Real Time Analysis for Early Warning Systems and Contingency Planning

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ABSTRACT

Water treatment and distribution systems are highly vulnerable to degradation of quality and reliability of supply as a result of many factors, natural, accidental, and intentional. Among the potential intentional factors that the utility manager and operators have to plan for is the introduction of toxic contaminants into the water supply or disruption of water service through sabotage of key components of the infrastructure. Rapid recognition of the nature and location of such occurrences is vital to protect the integrity of the water supply and safeguard the consumers from potentially harmful contaminants, determine appropriate changes in supply and treatment strategy, and ensure compliance with environmental regulations. The utility manager and the operations staff must be given the proper tools as well as be trained to identify an event, locate the extent and potential danger to the public, and be prepared to react in a proper and timely fashion.

Rapidly developing sophisticated software and real time instrumentation and monitoring systems provide the tools to design and develop early warning monitoring systems and to increase the preparedness of the water utility to react to such unexpected events. Proper integration of state of the industry hydraulic modeling systems, geographical information systems (GIS) for the water distribution network, and the installation of a SCADA system for both water treatment plant and active element control as well as the monitoring of critical points within the distribution system will be an invaluable resource for the operator to react to an event (real time response) as well as to plan for possible future events (contingency planning).

EARLY WARNING MONITORING SYSTEMS

The goal of an early warning monitoring system is to reliably identify low probability /high impact contamination events (chemical, microbial, radioactive) in source water or distribution systems in time to allow an effective local response that reduces or avoids entirely the adverse impacts that may result from the client (Brosnan, 1999).

Requirements for the ideal early warning system:

- Provides warning in sufficient time for action
- Cost is affordable
- Requires low skill and training
- Covers all potential threats
- Is able to identify the source
- Is sensitive to quality at regulatory levels
- Gives minimal false positive or negative responses
- Is robust
- Is reproducible and verifiable
- Functions year-round

A key component of early warning systems is the availability of a mathematical model for predicting the transport and fate of the spill/contaminant so that downstream utilities can be warned. However, a water quality model should be regarded as a guide only to what will happen, and increased monitoring during spill events is often critical to verifying the model and determining the fate of the spill and the safety of the supply.

The number of intentional threats and acts of sabotage against water supply systems is relatively small, and hoaxes are very likely. Intentional threats include:

- Destruction of a water supply system. Destruction of parts of the system can happen by physical destruction or computer hacking. Cyber attacks against various computerized components of water supply systems include attacks against SCADA systems.

- Contamination of the system with chemicals, microbes, toxins, or radioactive compounds. Examples of chemical agents are nerve agents, cyanide, arsenic, and nicotine. The most likely points of attack for intentional contamination include post treatment storage reservoirs, distribution tanks, and water mains (Haimes et al, 1998).

REAL TIME RESPONSE

Simulation tools (i.e. well calibrated hydraulic and water quality models) can be linked to SCADA real-time databases allowing for continuous, high-speed modeling of the pressure, flow, and water quality conditions throughout the water distribution network. Such models provide the operator with computed system status data within the distribution network. These "virtual sensors" complement the measured data. Anomalies between measured and modeled data are automatically observed, and computed values that exceed predetermined alarm thresholds are automatically flagged by the SCADA system. The operator, upon identification of an occurrence, can take appropriate action to either eliminate or contain the danger to public health or service interruption, or failing that, is able to map out the extent of the service disruption to guide both utility crews and emergency response units. Having taken corrective action, the operator can use the predictive modeling capability to extrapolate the future system performance. For example, in the case of introduction of contamination into the distribution system, the dispersion and dilution as a function of time can be calculated. By real time monitoring, the operator can continually update and adjust the model. Similarly, alternate water supply strategies can be quickly modeled and evaluated, guiding the operator until the situation is remedied or stabilizes.

CONTINGENCY PLANNING

The best time to prepare for an emergency, no matter how remote the possibility, is before it happens. The US Federal Government has required water suppliers to provide written emergency action plans. The utility engineer using the hydraulic modeling system has a powerful learning tool to assist in decision-making and planning. Any number of scenarios may be mapped out and the appropriate responses documented for future use. Operators can be trained to use the model to simulate various scenarios in advance of a critical need, including failure of critical facilities and introduction of toxic substances into the distribution system. They can learn to evaluate and choose an appropriate strategy for operation of pumping stations or settings of the control valves and to determine the most appropriate response to unusual operating conditions, as well as being able to predict the potential for health hazard or service disruption. Such exercises can also be used to identify and quantify critical points in the system and provide input in the planning of capital improvements.

In summary, proper design and integration of hydraulic modeling software, GIS, and the SCADA system allows the water utility to plan for and react to scenarios to hopefully assure reliability of service and water quality in the face of whatever man or nature can throw at us, or, at the minimum, identify and contain the damage and disruption of service.

HYDRAULIC AND WATER QUALITY ANALYSIS

MIKE NET is based upon the industry standard EPANET hydraulic and water quality algorithm. EPANET was developed by the Water Supply and Water Resources Division (formerly the Drinking Water Research Division) of the U.S. Environmental Protection Agency's National Risk Management Research Laboratory. The hydraulic model used by EPANET is an extended period hydraulic simulator that solves the following set of equations for each storage node s (tank or reservoir) in the system:

$$\partial y_s / \partial t = Q_s / S_v \tag{1}$$

$$Q_s = \Sigma_i Q_{is} - \Sigma_j Q_{sj} \tag{2}$$

$$h_s = E_s + y_s \tag{3}$$

along with the following equations for each link (between nodes i and j) and each node k:

$$h_i - h_j = f(Q_{ij}) \tag{4}$$

$$\Sigma_i Q_{ik} - \Sigma_j Q_{kj} - Q_k = 0 \tag{5}$$

Equation (1) expresses conservation of water volume at a storage node while Equations (2) and (5) do the same for pipe junctions. Equation (4) represents the energy loss or gain due to flow within a link. For known initial storage node levels ys at time zero, Equations (4) and (5) are solved for all flows q_{ij} and heads hi using Equation (3) as a boundary condition. This step is called "hydraulically balancing" the network, and is accomplished by using an iterative technique to solve the non-linear equations involved.

The method used by EPANET to solve this system of equations is known as the "gradient algorithm", Todini, E. and Pilati, S.[5], and has several attractive features. First, the system of linear equations to be solved at each iteration of the algorithm is sparse, symmetric, and positive-definite. This allows highly efficient sparse matrix techniques to be used for their solution, George-Liu [6]. Second, the method maintains flow continuity at all nodes after its first iteration. And third, it can readily handle pumps and valves without having to change the structure of the equation matrix when the status of these components changes.

After a network hydraulic solution is obtained, flow into (or out of) each storage node, q_s is found from Equation (2) and used in Equation (1) to find new storage node elevations after a time step dt. This process is then repeated for all subsequent time steps for the remainder of the simulation period.

MIKE Net's dynamic water quality simulator tracks the fate of a dissolved substance flowing through the network over time. It uses the flows from the hydraulic simulation to solve a conservation of mass equation for the substance within each link connecting nodes *i* and *j*:

$$\partial c_{ij} / \partial t = -(Q_{ij} / S_{ij}) (\partial c_{ij} / \partial x_{ij}) + \theta(c_{ij}) \qquad (6)$$

Equation (6) must be solved with a known initial condition at time zero and the following boundary condition at the beginning of the link, i.e., at node i where x_{ij} = 0:

$$c_{ij}(0,t) = \frac{\Sigma_k Q_{ki} c_{ki}(L_{ki},t) + M_i}{\Sigma_k Q_{ki} + Q_{si}} \qquad (7)$$

The summations are made over all links *k,i* that have flow into the head node (i) of link *i ,j*, while L_{ki} is the length of link *k,i*, Mi is the substance mass introduced by any external source at node i, and Q*si* is the source's flow rate. Observe that the boundary condition for link *i,j* depends on the end node concentrations of all links *k,i* that deliver flow to link i,j. Thus Equations (6) and (7) form a coupled set of differential/algebraic equations over all links in the network. Water quality simulator uses a Lagrangian time-based approach to track the fate of discrete parcels of water as they move along pipes and mix together at junctions between fixed-length time steps. These water quality time steps are typically much shorter than the hydraulic time step (e.g., minutes rather than hours) to accommodate the short times of travel that can occur within pipes.

By employing these features, MIKE NET can study such water quality phenomena as:

- Blending water from different sources
- Age of water throughout a system
- Loss of chlorine residuals

- Growth of disinfection by-products
- Contaminant propagation events

THE USE OF MODELS

Models of water supply networks (combined with GIS and SCADA) can be used as an instrument for increasing the public safety by providing answers to questions such as:

- How can we modify the water supply system or the operational procedures in order to reduce risks?
- How should we react, if an incident occurs?
- How do we get back to normal supply, when an incident has occurred?
- How will the supply of main be cut off if contaminated?
- What amount of time is required to flush each contaminated area?
- What neighborhoods are affected by each main?

How can we reduce risks?

Any given tap receives water, which arrives though a number of pipes in the supply network, the transport route, and ultimately comes from a source. However, in order to achieve maximum supply security in case of pipe failures or unusual demand patterns (such as fire flows) water supply networks are generally designed as complicated, looped systems, where each tap typically can receive water from several sources and intermediate storage facilities. This means that the water from any given tap can arrive through several different routes and can be a mixture of water from several sources. The routes and sources for a given tap can vary over time, depending on the pattern of water use.

A model can show:

- Which sources (well-fields, reservoirs, and tanks) contribute to the supply of which parts of the city.
- Where does the water come from (% distribution) at any specific location in the system (any given tap or pipe).
- How long time has the water been traveling in the pipe system, before it reaches a specific location.

One way to reduce the risk – and simplify the response to incidents – is by compartmentalizing the water supply system. If each tap receives water from one and only one reservoir, then pollution of one reservoir will affect one well-defined and relatively smaller part of the city. If a toxic substance is injected into any section of the water supply system, then one and only one part of the supply system will be polluted, thus reducing the potential risk in terms of the number of people involved.

Compartmentalizing the water supply system will reduce the spreading of toxic substances. On the flip side, it may increase the concentration of the toxic substance. It is also likely to have a negative impact on the supply of water for fire flow and on the robustness of the water supply network in case of failures of pipes or other elements. These problems can be eliminated, if the compartmentalization is done properly, allowing selected valves to be opened in case of fire emergencies or pipe failures.

How should we react, if an incident occurs?

Cities are now (if not before) establishing emergency and preparedness plans covering this kind of incidents. US Federal Law now requires the preparation of written emergency action plans for water utilities serving 3100 or more customers. A model is an invaluable tool in the preparation of such emergency plans. The model will be able to simulate a wide range of emergency scenarios, and the results can be condensed into very specific instructions for the emergency officers in charge at the time of the incident.

For instance:

A number of people in an area are reported ill with symptoms leading to suspicion that this might be caused by pollution of the drinking water. By looking up in an on-line GIS system containing pre-processed model results, the authorities have the following information readily available:

- What is the source(s) of the drinking water for the affected area?
- How long time has the water been traveling from the source(s) to the taps?
- Exactly which part of the city is receiving water from the same source(s)?
- How has the toxic substance in all likelihood been spreading? And hence, who should be warned first, and where can we expect to find most of the casualties?

This information can of course lead to actions such as sealing off the affected area from not-yet affected areas, warning of people within the affected district, starting medical treatment of people living in the affected area, setting up medical emergency centers, etc.

Other pre-computed information could include:

Assuming that several reservoirs were polluted simultaneously, where should we take samples in order to quickly discover pollution spreading from other reservoirs? If such samples are negative, then those segments were most likely not polluted and people living in those areas can be told that their drinking water is safe.

Or: Where do we sample within the polluted segment in order to find out exactly where the toxic substance was in fact injected? Based on concentration patterns, it is possible to rule out some locations and point towards the likely spots where the toxic substance can have been introduced into the water supply system.

How do we get back to normal supply, when an incident has occurred?

The term Artificial Recharge (AR) covers a range of technologies that typically utilize the natural cleaning capacity of natural subsoil systems to produce drinking water from surface water. The idea is to rapidly infiltrate surface water into the aquifer thereby increasing the groundwater formation and exploration possibilities. At many plants around Europe this is done in large plants where surface water is lead to large basins where it infiltrates. Traditionally these plants are operated based on measurements of water quality on a regular basis and in many cases on real-time measurements of various flow-related parameters. This AR, or mixing together of polluted and fresh water to bring the polluted water to acceptable standards for use, is one method of dealing with an attack.

Cleaning the pipe system by flushing it is a relatively simple method, but the model is needed in order to ensure that pockets of polluted water will not remain in the system after the flushing. These reactions should be pre-planned for each segment of the pipe system, leading to instructions such as:

"Flush for 3 hours by this and this method. Then change the flow in this and this manner and flush for another 2 hours."

"Turn off this main and drain via fire hydrants."
"To dilute, open this valve for water supply to this subdivision."

Etc…..

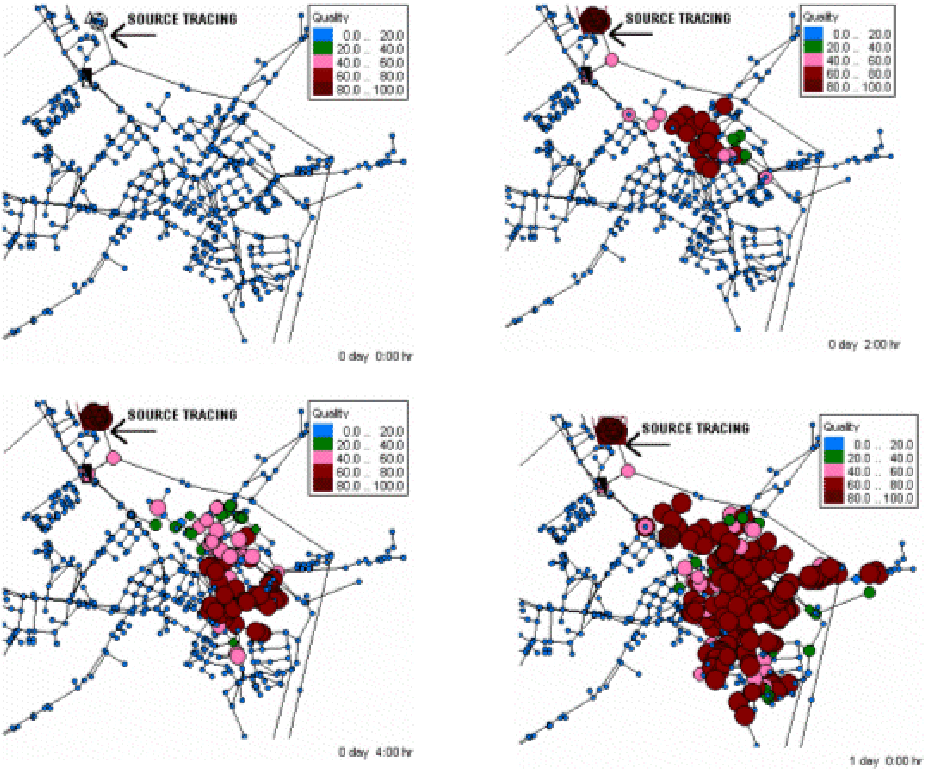
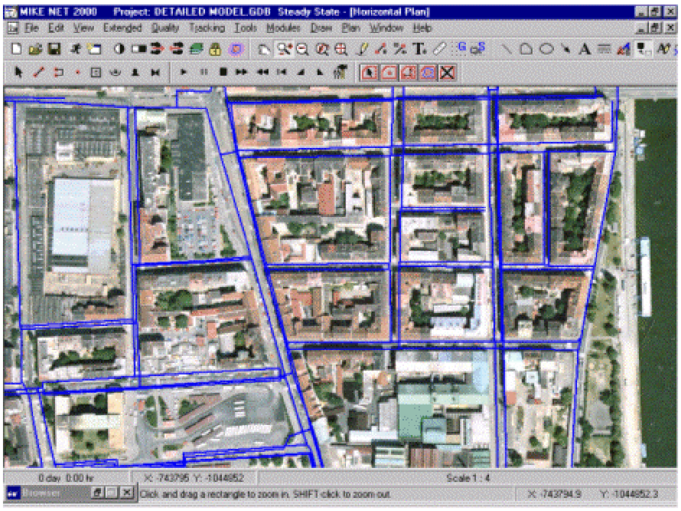


Fig.1. Spreading of pollution simulated by model

The four illustrations show the geographical extent of the pollution, at time 0, 2 hours, 4 hours and 24 hours after release of the substance in the point marked with an arrow (SOURCE TRACING). Parts of the network are not exposed to the pollution at all, as these areas are supplied from other sources.



Click and drag a rectangle to zoom in. SHIFT-click to zoom out.

Fig.2. GIS used at a front of a model

A GIS used as a front end for the model results will enable the emergency response staff to point-and-click on a specific address and get information about sources, areas affected, etc.

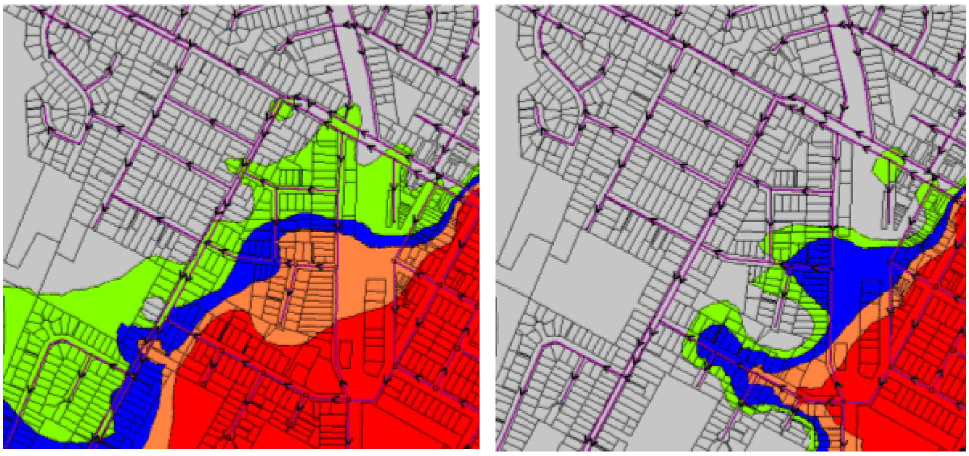


Fig.3. Spreading over time of a pollutant in a water supply system

The two figures below show another way of illustrating the spreading over time of a pollutant in a water supply system.

ON-LINE ANALYSIS OF THE WATER QUALITY PARAMETERS

Linking the hydraulic model to telemetry systems allowing the modelling of hydraulic, water quality and energy parameters is of growing interest. The DHI development team offers a new solution for water supply and distribution networks management. The goal of the project is to integrate the computational model MIKE NET with the central control system for solving problems related to water distribution network. MIKE NET implements a mathematical model that captures the infrastructure and flow conditions in the network. This model is calibrated and validated in real-time with data supplied by SCADA system. The integrated model monitors the pressure and flow conditions in the network in an automatic fashion - the energy parameters are evaluated in a parallel and their optimisation is enabled. Thus, any breakdown in the network can be readily identified, evaluated and rectified. The model also assists the practitioner to determine the most appropriate response to unusual operating conditions.

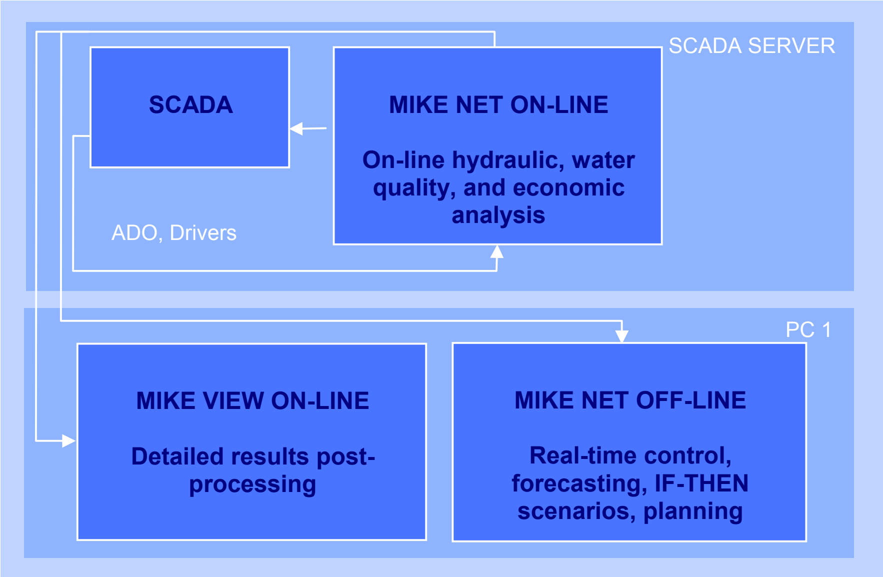


Fig.4. MIKE NET OnLine Scheme

MIKE NET-SCADA provides the capability to model the water distribution system in real-time, providing on-line modelling and monitoring of the system. This is essential when performing emergency response and it can greatly assist in confirming normal system performance, system trouble-shooting, improvement of

system operations, and projection of the current operating scenario. MIKE NET-SCADA can be linked to any existing SCADA monitoring system.
MIKE NET-SCADA consists of two modules:

- MIKE NET-SCADA On-Line
- MIKE NET-SCADA Off-Line

The On-Line Module operates on top of the SCADA system and performs an on-line analysis of the system. The model results are stored back into the SCADA database; MIKE NET On-Line viewer is used to display detailed model results.
The Off-Line Module is used to model if-then scenarios, model system breakdowns, and predict system behaviour based on the demand and control rules prediction. Microsoft Access is the database used to store and maintain model alternatives.

CONCLUSIONS

Linking calibrated hydraulic and water quality model to SCADA real-time databases allows for continuous, high-speed modeling of the pressure, flow, and water quality conditions throughout the water distribution network. Such model provides the operator with computed system status data within the distribution network. These “virtual sensors” complement the measured data. Anomalies between measured and modeled data are automatically observed, and computed values that exceed predetermined alarm thresholds are automatically flagged by the SCADA system. The operator, upon identifying an occurrence, can take appropriate action to either eliminate or contain the danger to public health or service interruption, or failing that, is able to map out the extent of the service disruption to guide both utility crews and emergency response units. Having taken corrective action, the operator can use the predictive modeling capability to extrapolate the future system performance. For example, in the case of introduction of contamination into the distribution system, the dispersion and dilution as a function of time can be calculated. By real time monitoring, the operator can continually update and adjust the model. Similarly, alternate water supply strategies can be quickly modeled and evaluated, guiding the operator until the situation is remedied or stabilizes.

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