Maintaining Distribution System Health and Security Through Continuous Monitoring

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Abstract

The distribution system represents the last analytical frontier in the water quality industry. The monitoring of source water and treatment plant processes has progressed to a level at which we can be confident that we are providing good quality water. Once the water reaches our aging distribution systems, our knowledge as to its continued integrity is limited by the quality and amount of available data. Most monitoring in the distribution system is relegated to the occasional snapshot provided by grab sampling for a few limited parameters or the infrequent regulatory testing required by mandates such as the Total Coliform Rule. The development of water security monitoring in the years since 9/11 has the potential to change this paradigm. Since 9/11 numerous communities have installed multi-parameter monitoring stations in various locations through out the distribution system as early warning systems based on potential water security threats. These continuous on-line systems have recorded large streams of data (some sites for a number of years) relevant to water quality in the distribution systems in which they have been deployed. In this study data streams from a number of communities (both small and large) are analyzed for pertinent information as to the health and operation of the distribution system. Changes in water quality are correlated with known causes attributable to day-to-day operational changes (source water switching, chlorine shocking, pumps turning on and off, pressure surges) and also anomalous events (pipe bursts, accidental back flows, cross connections, chemical over feeds, treatment plant problems, nitrification events, etc.) Case study information concerning what if any action was taken to ameliorate the problem will also be linked to the data for the identified events. The data streams also show the diversity in what could be termed "normal" operating conditions both within and between different classes and types of systems. Highlights form the database findings are presented here. This sort of information is critical in understanding and improving the operation of our distribution systems and can also be valuable as we consider regulations that effect that operation. Aany future efforts to regulate the distribution system will need to consider databases such as this before we determine the best course of action to ensure our public water supplies meet acceptable levels of quality and safety from source to tap.

Keywords
On-line monitoring, real time, deployment testing, field sites, algorithm

1. INTRODUCTION:

For the past several year scientists at Hach Homeland Security Technologies (HST) have been actively engaged in the development and testing of an early warning system for detecting water quality problems including those related to an intentional terrorist attack. This paper gives a brief summary of how the system operates and presents results form some of the recent field-deployment efforts that have been undertaken.

Monitoring in the distribution system is a difficult proposition. The shear number and diversity of potential threat agents that could be utilized in an attack against the system makes monitoring for them on an individual basis an effort that is doomed to failure from the start. This doesn't even take into account the even larger number and diversity of compounds that may accidentally find their way into our drinking water. To counter and detect the unprecedented number and types of compounds that may be encountered, what is needed is a broad-spectrum analyzer that can respond to any likely threat and even unknown or unanticipated events.

The difficult mission of detecting such a wide variety of potential threats is not the only challenge confronting a monitoring system for the distribution system. The environment that any such sensor would be exposed to is extremely harsh. Extreme variability in water conditions is routinely encountered in the pipes. Much of the existing water supply infrastructure is also aging and in poor condition. This results in conditions of corrosion and scaling that may cause the fouling of sensors that are not robust enough to operate under such conditions on an extended deployment timeframe. Biofilms may also form on exposed surfaces leading to sensor failure over time. What is needed is an extremely rugged sensor that is capable of withstanding long-term deployment and has the ability to respond to all types of threat agents.

2. THE HACH HST APPROACH

Rather than attempting to develop individual sensors to detect contaminants or classes of contaminants, the Hach HST approach was to utilize a sensor suite of commonly available off-the-shelf water quality monitors such as pH, electrolytic conductivity, turbidity, chlorine residual and total organic carbon (TOC) linked together in an intelligent network. The logic behind this is that these are tried and true technologies that have been extensively deployed in the water supply industry for a number of years and have proven to be stable in such situations. One of the difficulties encountered when designing such a device is that the normal fluctuations in these parameters found within the water can be quite pronounced.

The problem then becomes, can we differentiate between the changes that are seen as a result of the introduction of a contaminant and those that are a result of everyday system perturbation? The secret to success, in a situation such as this, is to have a robust and workable baseline estimator. Extracting the deviation signals in the presence of noise is absolutely necessary for good sensitivity. Several methods of baseline estimation were investigated. Finally, a proprietary, patented, non-classical method was derived and found to be effective.

In the system as it is designed, signals from 5 separate orthogonal measurements of water quality (pH, Conductivity, Turbidity, Chlorine Residual, TOC) are processed from a 5-paramater measure into a single scalar trigger signal in an event monitor computer system that contains the algorithms. The signal then goes through the crucial proprietary baseline estimator. A deviation of the signal from the established baseline is then derived. Then a gain matrix is applied that weights the various parameters based on experimental data for a wide variety of possible threat agents. The magnitude of the deviation signal is then compared to a preset threshold level. If the signal exceeds the threshold, the trigger is activated.

The deviation vector that is derived from the trigger algorithm is then used for further classification of the cause of the trigger. The direction of the deviation vector relates to the agents characteristics. Seeing that this is the case, laboratory agent data can be used to build a threat agent library of deviation vectors. A deviation vector from the monitor can be compared to agent vectors in the threat agent library to see if there is a match within a tolerance. This system can be used to classify what caused the trigger event. This system can also be very useful in developing a heuristic system for classifying normal operational events that may be significant enough in magnitude to activate the trigger. When such an event occurs the profile for the vector causing it is stored in a plant library that is named and categorized by the system operator. When the event trigger is set off the library search begins.

The agent library is given priority and is searched first. If a match is made, the agent is classified. If no match is found, the plant library is then searched and, the event is identified if it matches one of the vectors in the plant library. If no match is found, the event is classified as an unknown and can be named if an investigation determines its cause. This is very significant because no profile for a given event need be present in the libraries for the system to trigger. This gives the system the unique ability to trigger on unknown threats. Also, the existence of the plant library with its heuristic ability to learn plant events results in a substantial and rapid decrease in unknown alarms over time. The developed system has been subjected to strenuous testing in both laboratory and field scenarios. The remainder of this paper will detail the results of numerous field studies that have taken place throughout the country at a wide variety of sites.

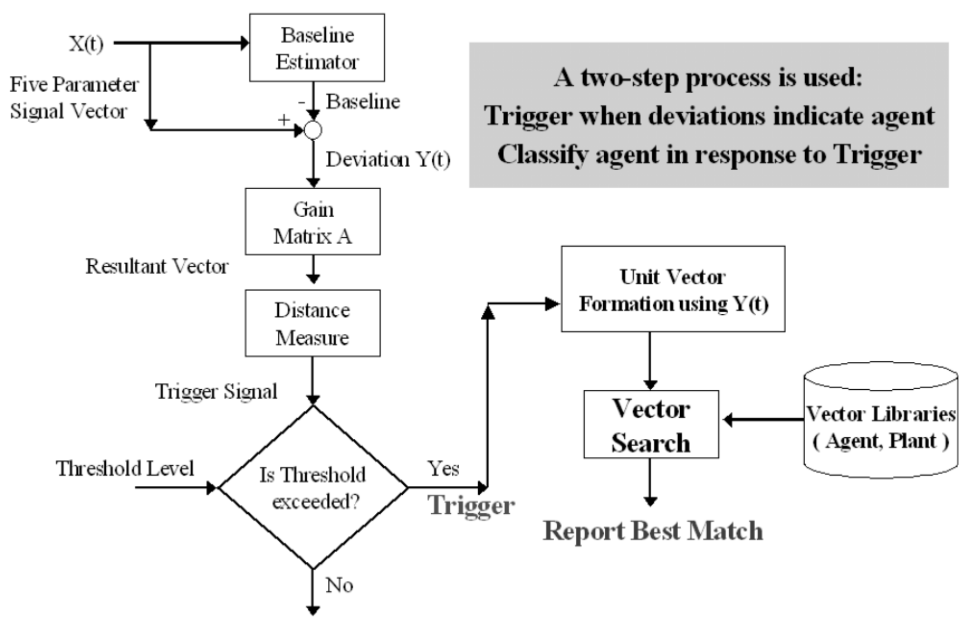


Fig 1. The use of intelligent algorithms with standard bulk parameter monitoring equipment allows for a robust system that is capable of triggering on and classifying a wide diversity of threat agents including unknown events.

Fig. 2. A real world deployment site showing the system in operation.

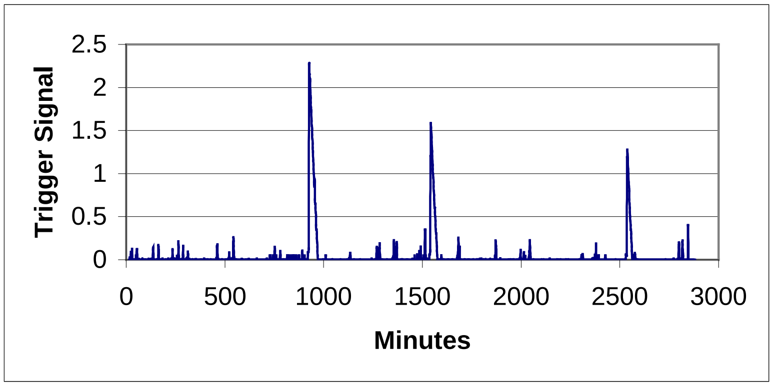
3. FIELD TESTING OF THE DEVELOPED SYSTEM:

Prior to the onset of this project, there was a definite lack of data concerning conditions in the distribution system. Very few utilities carried out data collection in the distribution system other than periodic grab samples. Those that did have some on-line continuous data were usually limited to only one or two parameters. Since the out set of this program over, 120,000 hour of real time data has been collected across a wide variety of different distribution systems exhibiting different water matrix profiles revealing many interesting attributes of the distribution systems. These systems represent a wide diversity of water quality conditions and operational situations. The site locations need to remain anonymous due to security considerations and non-disclosure agreements but, they represent a wide diversity of system sizes and geographic locations throughout the United States. The deployments are at both civilian and military sites. As of the time of the preparation of this article all deployments are within the United States. Hach HST is actively seeking International Traffic in Arms Regulation (ITAR) clearance from the US Department of State to deploy the systems on an international basis. The following are a few examples of incidents that have been recorded during these real world deployments. These incidents help to demonstrate the systems ability to learn and to become a useful tool not just for security but also for every day operational improvements.

3.1 A Chlorine Upset Event

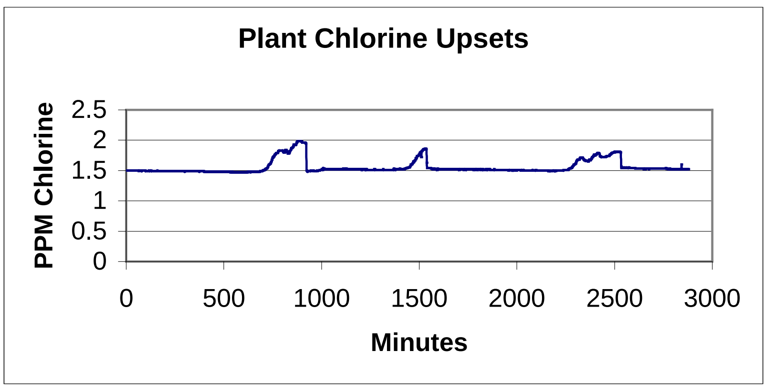
A water panel distribution monitor and an event monitor were installed at a location in a major east coast city just down stream from a water storage tank. The event monitor recorded a regular alarm. See graph 1.

Graph 1. East Coast Location showing regular alarm events



Careful evaluation of the baseline parameter data showed that the alarms were being triggered by a chlorine upset. The chorine levels would gradually rise over time and then suddenly drop. It was this sudden drop that was triggering the alarm. See graph 2.

Graph 2. Chlorine readings caused the trigger.



Further investigation revealed that these upsets were due to the fact that the storage tank was normally filled from water source A, but at times of peak demand both source A and source B were turned on to fill the tanks. Source B has a higher chlorine residual than source A, therefore, when it is used to fill the tank the chlorine level slowly creeps up. When source B is turned off, due to hydrodynamic short circuiting, the chlorine level drops rapidly to the concentration of source A. This rapid drop to the level of A was adequate to cause an alarm trigger. After this was determined the learning capability of the algorithm was used to name and classify this event as benign, so, when it occurred again the alarm was recognized. The screen would report the event as **Name: Pump Shut Off, Type: NORMAL.**

3.2 The Strange Case of the Chlorine Spikes

In one field deployment scenario, the system was very quiescent and rarely came anywhere close to causing a trigger alarm to go off. Except, that every night at around midnight, the chlorine level would spike dramatically and cause an alarm. This was deemed very strange and extensive trouble shooting of the instruments and power supply revealed no abnormal conditions that could be causing the problem.

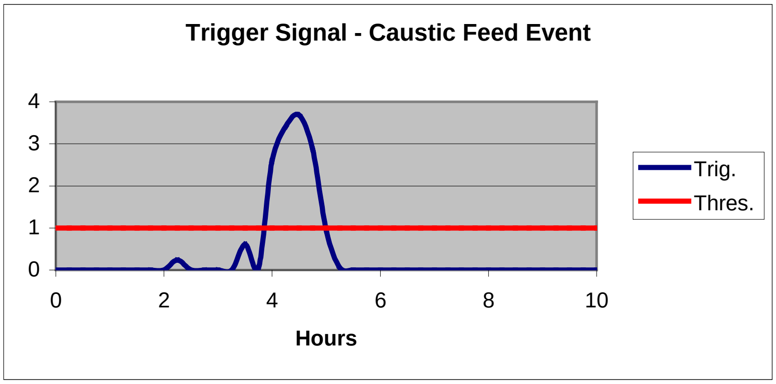
After a thorough investigation, the night operator for the treatment plant was queried about the strange chlorine response. His reply was that of course the system's chlorine level spikes every night at midnight that is when he super chlorinates the system just like he had been told to do.

It appears that several years ago, when there was a pipe rupture in the system that may have allowed contamination to seep in, the night operator had been told to super chlorinate the system. Unfortunately, the operator was new at the time and the instructions were not explicit that the super chlorination should take place that night only. The operator had continued to perform the operation every night for years resulting in a huge unnecessary cost in chlorine. This situation was remedied and should result in substantial chemical cost savings in the future.

3.3 Caustic Overfeed Event

In this deployment scenario, the plant uses caustic feed to control water pH. The system experienced a trigger alarm that when investigated was identified as an operational problem that resulted in the feed of excess caustic. The result was that the overfeed affected the pH and the conductivity of the water, causing the Event Monitor to alarm. See graph 3.

Graph 3. Caustic Event.

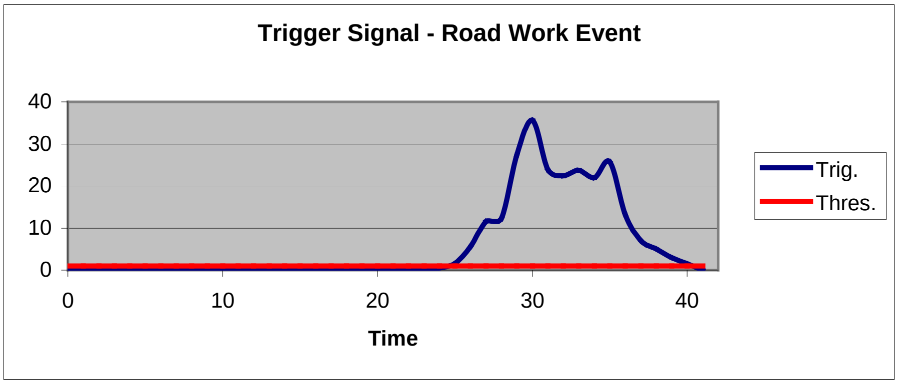


The reason behind this was that the vendor from which the casuistic was being purchased had delivered the wrong concentration of the solution. No one had checked to see if the concentration was correct before feeding in the material. New procedures were put in place to verify the identity and strength of chemical additives before addition to the treatment process. The Event Monitor learned this Plant Event and can identify a recurrence of the event in the future if there is another failure in the system and it is repeated.

3.4 Road Work Event.

In this event, roadwork (jackhammers) near a distribution line dislodged biomass and other particulate matter from the lining of the pipe. There was a massive increase in turbidity, which not only showed up on the turbidimeter, but also showed up as an interference in the chlorine measurement (optical). As expected, the conductivity and pH also showed minor changes. The increase in biomass in the water was indicated by the TOC analyzer. See graph 4. This event illustrates the ability of the Event Monitor to detect and alarm on unanticipated events. This event also provides a signature for the materials adhering to the walls of the pipes in this location and should recognize any future excursions of this type.

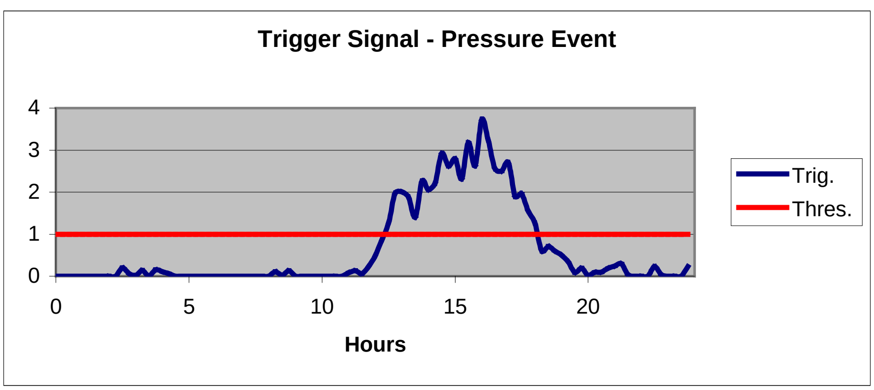
Graph 4. Roadwork Event.



3.5 Pressure Event.

In this scenario, the system was located in a building, which experiences a daily variation in water pressure. The sample variation is associated with a turbidity increase that causes a Trigger. See graph 5. There is also a small pH decrease at that time, possibly because of increased solubility of CO_2 in the water, dropping the pH slightly. After recognition of the cause and proper naming of this pattern, it is recognized by the Event Monitor as a "Normal" event, rather than an alarm condition, and appropriately classified and named as such.

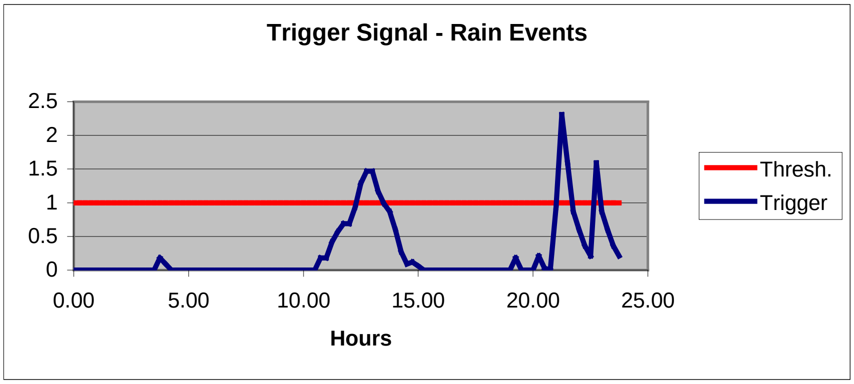
Graph 5. Pressure Event.



3.6 Rain Events.

Large amounts of rain fell in the area of a reservoir, raising turbidity and affecting other water quality parameters. These events were large enough to cause a Trigger. See graph 6. The system was able to store this pattern and recognize it upon recurrence.

Graph 6. Rain Events.

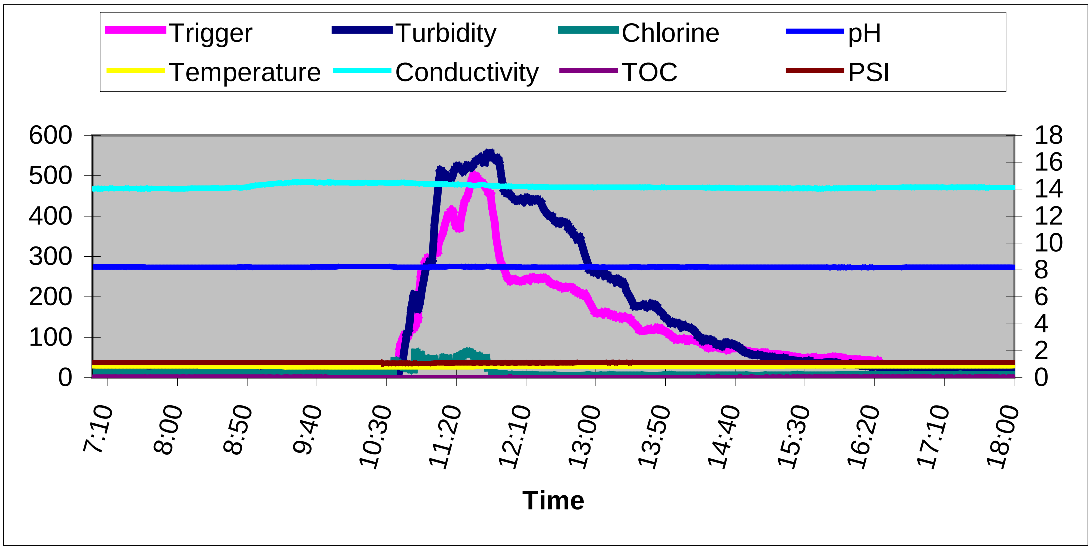


3.7 Main Break Event.

In this situation the system had only just been installed a few days previously. Hach HST personnel were informed that the instruments were behaving abnormally and were giving strange readings. An investigation of the sensors found no problems. A short time later a major main ruptured in a catastrophic mode. See graph 7 and fig. 3. The system was able to detect the perturbation in water quality parameters that were precursors to the main break and trigger upon them. Unfortunately, the system was newly installed and the event was not recognized until it was too late. The system has memorized this pattern and hopefully if a similar situation arises it may be able to alert before the problem is out of control and a catastrophic failure occurs.

Fig. 3 The system was able to detect water quality perturbations that were forerunners to this catastrophic main break.

Graph 7. Main Break Event.

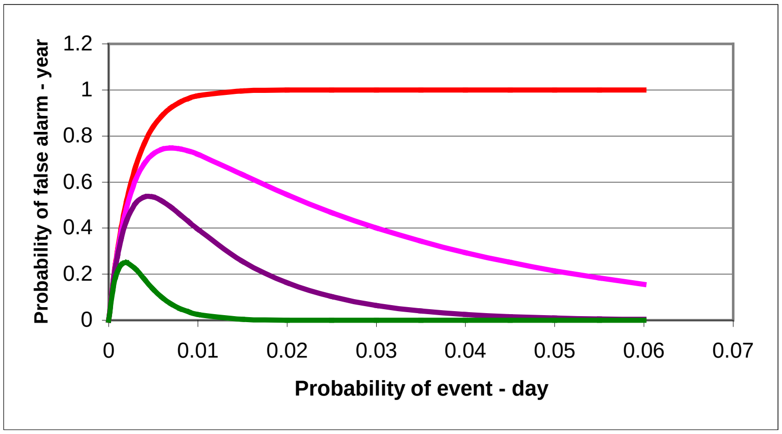


3.8 Learning Ability

As has been previously indicated, the system is equipped with a learning algorithm, so that as unknown alarm events occur over time the system has the ability to store the signature that is generated during the event. The operator can then go into the program and identify that function and associate it with a known cause such as the turning on of a pump or the switching of water sources, etc. Then the next time that event occurs it will be recognized and identified appropriately. Over time, as the system learns, the probability of an unknown alarm that has not been previously encountered and classified will continue to decrease and will eventually approach zero. One point however that should be noted, is that as soon as the system is turned on, it will be actively working and will have the ability to trigger and classify immediately if the signature of a known threat agent is encountered.

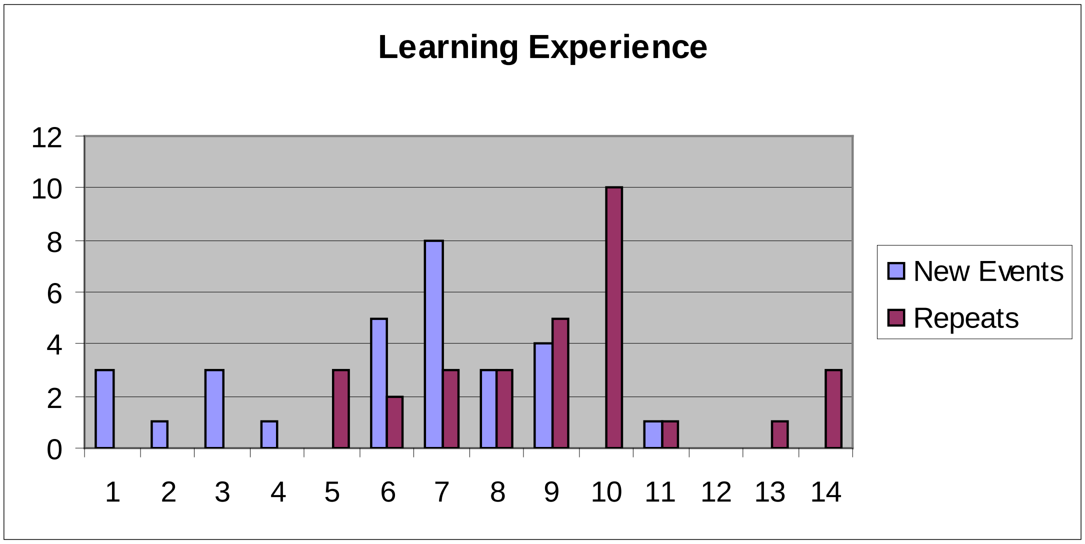
The probability of an unknown alarm due to a given event depends upon the frequency of the occurrence of such an event and the time that the algorithm has had to learn that event. Events that occur frequently will be quickly learned while rare or singular events will take longer to be learned and stored. This should result in a fairly rapid drop off in the number of false alarms as common events are quickly learned. See Graph 8.

Graph 8 Reduction of Unknown Alarms via Hach Learning Algorithm
Learning period = 0, 30, 90, 365 days
P(unknown alarm) = P(not learned)*P(event)



The data in this case represent a real world deployment situation that had very noisy water quality. In this scenario, there were 26 unique trigger events in the first 11 days of operations. All were fingerprinted and learned by the system. 11 of the events were repeated. This demonstrates that common events are rapidly learned by the system resulting in a rapid decrease in unknown alarms. See graph 9.

Graph 9. Learning Speed Demonstrated.



4. CONCLUSION

Extensive laboratory and pipe loop testing that is detailed in a separate paper indicate that these systems appear to be a good choice for detecting water quality excursions that could be linked to water security events. There are a number of advantages to using such systems. The chief advantage is that these instruments are not new. They are based on common everyday parameters that the average industry worker is quite familiar with, thus, adding a degree of comfort in operations not afforded by other new technology. As existing technologies, these instruments have been proven to be robust and dependable in prior field deployments. They represent measurements that would be of interest and use to water utility personnel above and beyond their role as water security devices. The testing detailed in this paper confirms this and also demonstrates the applicability of utilizing these everyday parameters by linking them with advanced algorithms. The field deployment studies not only demonstrate robustness in the field and the ability to recognize a wide variety of events, but these studies also demonstrate such system's ability to learn. It is foreseeable that these devices will become much more than a system that is capable of detecting terrorist events. They could easily become a critical tool for improving everyday operations.

For example, through many years of experience, the best old hands at treatment plant operations have developed "a sense" for knowing something in the treatment system is amiss. It can be a smell, color, clarity (or lack there of), sound or just tingling in the nape of the neck. One gains this sense only by extensive experience in a particular facility. These senses do not exist in distribution systems because there has typically been little measurement done upon which to gain these "senses" and, therefore; "Bulk Parameter Monitoring in the Distribution System with Interpretive Algorithms" has the potential to become the artificial "sense" able to quickly "learn" the quirks of the distribution system and have those quirks labeled by those with extensive experience so that less experienced employees have the benefit of that knowledge without having to wait 5, 10 or more years. A good phrase to describe this knowledge base would be "institutional intuition." (Kroll 2006) With the aging of the work force and rapid employee turnover "institutional intuition" has the chance of quickly dying out. Above and beyond their obvious security benefits, algorithms could be a way to circumvent this loss of knowledge and to build a knowledge base where none has previously existed. This in turn could allow improvements is system operation that may result in cost savings and definitely will result in a higher quality product being delivered to the consumer

References

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