Studying Distribution System Hydraulics and Flow Dynamics to Improve Water Utility Operational Decision Making

Operational Decision Support System Evaluation Report

Prepared for the
National Institute for Hometown Security
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Somerset, KY 42503

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CHAPTER 1

1.0 Introduction

1.1 Background

The United States Department of Homeland Security (DHS) has established 18 sectors of infrastructure and resource areas that comprise a network of critical physical, cyber, and human assets. One of these sectors is the Water Sector. The Water Sector Research and Development Working Group has stated that water utilities would benefit from a clearer and more consistent understanding of their system flow dynamics. Understanding flow dynamics is important to interpreting water quality measurements and to inform basic operational decision making of the water utility. Such capabilities are critical for utilities to be able to identify when a possible attack has occurred as well as knowing how to respond in the event of such an attack. This research sought to better understand the impact of water distribution system flow dynamics in addressing such issues. In particular, the project: (1) evaluated the efficacy and resiliency of the real-time hydraulic/water quality model using stored SCADA data in order to understand the potential accuracy of such models, and understand the relationship between observed water quality changes and network flow dynamics, and (2) developed a toolkit for use by water utilities to select the appropriate level of operational tools in support of their operational needs.

1.2 Operational Decision Support System

The Water Distribution System Operational Decision Support System (WDSODSS) has been developed to assist water utilities in designing a monitoring/control system for their water distribution system that will provide water distribution system data (WDSD) for use in support of various system operations. Such data could include both general operational data as determined from either real time telemetry or off-line computer models, or on-line data (including data from both hydraulic and water quality sensors). Operational applications could include 1) energy management, 2) water quality management, 3) emergency response management, and 4) event detection.

The operational support data, information, an tools that have been developed as part of this project have been arranged in an operational hierarchy that can be visualized in a ladder of components, in which each rung on the ladder will be dependent upon the previous rung. The four basic components or rungs included in the operational decision support system are illustrated below. These include 1) a Supervisory Control and Data Acquisition System (SCADA), 2) spatial visualization of network components, 3) an off-line computer model of the water distribution system, 4) an on-line computer model of the water distribution system.
1.3 Decision Support System Architecture

The decision support system has been developed to allow the user to access the different operational components through two different methods: 1) an explicit decisional response path based on predetermined decisional decision trees (e.g., flowcharts) or 2) an implicit evolving decisional response path as developed an expert system inference engine in response to sequential answers as provided through the user interface (see Figure 1). The explicit response path is supported through a customized website: www.uky.edu/WaterSecurity. The implicit response path is supported through a stand-alone toolkit that can either be run on the web or on a cell phone or iPad. The toolkit uses expert system technology to guide the user through the associated content. The overall structure of the decision support system is summarized in Figure 2.
2.0 Decision Support System Evaluation Workshops

In order to evaluate the utility of the WDSODSS, the system was evaluated by the three project utility partners through a half-day workshop. The three utilities and the dates of the associated workshops are summarized below:

Northern Kentucky Water District (May 27, 2014)
Paris Water Utility (June 12, 2014)
Nicholasville Water Utility (June 25, 2014)

Each workshop consisted of a series of presentations on the different content and components of the WDSODSS. An outline of the presentation is provided below:

- 1. Project Overview
- 2. Overview of Project Website
• 3. Overview of Visualization Models
  – Graphical Flow Model
  – Pipe Break Model
• 4. Off-line network modeling
• 5. Overview of SCADA
• 6. Overview of Sensor Placement
  – Sensor Placement Model
• 7. On-line network modeling
  – Real-time predictive analytics: process and benefits
  – Real-time network modeling: NKWD field study
• 8. Overview of Toolkit
• 9. Wrap up discussion

A copy of the workshop notes is provided in Appendix A.

3.0 Decision Support System Evaluation Workshop Assessment

Following the workshop, the workshop participants were asked to evaluate workshop using the survey instrument provided in Appendix B. Both quantitative and qualitative data were collected. These results from this assessment are provided in the following sections:

3.1 Quantitative Assessment
Figure 3.1 Importance of information on sensors and telemetry
(1= not important, 9 = very important)

Figure 3.2 Importance of information on SCADA
(1= not important, 9 = very important)
Figure 3.3 Importance of information on network visualization
(1 = not important, 9 = very important)

Figure 3.4 Importance of information on sensor placement
(1 = not important, 9 = very important)
Figure 3.5 Importance of information on off-line modeling
(1= not important, 9 = very important)

Figure 3.6 Importance of information on model calibration
(1= not important, 9 = very important)
Figure 3.7 Importance of information on real-time modeling
(1= not important, 9 = very important)

Figure 3.8 Likelihood of use of the project website
(1= not important, 9 = very important)
Figure 3.9 Likelihood of use of the user-defined (guidance) functionality
(1= not important, 9 = very important)

Figure 3.10 Likelihood of use of the user-assisted (expert system) functionality
(1= not important, 9 = very important)
Figure 3.11 Likelihood of use of the graphical flow model
(1 = not important, 9 = very important)

Figure 3.12 Likelihood of use of the decon/pipe-break model
(1 = not important, 9 = very important)
Figure 3.13 Likelihood of use of water quality modeling
(1 = not important, 9 = very important)

Figure 3.14 Likelihood of use of the sensor placement tool
(1 = not important, 9 = very important)
Figure 3.15 Likelihood of use of real-time operations
(1= not important, 9 = very important)

Figure 3.16 Project presentation evaluation
(1= poor, 9 = excellent)
3.2 Qualitative Assessment

3.2.1 What additional content would you like to see added to the decision support system?

No response

3.2.2 What features would you like to see changed?

No response

3.2.3 What features would you like to see added?

No response

3.2.4 What additional information would you like to see in the workshop?

One participant indicated a desire to see cost information added.

3.2.5 What information, if any, do you feel was not necessary as part of the workshop?

No response

3.2.6 What possible changes could be made to make the presentation more useful to your operations?

One participant indicated the helpfulness of the real system example and hand-on use of the system scenarios.
APPENDIX A: Workshop Notes

Improved Network Operations Through Computer Modeling and Support System
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www.uky.edu/WaterSecurity

Workshop Agenda

1. Project Overview
2. Overview of Project Website
3. Overview of Visualization Models
   - Graphical Flow Model
   - Pipe Break Model
4. Off-line network modeling
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   - Real-time network modeling: NKWD field study
8. Overview of Toolkit
9. Wrap up discussion

Project Goal

To assist water utilities in improving the operation of their water distribution systems through a better understanding of the impact of water distribution system hydraulics and flow dynamics on operational decision making:
- Normal operations
- Emergency operations
  - Natural events
  - Man made events

Project Objectives

- Develop knowledge and tools to support water distribution system operations
- Develop a decision support system
  - Operational guidance
  - Operational toolkit
APPENDIX A: Workshop Notes

WDS Operational Objectives
• Maintain Adequate Pressures
• Minimize Water Quality Problems
• Minimize Operational Cost
• Schedule Maintenance
• Emergency Response

Operational Questions
• How long will it take to fill or drain my tanks under:
  – Normal conditions?
  – Emergency conditions?
• When and how long should I run my pumps to minimize cost?
• Can I improve my water quality by changing my operations?
• How will my system perform if I have to close several pipes?
• Which valves do I need to close to isolate a pipe break? What are the impacts on pressures and flows?

Operational Support
• Supervisory Control and Data Acquisition System
• Computer Models

Need for SCADA
• Why do we need a monitoring/ control system?
  – Normal Operations
  – Pipe Breaks/Leaks
  – Pump/Tank Failures
  – Contamination Events
  – Maintain Energy Efficiency
  – Minimize Operational Costs

Need for Models
• Graphical representation of system
  – Network schematic
  – Background map
• Infrastructure database
• Customer database
• Computer analyses

Notes:
APPENDIX A: Workshop Notes

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Water Distribution System Operations Website

• PURPOSE: To assist water utilities with designing a monitoring/control system.
• Operational Applications
  – Normal Operations
  – Emergency Response Management
  – Water Quality Management
  – Energy Management
  – Event Detection

www.uky.edu/WaterSecurity

WDS Operational Decision Support Tool

User Defined Decisional Process (Guidance)

User Assisted Decisional Process (toolkit)
APPENDIX A: Workshop Notes

WDS Toolkit

Notes

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Spatial Visualization

Spatial Visualization of Network Components

Water Distribution System Operations

Spatial Visualization of Network Components

Download and installing the Graphical Flow Model:
The Graphical Flow Model and associated user manual can be accessed below. The user should first download the user’s manual and carefully review instructions for downloading the computer program on the user’s computer.

- Graphical Flow Model
- Graphical User Manual
- Graphical User Manual Download

Download and installing the Network Determination Model:
In addition to the Graphical Flow Model, a Network Determination Model has also been developed for use by water utilities. This model can be used to help determine which sections of the water distribution system are operating at a safe and effective level. The user should first download the user’s manual and read the instructions provided in the manual before installing the computer program on the user’s computer.

- Network Determination Model (User Manual)
- Network Determination Model (User Manual Download)
APPENDIX A: Workshop Notes

Graphical Flow Model User Interface

Program Command Bar

Map Function Menu

Network Data Management
You can also use GFM to manage facilities data. If you click on the Table icon, the program will take you to a table that contains information about your system.

These results can also be viewed from the Map menu. In order to "turn on" a particular set of data, first go to the Map Settings Tab and then click on the Labels Tab.

Now you can use the drop down menu to select a particular type of data. Here we have selected diameter data.

To show this data on your map, make sure to click on the box next to the selected parameter (e.g. Diameter as shown). Now, click on the Map tab to take you back to the map viewing area.

Hydraulic Model
APPENDIX A: Workshop Notes

Model Results

1. Display Flowrates
2. Display Pressures
3. Display Pressures Contours
4. Print Out Report

Generating a Flow Analysis

Flow analysis options are provided in a menu after the run completes.

Pipe flowrates displayed by yellow boxes.

Nodal system inputs/outputs displayed by blue boxes.
APPENDIX A: Workshop Notes

Result of Screen Capture

Elements of a Flow Analysis Report

1. File name of the network
2. Regulatory valve data and properties
3. Pipeline data and properties
4. Node data and properties
5. Regulatory valve flow analysis results (upstream and downstream pressure and through flowrate)
6. Pipeline Flow analysis (flowrates)
7. Node flow analysis results (external demand, hydraulic grade, pressure head and node pressure in psi)
8. Summary of system inflows and outflows
APPENDIX A: Workshop Notes

Pipe Break/Contamination Extent Visualization

Generate a contamination report by a point

1. Click on “Facilities Management” on the top menu bar
2. Select “Contamination (point)” from the menu
3. Click on a pipe in the network map in the location of the contamination
4. Click on a valve to expand the contamination beyond the valve
5. Go back to the Facilities Management menu and select “Contamination Report”
APPENDIX A: Workshop Notes

Elements of a Contamination Report (Point Selection)
1. File name of the network
2. Date that the analysis was performed
3. Name of the pipe that contains the source of the contaminant (this is defined by where the user clicked to insert the point intrusion)
4. Volume of water contained in the contaminated pipes
5. Volume of water contained in pipes that are not contaminated but are isolated from a source
6. List of valve that must be turned off in order to isolate the contamination
7. List of hydrants that are in the contaminated region
8. Name and elevation of the lowest hydrant in the contaminated area (for use in flushing)
9. List of the lengths of all of the types of pipes within the contaminated region; categorized by material, rating, and diameter

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OFF-LINE COMPUTER MODELS

Computer Models
• Computer models for network modeling have been around since the late 1950s.
APPENDIX A: Workshop Notes

Potential Model Uses
- Static hydraulic analyses
  - Flows and pressures in the system
  - Fire flow tests
  - Valve closure
- Dynamic hydraulic analyses
  - Tank turnover
  - Pump operations
  - Emergency response
- Water Quality analyses
  - Age analysis
  - Chlorine residual analysis
  - Tracer analysis
- Real Time Analysis
  - Real Time Operations
  - Emergency Response

OFF-LINE COMPUTER MODELS

OFF-LINE COMPUTER MODEL GUIDANCE
- Network Analysis
- Model Development
- Model Calibration
- Model Calibration Literature
- Laboratory Model Calibration Case Study
- Actual System Calibration Case Studies
- Model Application
- Examples of Model Applications
- Model Selection
- EPANET
- KYPIPE

The hydraulic model was last calibrated
- Never calibrated, 5%
- <1 year ago, 24%
- 1-2 years ago, 23%
- 2-4 years ago, 13%
- >5 years ago, 25%
APPENDIX A: Workshop Notes

OFF-LINE COMPUTER MODEL GUIDANCE

- Network Analysis
- Model Development
- Model Calibration
- Model Calibration Literature
- Laboratory Model Calibration Case Study
- Actual System Calibration Case Studies
- Model Application
- Examples of Model Applications
- Model Selection
- EPANET
- KYPIPE

Water Quality Analysis

KYPIPE provides a powerful interface to the EPANET program to perform water quality simulations on an existing hydraulic model.

Through this EPANET interface it is possible to:
- Calculate chemical concentrations (e.g. chlorine)
- Calculate water age (residence time)
- Trace a chemical from a source

Calculating Chemical Concentrations

*WQ Simulations are performed over an extended period of time, therefore ensure your system is set up for an EPS prior to the WQ analysis

1) Click the tab “Other Data”
2) Click the tab “Quality”
3) Select which quality parameter you would like to calculate
4) Fill in the required parameter tables

5) Click “Generate Tabulated Results”
6) Click “Run and Exit”
Calculating Chemical Concentrations

View the maximum chemical concentrations at each node.

Click on any node to view the concentration time series data.

Calculating Chemical Concentrations

Create contours showing the chemical concentrations in your system at various time steps.

Residence Time Calculations

Select “Age” in the Quality Parameter box. Input source data and initial conditions.

Click on storage tank and view time series plot to show the age of water in the tank at a given time.

Tracer Analysis

1) Select “Trace” as the Water Quality Parameter
2) Fill in required parameter tables and initial conditions

Click on any node in the system

View the percent contribution at that node at a given time
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SCADA

Water Distribution System Operations

SCADA Functions

• Data Acquisition (Collection)
• Data Communication (Monitoring)
• Data Presentation
• Equipment Control

SCADA Components

• Sensors and Controllers
• SCADA Interface Units
• Communications Network
• SCADA Master

SCADA SYSTEMS GUIDANCE

• Potential SCADA Uses
• SCADA Functions
• SCADA Survey
• SCADA Components
• Supervisory Control Schemes
• SCADA Implementation Process
• SCADA Sensor Location
• SCADA Sensor Placement Decision-Making Sequence
• SCADA CWS Sensor Placement Optimization Program Inputs
• SCADA Sensor Placement Guidance
• SCADA Sensor Placement Software
APPENDIX A: Workshop Notes

Hydraulic Sensors

- Types of Hydraulic Sensors
  - Pressure Sensors
  - Flow Sensors

Hydraulic Sensors

- Sources of Hydraulic Sensors:
  - ABB, abb.com
  - Ashcroft, ashcroft.com
  - Holykell, holykell.com
  - Honeywell, honeywell.com
  - Keyence, keyence.com
  - Truck, truck-usa.com

Water Quality Sensors

- Types of Water Quality Sensors
  - Chlorine Residual Sensor
  - TOC Sensor
  - Turbidity Sensor
  - Conductivity Sensor
  - pH Sensor
  - ORP Sensor

Water Quality Sensors

- Sources of Water Quality Sensors
  - ABB, abb.com
  - GE, ge.com
  - Hach, hach.com
  - Siemens, siemens.com
  - Emerson, emersonprocess.com
  - Yokogawa, yokogawa.com/us

Picture of Water Quality Control Station

Control Equipment (Pumps)
APPENDIX A: Workshop Notes

Control Equipment (PRVs)

Control Equipment (Control Valves)

SCADA Interface Units
- Remote Telemetry Units (RTU1s)
- Remote Terminal Units (RTU2s)
- Programmable Logic Controllers (PLCs)

RTU: Remote Telemetry Unit
- Field interface unit compatible with the SCADA system language
- Convert electronic signals received from field sensors (i.e. pressure sensors, tank level sensors, etc.) into protocol and transmit data to the SCADA Master
- Typically consist of a box which contains a microprocessor and a database

RTU: Remote Terminal Unit
- Field interface unit compatible with the SCADA system language
- Convert electronic signals received from field sensors (i.e. pressure sensors, tank level sensors, etc.) into protocol and transmit data to the SCADA Master
- Typically consist of a box which contains a microprocessor and a database

PLC: Programmable Logic Controller
- Basic alternative to RTU; higher cost
- Typical components include
  - CPU
  - Memory
  - Control Software
  - Power Supply
  - Input/Output Modules
- A digital computer used to monitor and control certain aspects of equipment such as motor speed, valve actuation, and other functions
**APPENDIX A: Workshop Notes**

### SCADA

*Supervisory Control and Data Acquisition*

#### 2 Supervisory Control Schemes

<table>
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<tr>
<th>Hierarchical Control</th>
<th>Distributed Control</th>
</tr>
</thead>
</table>

#### Control Schemes: Advantages/Disadvantages

**Hierarchical Control**

**ADVANTAGES:**
- Low cost (RTUs vs. PLCs)

**DISADVANTAGES:**
- Inability to operate in case of communication failure
- Potential problems from data transmission rates and computer scan rates

**Distributed Control**

**ADVANTAGES:**
- Normal operations maintained despite communications failure
- Potential differences are minimized for scan and transmission rates

**DISADVANTAGES:**
- High cost (PLCs vs. RTUs)

### Need for SCADA

- Why do we need a monitoring/ control system?
  - Normal Operations
  - Pipe Breaks/Leaks
  - Pump/Tank Failures
  - Contamination Events
  - Maintain Energy Efficiency
  - Minimize Operational Costs

### EPA Water Security Initiative

- The Water Security (WS) initiative is a U.S. Environmental Protection Agency (EPA) program that addresses the risk of contamination of drinking water systems.
- EPA established this initiative in response to Homeland Security Presidential Directive 9, under which the Agency must “develop robust, comprehensive, and fully coordinated surveillance and monitoring systems, including international information, for...water quality that provides early detection and awareness of disease, pest or poisonous agents.”

### EPA Water Security Operational Phases

- Phase 1: Research & Development & Demonstration
- Phase 2: Program Evaluation & Field Testing
APPENDIX A: Workshop Notes

EPA Water Security Initiative

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Water Quality Sensor Placement
- General guidelines
  - Single sensor placement
  - Graphical method
  - Simplified graphical method
- Placement Software
  - TEVA SPOT
  - KYPIPE
APPENDIX A: Workshop Notes

Sensor Location Tool

INPUT
• Number of sensors to be placed in system
• Mass injection rate of contaminant (1000 mg/min)
• Duration of injection (1 hr)

OUTPUT
• Optimal sensor placement locations within system
• Contamination Report

* Be sure you are using an Extended Period Simulation (EPS)
APPENDIX A: Workshop Notes

Sensor Location Tool

Sensor Location Tool

Sensor Location Tool

Notes:

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ON-LINE COMPUTER MODELS
ON-LINE COMPUTER MODELS

Water Distribution System Operations

ON LINE COMPUTER MODELS

ON-LINE COMPUTER MODEL GUIDANCE

- Model / SCADA Integration / Calibration
- Implementation Strategies and Barriers for Real-Time Modeling
- Potential Applications of Real-Time Simulation
- Actual Applications of Real-Time Simulation

The current situation:
Lots of models...
and lots of data...
Isolated from each other
What will real-time analytics look like when I see it?
APPENDIX A: Workshop Notes

Is this practical?

SCADA historian

infrastructure model

Noisy Time Series

Transformations

Smooth Time Series

System Model

Billing

Analytics Engine (Epanet-RTX)

SPARC

System Performance and Reporting Console

SCADA historian infrastructure model

Transformations Smooth Time Series

Noisy Time Series
Summary:
Real-time modeling tools are available.
Analytics that derive value from existing data sources should be anticipated and expected.
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User Assisted Decisional Process (toolkit)

Decision Support Categories

Semantic Knowledge Development

Water Wizard

Wizard Selection
version 0.8.1

A-25
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Survey

- On a scale of 1-9, how important are the following knowledge databases to your operations?
  - Information on sensors and telemetry.
  - Information on SCADA.
  - Information on network visualization.
  - Information on sensor placement.
  - Information on off-line modeling.
  - Information on model calibration.
  - Information on water quality modeling.
  - Information on real-time modeling.
- What additional content would you like to see added?

Questions?

Survey

- On a scale of 1-9, how likely would you be to use the following models?
  - Graphical flow model
  - Decon/pipe break model
  - Sensor placement tool
  - Water quality model
  - Real-time operations

Survey

- How useful was the project presentation?
- What additional information would you like to see?
- What information, if any, do you feel was not necessary?
- What changes could be made to make the presentation more informative or useful to your operations?
APPENDIX B: Workshop Assessment Survey

Workshop Survey

1. On a scale of 1-9, how important are the following knowledge databases to your operations?

a. Information on sensors and telemetry.
   1..........2.........3........4.........5.........6.........7.........8.........9

b. Information on SCADA.
   1.........2.........3........4.........5.........6.........7.........8.........9

c. Information on network visualization.
   1.........2.........3........4.........5.........6.........7.........8.........9

d. Information on sensor placement.
   1.........2.........3........4.........5.........6.........7.........8.........9

e. Information on off-line modeling.
   1.........2.........3........4.........5.........6.........7.........8.........9

f. Information on model calibration.
   1.........2.........3........4.........5.........6.........7.........8.........9

g. Information on real-time modeling.
   1.........2.........3........4.........5.........6.........7.........8.........9
2. What additional content would you like to see added?

3. On a scale of 1-9 how likely would you be to use the project website?

1........2........3..........4........5........6..........7........8........9

a. The user-defined (guidance) functionality?

1........2........3..........4........5........6..........7........8........9

b. The user-assisted (expert system) functionality?

1........2........3..........4........5........6..........7........8........9

4. What features would you like to see changed?

5. What features would you like to see added?
6. On a scale of 1-9, how likely would you be to use one of the following models?

   a. Graphical flow model

   1........2........3........4........5........6........7........8........9

   b. Decon/pipe-break model

   1........2........3........4........5........6........7........8........9

   c. Water Quality Modeling

   1........2........3........4........5........6........7........8........9

   d. Sensor placement tool

   1........2........3........4........5........6........7........8........9

   e. Real-time operations

   1........2........3........4........5........6........7........8........9
7. On a scale of 1-9, how useful was the project presentation?

1........2........3........4........5........6........7........8........9

8. What additional information would you like to see?

9. What information, if any, do you feel was not necessary?

10. What possible changes could be made to make the presentation more useful to your operations?