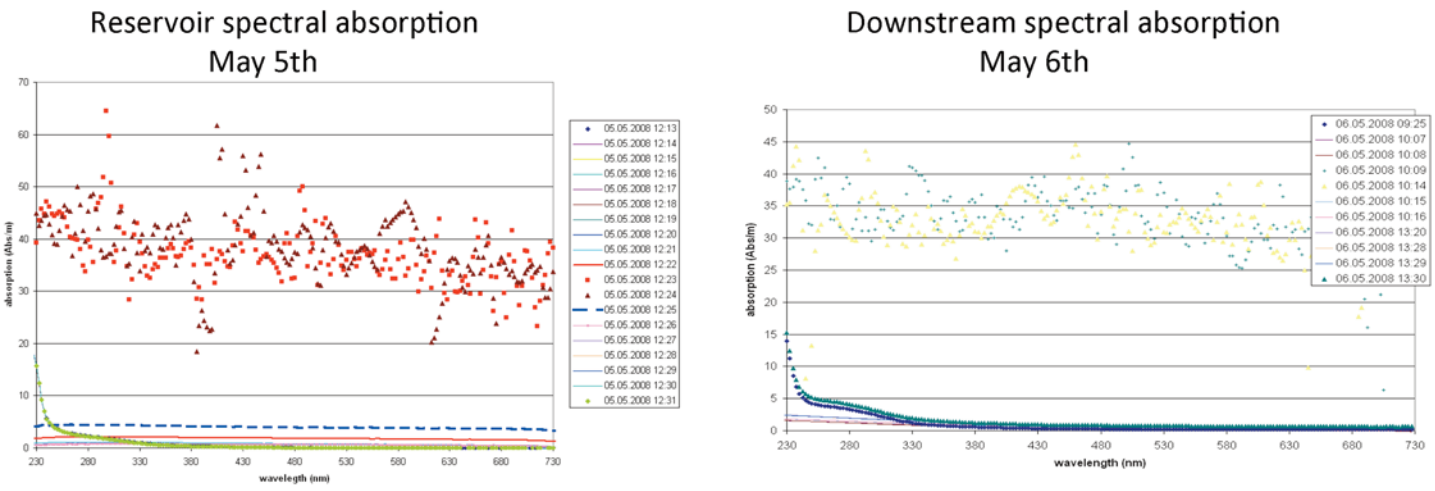

Figure 7. On-Line Water Quality Monitoring Identified Changes in Spectral Characteristics Indicate Equipment Failure.

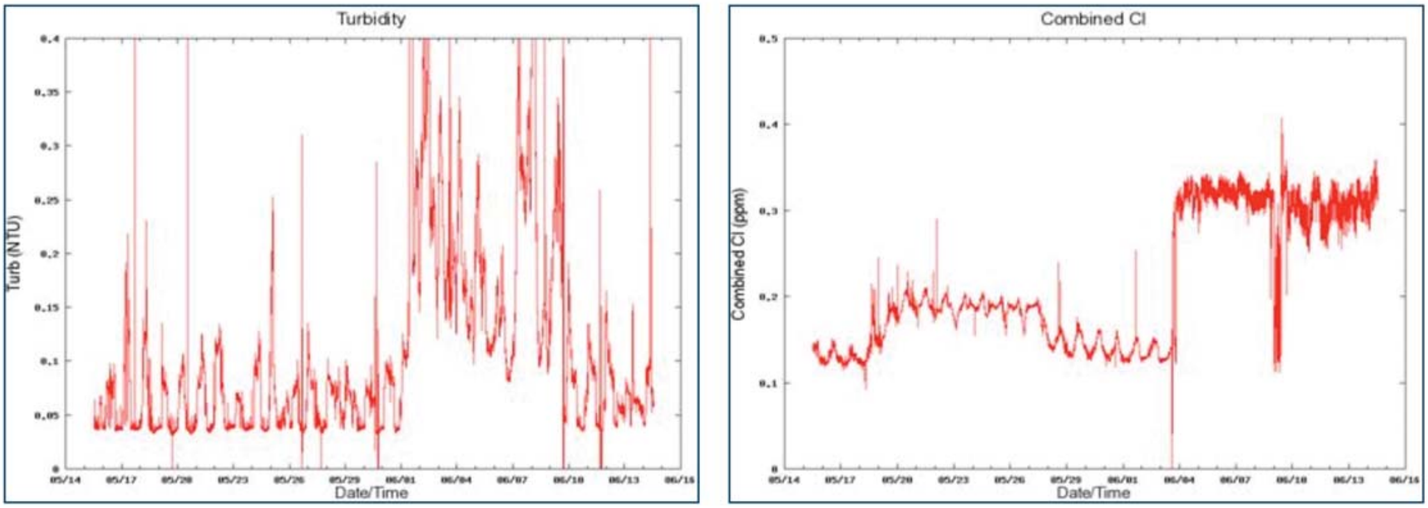

Figure 8. On-Line Water Quality Monitoring System Identifies Changes in Source Water as the Cause of Water Quality Problems.

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implemented a flushing program to reduce the sediment that had accumulated in distribution system pipelines, largely correcting the problem.

Conclusions

Installation and operation of OWQM stations at water treatment plants, reservoir outlets, and strategic locations throughout the distribution system provide an understanding of water delivery conditions that may have been previously unknown or incompletely understood. These systems enable correction of problems and improvement in delivered water quality, as well as substantial savings in operational and maintenance/replacement costs. A mix of well-known and new technology sensors and analyzers may be used to obtain and report the substantial amount of data required for a complete picture of distribution system operation. The data can be displayed in an optimized manner on a central dashboard, as well as through mobile technologies, to support and improve water utility operations.

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