Real-Time Water-Quality Monitoring for Water Security Applications

General Meeting of the Federal Remediation Technologies Roundtable, Arlington, VA, Dec. 7, 2005

Real-Time Water-Quality Monitoring for Water Security

• Can water-quality monitoring increase security?
• What sensors should be used?
• How reliable are the available sensors?
• What are the maintenance and replacement intervals?
"The need to develop near real-time monitoring technologies which would be particularly useful in quickly detecting contaminants in water that has already left the treatment plant for the consumer, has by far the strongest support."

Nearly 100% of experts consider this a high priority.
Existing USGS real-time systems

Map of real-time streamflow compared to historical streamflow for the day of the year (United States)

Friday, June 21, 2002 10:20ET

Daily Streamflow Conditions
Select a site to retrieve data and station information.

Frl., June 21, 2002 05:20ET
Objectives of the Overall Water Security Research Program

• To develop a real-time water-quality monitoring system for drinking water safety and security
• To evaluate available sensors for use in such a system
• To install and test the system in water distribution systems
Site Installations

• 5 distribution-system sites established
• Free Chlorine, Specific Conductance, pH, Oxidation-Reduction Potential, and temperature measured at all sites
• Total Organic Carbon and UV/VIS (on loan) at one site
• Additional sites based on model results to be installed (locations optimized for public health protection) – pending logistical issues
Water-Quality Monitoring System
Sensor locations: Based on distribution-system modeling
  - Water utility facilities, pumping stations, homes, government buildings, hospitals...

Sensors: free chlorine, oxidation-reduction potential, specific conductance, pH, temperature
Data telemetry and management: Sensors data transmitted to USGS secure webpage using satellite telemetry.

15-minute recording interval

1 hour transmission
USGS 405307074090201 TAP WATER AT MAIN AVENUE AT CLIFTON NJ (internal access only)

PROVISIONAL DATA SUBJECT TO REVISION

Temperature, water, degrees Celsius

Most recent value: 10.1  04-01-2005  19:15
USGS 405307074090201 TAP WATER AT MAIN AVENUE AT CLIFTON NJ (internal access only)

PROVISIONAL DATA SUBJECT TO REVISION

**Available data for this site**

- **Real-time**

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**Available Parameters**

- All parameters available at this site:
  - Temperature, water (DD 01)
  - Specific conductance, wat/m (DD 02)
  - Dissolved oxygen, mg/L (DD 03)

**Output format**

- Table

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**Days**

- 7 (1-31)

**Available Data**

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<th>Date / Time</th>
<th>Temperature, water (deg C/DD 01)</th>
<th>Oxidation reduction potential, mV/DD 16</th>
<th>Specific conductance, wat/m (DD 02)</th>
<th>Dissolved oxygen, mg/L (DD 03)</th>
<th>Dissolved oxygen, percent of saturation (DD 04)</th>
<th>pH, water, mEq/L (DD 05)</th>
<th>Turbidity, mNTU (DD 06)</th>
<th>DCP battery voltage volts (DD 07)</th>
<th>Estimate of DCP transmit. power, dB (DD 09)</th>
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Some Realities of Field Work with Sensors

• Often heard questions and comments:
  – Did anyone bring the manual for this thing?
  – Oh, No, not again!
  – Do we have a spare?
  – Did I really spend (X) years in college to do this?
  – If one more thing goes wrong I will miss (fill in favorite 9:00 pm TV show).
Example 3: Dissolved Oxygen Sensor
Membrane Replacement

Gradual decline in response, noticeable as higher-than-normal calibration drift. Membrane needs to be replaced.

Sudden decline in response indicates membrane needs to be replaced.
Example 4: Turbidity Sensor Fouling

Wiper keeps particles from building up on window. Removal of wiper causes inaccurately high readings.
Example 1: pH Sensor that Needs to be Replaced

As probe signal degrades, response in buffer deviates farther from standard value.

Result: Data from 11/04 – 12/04 not accurate, and variability not representative of true system conditions.
Example 2: Oxidation-Reduction-Potential (OPR) Sensor Performance: Calibration Drift of New Sensors

New sensors: Response (mV reading) increases after deionized water rinse

Possible reason: Platinum electrode builds up an oxide coating which is removed by de-ionized water.

Over time coating becomes resistant to rinsing, reducing post-cleaning calibration drift

What does this mean? Must account for post-cleaning variability on newer probes!
Summary of Observations of the Sensors Tested

- **pH**: Mostly stable and accurate. Requires replacement after 1-2 years. Drift noticed over time, electrode requires reconditioning every 4-5 months.
- **SC sensor**: excellent performance
- **ORP sensor**: very accurate after initial “break-in” time
- **Chlorine residual sensor**: still beta testing, needs membrane replacement every 1-2 months. Needs calibration every 2 weeks.
Sensor Performance: Key Issues

• The need for sensor maintenance or replacement is not always obvious by data observation alone:
  – Data from a nonresponsive sensor may look reasonable

• Sensors must be maintained properly:
  – Calibration drift affects data accuracy and precision
  – Quality assurance includes assessing and correcting data to reflect drift
  – Shorter maintenance intervals and more frequent calibrations reduce chances of significant sensor drift and improve data accuracy
RELATION BETWEEN FREE RESIDUAL CHLORINE AND ORP, DISTRIBUTION SITE 3

Free chlorine residual influences ORP

DATE

FREE CHLORINE IN mg/L

OR (ORP/1000)^2-0.2

Free chlorine residual influences ORP

Current Work: Characterizing water-quality variability in a distribution system

- **USEPA**
  - Conduct controlled laboratory experiments
  - Select sites based on distribution-system modeling

- **Sandia National Laboratories (SNL)**
  - Develop distribution-system and sensor network models

- **USGS**
  - Establish and operate a network of field sites
  - Collect and manage water quality data
  - Prepare interpretive reports

- **Cooperating Water Utility**
  - Provide and allow access to distribution system sites
  - Provide distribution system description and model
  - Support the field effort by preparing water and electrical connections and drains
New Technologies Being Tested At Site DW3

• First commercial use of chlorine probe in a YSI multiparameter water-quality monitoring system
• Total organic and inorganic carbon analyzer (General Electric)
• UV-VIS spectrophotometer with software for estimating water-quality parameter values and detecting unexpected changes in water quality (S::can Co.)
Trends observed: Most carbon is organic, concentration is within a narrow range (800-1600 ppb), some outliers are present.
Trends observed: Little variability in 2-day period, twice-daily peak concentrations resembling tidal pattern, “step function” concentration pattern.
Specific Conductance, Total Organic Carbon, and Oxidation Reduction Potential - in the absence of Chlorine Residual

[Graph showing data trends over time for Total Organic Carbon (ppm), Specific Conductance (µS/cm), and Oxidation-Reduction Potential (mV).]

USGS
science for a changing world
Oxidation-Reduction Potential (ORP) at Five Sites

- Columbia Lakes
- Stephens Lane
- Church Road
- Beverly
- Camden
Free Chlorine Residual at Five Sites

- Columbia Lakes
- Stephens Lane
- Church Road
- Beverly
- Camden

FREE CHLORINE (mg/L AS Cl)

DATE

07/12/05 07/17/05 07/22/05 07/27/05 08/01/05 08/06/05 08/11/05
Analysis of Water-Quality Variability

- Spatially
  - Age of water
  - Distance between monitoring sites
  - Type of water (SW, GW, mixed)

- Temporally
  - 15-minute intervals (or more frequent if needed)
  - Hourly
  - Daily
  - Weekly
  - Monthly
  - Seasonally
  - Annually
Explanation of the Density Diagram

A “smoothed histogram”, showing the shape of a data set.

**X axis:** The difference between each measurement (e.g., pH) and the mean of measured values (moving average) within a time increment (15 minutes, 4 hours or 24 hours).

**Y axis:** Density, or relative frequency of occurrence, of a range of X values

**Evaluating density diagrams:** Relative magnitudes of density values (not the actual values) are most informative for understanding the shape of the data.
Comparison of Temporal Water-Quality Variability Among 3 Distribution-System Sites

SPECIFIC CONDUCTANCE (SC, $\mu$s/cm)

- Site DW1 (Northern NJ, surface water)
- Site DW2 (Southern NJ, surface water)
- Site DW3 (Southern NJ, surface water and groundwater)

PERCENT DIFFERENCE BETWEEN SC MEASUREMENTS 15 MINUTES APART

RELATIVE FREQUENCY OF OCCURRENCE
OXIDATION-REDUCTION POTENTIAL (ORP, mV): DISTRIBUTION OF DIFFERENCES BETWEEN MEASUREMENTS AND MOVING AVERAGES OVER 3 TIME INTERVALS

**DISTRIBUTION SITE 1**
- Fifteen Minute Intervals:
  - 95% of values = ± 5.43
  - 99% of values = ± 7.14
- Four Hour Intervals:
  - 95% of values = ± 15.5
  - 99% of values = ± 21.7
- Daily Intervals:
  - 95% of values = ± 29.0
  - 99% of values = ± 38.1

**DISTRIBUTION SITE 2**
- Fifteen Minute Intervals:
  - 95% of values = ± 2.72
  - 99% of values = ± 3.57
- Four Hour Intervals:
  - 95% of values = ± 11.4
  - 99% of values = ± 14.9
- Daily Intervals:
  - 95% of values = ± 27.8
  - 99% of values = ± 36.5

**DISTRIBUTION SITE 3**
- Fifteen Minute Intervals:
  - 95% of values = ± 23.53
  - 99% of values = ± 30.91
- Four Hour Intervals:
  - 95% of values = ± 70.02
  - 99% of values = ± 91.99
- Daily Intervals:
  - 95% of values = ± 133.1
  - 99% of values = ± 174.8
SPECIFIC CONDUCTANCE (uS/cm): DISTRIBUTION OF DIFFERENCES BETWEEN MEASUREMENTS AND MOVING AVERAGES OVER 3 TIME INTERVALS

**DISTRIBUTION SITE 1**
- **15 MINUTE INTERVALS**: 95% of values = ± 7.55, 99% of values = ± 9.92
- **4 HOUR INTERVALS**: 95% of values = ± 22.7, 99% of values = ± 29.9
- **DAILY INTERVALS**: 95% of values = ± 41.3, 99% of values = ± 54.3

**DISTRIBUTION SITE 2**
- **15 MINUTE INTERVALS**: 95% of values = ± 1.43, 99% of values = ± 1.87
- **4 HOUR INTERVALS**: 95% of values = ± 5.88, 99% of values = ± 7.73
- **DAILY INTERVALS**: 95% of values = ± 10.8, 99% of values = ± 14.3

**DISTRIBUTION SITE 3**
- **15 MINUTE INTERVALS**: 95% of values = ± 1.088, 99% of values = ± 1.429
- **4 HOUR INTERVALS**: 95% of values = ± 3.674, 99% of values = ± 4.827
- **DAILY INTERVALS**: 95% of values = ± 6.150, 99% of values = ± 8.150
Beverly Free Chlorine Data Through 09/07/05: Cumulative Fractions of Samples Having Consecutive-Concentration Differences At or Above Thresholds
Beverly Specific Conductance Data Through 09/07/05: Cumulative Fractions of Samples Having Consecutive-Concentration Differences At or Above Thresholds

- 15 minute intervals
- 60 minute intervals
- 24 hour intervals

Cumulative Fraction

Specific Conductance Difference Threshold (μS/cm)
Specific Conductance Data Through 09/07/05: Cumulative Fractions of Samples Having Consecutive-Concentration Differences At or Above Thresholds

Bevery Camden Church Delran Col Lakes Stephen
Long Term Program Objectives

- Distribution system sites will serve as practical test beds for sensors and EWS components in the field
- Potential model calibration effort using a tracer in a sub-area of the distribution system
- Support collaborative efforts of the EPA/NHSRC and Sandia National Laboratories (SNL) to characterize water-quality variability for distribution systems
What will be learned?

- Use of hydrologic and water-quality model to select sensor location
- Natural variability of water-quality characteristics in a distribution system
- Capabilities, limitations and maintenance requirements of sensors
Summary

• Overall Program Goal: Design and test a network of water-quality sensors for drinking water safety and security
• Sensors have been selected, site design and telemetry were developed, and water-quality data are being collected at 6 sites
• Real-time data will be used to determine the temporal and spatial variability of water quality in a distribution system
• **Most important question remaining:** Will introduction of contaminants of concern cause detectable changes in water quality?