Water Distribution Systems Security: Overview and Challenges

Avi Ostfeld

PhD, P.E., D.WRE, Associate Professor
Chief Editor, Journal of Water Resources Planning and Management, American Society of Civil Engineers (ASCE)
Faculty of Civil and Environmental Engineering
Technion - Israel Institute of Technology
Haifa 32000, ISRAEL
Email: ostfeld@tx.technion.ac.il
www.technion.ac.il/~avi/avi.htm
Outline

- Introduction
- **Review** of Drinking Water Distribution Systems Security Modeling
- **Challenges** for Drinking Water Distribution Systems Security Modeling
- Conclusions
Outline

- Introduction
- Review of Drinking Water Distribution Systems Security Modeling
- Challenges for Drinking Water Distribution Systems Security Modeling
- Conclusions
A water distribution system is a collection of hydraulic control elements connected together to convey quantities of water from sources to consumers.

Such a system can be described as a graph, with the nodes representing the sources and consumers, and the arcs - the connecting elements: pipes, pumps, valves.

The behavior of a water distribution system is governed by: (1) the physical laws describing flow and water quality distributions; (2) the consumers' demands; and (3) the system layout.
Simple example:

Uniqueness: nonlinear head - flow relationship; storage; water quality
Non smoothness of the objective function surface


\[ H_i - H_j = RQ^2 \]

Non smoothness when flow reverses

\[ H_i - H_j = R | Q | Q \]

Discontinuity of water quality when flow reverses

\[ C1Q1 + C2Q2 - C3Q3 - C3Q4 = 0 \]

\[ C2Q2 - C3Q1 - C3Q3 - C3Q4 = 0 \]
Water distribution systems analysis

In reality systems will have thousands of links and consumers

Tel-Aviv, Israel

Baltimore, Maryland
WDS problems classification

- Layout - connectivity
- Design - sizing
- Operation

- Reliability
- Security
- Unsteady

- # of Loadings
- Flow - Head - Quality
- Flow - Head
- Maintenance
- Aggregation

- Deterministic/stochastic
- Branched/looped, gravitational/pumping/storage
- Type
Introduction

- The events of *9/11 2001* in the US have brought to the foremost the world public awareness to *possible terrorist attacks on water distribution systems* causing *the security* of drinking water distribution systems to become *a major concern* around the globe.

- A drinking water distribution system is typically comprised of tanks, pipes, and pumps delivering treated water from treatment plants to consumers. *Even a moderate system* may contain hundreds of kilometers of pipes and numerous delivery points, making such a system inherently vulnerable.
Introduction

The threats on a water distribution system can be partitioned into three major groups according to the resulted means of their enhanced security:

(1) A direct attack on main infrastructure (vertical assets): dams, treatment plants, storage reservoirs, pipelines, etc.

Addressed by: improving the system's physical security (i.e., additional alarms, locks, fencing, surveillance cameras, guarding, etc.)
Introduction

(2) A cyber attack disabling the functionality of the water utility SCADA (Supervisory Control and Data Acquisition) system, taking over control of key system components

Addressed by: Software engineering - establishing an optical isolator between communication networks; use a Router to restrict data transfer; use Firewalls; install anti-virus software on all servers and workstations, etc.

BOTH THE PHYSICAL AND THE CYBER ATTACK THREATS HAVE NO DIRECT CONNECTION TO WATER SYSTEMS (e.g. an electrical system should be defended similarly)
Introduction

(3) A deliberate chemical or biological contaminant injection at one of the system nodes

An **online contaminant monitoring system (OCMS)** should be considered (ASCE, 2004) as the major tool to reduce the likelihood of a deliberate contaminant intrusion.

An online contaminant monitoring/sensors system should act as the guard or “multiple eye” setting for defending the distribution system (**horizontal asset**).
Water distribution systems security - modeling map

Offline/design decisions
- Sensor placement
- Contaminant source identification
- Response
- Recovery

Online/real time decisions
- Event detection
- Response
Water distribution systems security - modeling map

Offline/design decisions
- Sensor placement
- Contaminant source identification
- Response
- Recovery

Online/real time decisions
- Event detection
- Response
Sensor placement

Problem definition: sensor locations for minimizing impacts

Lee and Deininger (1992) were the first to address the problem of sensor placement by maximizing the coverage of the demands using an integer programming model.

Kessler et al. (1998) suggested the pollution matrix concept and a set covering graph algorithm for sensor’s layout for one representative loading condition.

Sensor placement

**Woo et al. (2001)** developed a sensor location design model by linking EPANET (USEPA, 2002) with an integer programming scheme.

**Berry et al. (2006)** presented a mixed-integer linear programming (MILP) formulation for sensor placement showing that the MILP formulation is mathematically equivalent to the *p*-median facility location problem.

**Propato (2006)** introduced a MILP model to identify sensor location with the ability to incorporate different design objectives.
Sensor placement

Watson et al. (2004) were the first to introduce a multiobjective formulation to sensor placement by employing a MILP formulation over a range of design objectives.

The multiobjective nature of the sensor placement problem became evident and extended at the Battle of the Water Sensor Networks (BWSN) 2006 at the 8th Water Distribution Systems Analysis (WDSA) symposium in Cincinnati, Ohio.
Sensor placement

BWSN 2006 8th WDSA, Cincinnati (Ostfeld et al., 2008): The sensor placement problem is inherently a multiobjective problem as the impacts compete against the detection likelihood.

The impact was measured through: the expected time of detection (Z1), the expected population affected prior to detection (Z2), the expected contaminated water demand prior to detection (Z3).
Sensor placement

Network 1

Layout of Network 1 (126 nodes, 1 reservoir, 2 tanks, 168 pipes, 2 pumps, 8 valves) (USEPA, 2001)

Network 2

Layout of Network 2 (12523 nodes, 2 reservoirs, 2 tanks, 14822 pipes, 4 pumps, 5 valves) (USEPA, 2001)

Ostfeld et al. (2008)
## Sensor placement

**Example: Network 1, five sensors**

<table>
<thead>
<tr>
<th>Team</th>
<th>Sensors</th>
<th>Z1</th>
<th>Z2</th>
<th>Z3</th>
<th>Z4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berry et al. (2006)</td>
<td>17, 21, 68, 79, 122</td>
<td>542</td>
<td>140</td>
<td>2,459</td>
<td>0.609</td>
</tr>
<tr>
<td>Dorini et al. (2006)</td>
<td>10, 31, 45, 83, 118</td>
<td>1,068</td>
<td>258</td>
<td>7,983</td>
<td>0.801</td>
</tr>
<tr>
<td>Eliades and Polycarpou (2006)</td>
<td>17, 31, 45, 83, 126</td>
<td>912</td>
<td>221</td>
<td>7,862</td>
<td>0.763</td>
</tr>
<tr>
<td>Ghimire and Barkdoll (2006a)</td>
<td>126, 30, 118, 102, 34</td>
<td>432</td>
<td>357</td>
<td>4,287</td>
<td>0.367</td>
</tr>
<tr>
<td>Ghimire and Barkdoll (2006b)</td>
<td>126, 30, 102, 118, 58</td>
<td>424</td>
<td>331</td>
<td>3,995</td>
<td>0.402</td>
</tr>
<tr>
<td>Guan et al. (2006)</td>
<td>17, 31, 81, 98, 102</td>
<td>642</td>
<td>159</td>
<td>2,811</td>
<td>0.663</td>
</tr>
<tr>
<td>Gueli (2006)</td>
<td>112, 118, 109, 100, 84</td>
<td>794</td>
<td>403</td>
<td>10,309</td>
<td>0.699</td>
</tr>
<tr>
<td>Huang et al. (2006)</td>
<td>68, 81, 82, 97, 118</td>
<td>541</td>
<td>280</td>
<td>4,465</td>
<td>0.676</td>
</tr>
<tr>
<td>Krause et al. (2006)</td>
<td>17, 83, 122, 31, 45</td>
<td>842</td>
<td>181</td>
<td>3,992</td>
<td>0.756</td>
</tr>
<tr>
<td>Ostfeld and Salomons (2006)</td>
<td>117, 71, 98, 68, 82</td>
<td>461</td>
<td>250</td>
<td>4,499</td>
<td>0.622</td>
</tr>
<tr>
<td>Propato and Piller (2006)</td>
<td>17, 22, 68, 83, 123</td>
<td>711</td>
<td>164</td>
<td>3,148</td>
<td>0.725</td>
</tr>
<tr>
<td>Trachtman (2006)</td>
<td>1, 29, 102, 30, 20</td>
<td>391</td>
<td>142</td>
<td>2,504</td>
<td>0.237</td>
</tr>
<tr>
<td>Wu and Walski (2006)</td>
<td>45, 68, 83, 100, 118</td>
<td>704</td>
<td>303</td>
<td>8,406</td>
<td>0.787</td>
</tr>
</tbody>
</table>
Sensor placement

Example: Network 1, five sensors

Map of the different team solutions
Sensor placement

The U. S. Environmental Protection Agency (EPA), Sandia National Laboratories (SNL), Argonne National Laboratory (ANL), and the University of Cincinnati developed the Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool (TEVA-SPOT) (USEPA, 2008a and 2008b)

TEVA-SPOT utilizes MILP, the $p$-median methodology (Mirchandani and Francis, 1990) and heuristics for sensor placement

TEVA-SPOT can be freely downloaded and is the most advanced available toolkit for sensors placement
SENSOR NETWORK DESIGN FOR DRINKING WATER CONTAMINATION WARNING SYSTEMS

A Compendium of Research Results and Case Studies

Regan Murray, Terra Haxton, and Robert Janke
National Homeland Security Research Center
Cincinnati, OH 45268

William E. Hart, Jonathan Berry, and Cynthia Phillips
Sandia National Laboratories
Albuquerque, NM
Water distribution systems security – modeling map

**Offline/design decisions**
- Sensor placement
- Contaminant source identification
- Response
- Recovery

**Online/real time decisions**
- Event detection
- Response
Contaminant source identification

Problem definition: given a contaminant detection at one or more sensor stations – identify the injection characteristics: (1) location, (2) starting time, (3) intensity (mass/time), and (4) duration

Islam at al. (1997), Shang et al. (2002), Laird at al. (2005), Sanctis et al. (2010) used backtracking algorithms for solving the inverse problem of contamination source identification


Preis and Ostfeld (2006) used a MT-GA approach, logistic regression and local search (Liu et al., 2008), cluster analysis and Bayesian networks (Perelman and Ostfeld, 2010)
## Water distribution systems security - modeling map

<table>
<thead>
<tr>
<th>Offline/design decisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor placement</td>
</tr>
<tr>
<td>Contaminant source identifiation</td>
</tr>
<tr>
<td>Response</td>
</tr>
<tr>
<td>Recovery</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Online/real time decisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event detection</td>
</tr>
<tr>
<td>Response</td>
</tr>
</tbody>
</table>


Response

Problem definition: Once a contamination warning system has detected the presence of a contaminant in a water distribution system, a variety of response actions must be examined for implementing the most beneficial consequence management strategy, including public notifications and operational changes (e.g., valve closures and flushing).

Potential utility response options to help mitigate the economic and public health impacts of a contamination release are required.

Water distribution systems security - modeling map

Offline/design decisions
- Sensor placement
- Contaminant source identification
- Response
- Recovery

Online/real time decisions
- Event detection
- Response
Recovery

Problem definition: recovery addresses long term strategies for returning the system to normal operation.

None of the current modeling efforts addressed long term modeling of system recovery besides flushing (other means for recovery can include: change of sampling locations and frequencies, adaptation of operational rules, sensors addition, etc.)
Summary - number of offline decision modeling publications

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>NUMBER OF PUBLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor placement</td>
<td>80</td>
</tr>
<tr>
<td>Source identification</td>
<td>20</td>
</tr>
<tr>
<td>Response</td>
<td>10</td>
</tr>
<tr>
<td>Recovery</td>
<td>0</td>
</tr>
</tbody>
</table>
Water distribution systems security - modeling map

Offline/design decisions
- Sensor placement
- Contaminant source identification
- Response
- Recovery

Online/real time decisions
- Event detection
- Response
Event detection

Change of concept from Early Warning Systems (EWS) [2001-2005] to Contamination Warning Systems (CWS) [2006 and later]

These parameters are known to vary considerably over time in water distribution systems due to different circumstances such as changes in the operations of tanks, pumps, and valves, and daily and seasonal changes in the source and finished water quality, as well as fluctuations in demands.

The assumption is that a contaminant present in the system will cause detectable changes in these water quality parameters (i.e., at one or multiple sensors, simple or complex).

Event detection methodologies try to capture those changes and distinguish between normal variations in water quality and changes in water quality triggered by the presence of contaminants.
Event detection

The most known event detection systems is CANARY which is part of the TEVA project of US EPA and Sandia National Laboratories (Hart et al., 2007) which can be freely downloaded.

There are in addition a few commercial systems: the most known is GUARDIAN BLUE (HACH).

Others - BlueBox (White Water Security), TOX\textsuperscript{Control} (microLAN) and more.
August 7, 2012: Vol. 46, Iss. 15

Table of Contents for this issue | Browse Issues in Cover Gallery

Estimation and classification of measured water quality data aimed at identifying contamination events in water distribution systems is one of the most challenging topics in water distribution systems analysis. In this study, data driven modeling coupled with sequential Bayesian updating are utilized to estimate future water quality data and classify outputs. See Perelman and co-workers, p. 8212. View the article.

Water distribution systems security – modeling map

**Offline/design decisions**
- Sensor placement
- Contaminant source identification
- Response
- Recovery

**Online/real time decisions**
- Event detection
- Response
Response

Same problem as for the offline/design decisions for possible scenarios

Response in real time needs an adaptive mechanism to accommodate for real time operation modifications as of consumers response

No model is currently available for this purpose
Outline

- Introduction
- Review of Drinking Water Distribution Systems Security Modeling
- Challenges for Drinking Water Distribution Systems Security Modeling
- Conclusions
Water distribution systems security - modeling map

**Offline/design decisions**
- Sensor placement
- Contaminant source identification
- Response
- Recovery

**Online/real time decisions**
- Event detection
- Response
- Real time operation

**Saturated**

**Emerging**
Challenge I

Hydraulics - obtain a real time hydraulic reliable flow and pressure distribution picture

Requirements

1. Instrumentations - cheap/affordable sensors for flow (direction/quantity) and pressure

2. Online transmission (e.g., using cell phone infrastructure)

3. Adaptive real time hydraulic modeling for calibration and verification

4. Utility preparedness/willingness to adopt

Scale: 1 = ready -- 5 = not ready
Challenge II
Water quality - obtain a real time water quality reliable picture

For what purpose?

Requirements
1. Instrumentations - cheap/affordable
2. Online transmission (e.g., using cell phone infrastructure)
3. Adaptive real time water quality modeling for calibration and verification
4. Utility preparedness/willingness to adopt

Scale: 1 = ready -- 5 = not ready

Availability: residual chlorine, pH, turbidity, conductivity, ORP (Oxidation-Reduction Potential), TOC (Total Organic Carbon), temperature, UV absorption

Surrogates

BWSN Network 2 (Ostfeld et al., 2008)
Challenge III

Real time hydraulic model

Hydraulics - obtain a real time hydraulic reliable flow and pressure distribution

Requirements
1. Instrumentations - cheap/affordable sensors for flow (direction/quantity and pressure
2. Online transmission (e.g., using cell phone infrastructure)
3. Adaptive real time hydraulic modeling for calibration and verification
4. Utility prepareness/willingness to adopt

Scale: 1 = ready -- 5 = not ready

Water quality - obtain a real time water quality reliable picture

Requirements
1. Instrumentations - cheap/affordable
2. Online transmission (e.g., using cell phone infrastructure)
3. Adaptive real time water quality modeling for calibration and verification
4. Utility prepareness/willingness to adopt

Scale: 1 = ready -- 5 = not ready

For what purpose?

BWSN Network 2 (Ostfeld et al., 2008)
Outline

- Introduction
- Review of Drinking Water Distribution Systems Security Modeling
- Challenges for Drinking Water Distribution Systems Security Modeling
- Conclusions
Conclusions

- An **overview** of water distribution systems security modeling was presented and demonstrated.

- Modeling is **shifting** from offline design/decisions to online/real time modeling.

- **Event detection** is in its early stages of exploration - interpreting data from multiple locations and incorporating water quantity (hydraulic) and water quality information is a prim challenge.

Thanks!