Contamination Events in Water Distribution Systems: Assessing Potential Adverse Health Effects

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Outline

• Nature of water distribution systems (WDSs)
• Feasibility of intentional contamination of WDS and historical experiences
• Role of EPA and EPA’s National Homeland Security Research Center (NHSRC)
• Need for quantitative models:
  – Consequence assessment
  – Design of contamination warning systems
  – Policy support
• Two approaches for assessing adverse health effects:
  – Detailed model approach
  – Simple or bounding approach
• Case study results
• Next steps, summary, and further reading
Nature of Water Distribution Systems (WDSs)
Typical Drinking Water System

Major Components:

- Source water
- Treatment
- Storage
- Transmissions, Distribution, and Pumping Facilities
U.S. Water Systems

- A community water supply (CWS) system serves year-round residents. They can serve as few as 25 people to several million.

- Greater than ¾ of U.S. population receive their water from community water systems serving 10,000 or more people.

<table>
<thead>
<tr>
<th>Water System Population Size Category</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Small 500 or less</td>
<td>51,356</td>
</tr>
<tr>
<td>Small 501-3,300</td>
<td></td>
</tr>
<tr>
<td>Medium 3,301-10,000</td>
<td></td>
</tr>
<tr>
<td>Large 10,001-100,000</td>
<td></td>
</tr>
<tr>
<td>Very Large &gt;100,000</td>
<td></td>
</tr>
</tbody>
</table>

| # Systems  | 28,462  | 13,737 | 4,936 | 3,802 | 419 | 51,356 |
| Pop. Served| 4,763,672| 19,661,787| 28,737,564| 108,770,014| 137,283,104| 299,216,141 |
| % of Systems| 55%    | 27%    | 10%   | 7%    | 1%  | 100%   |
| % Of Pop.  | 2%     | 7%     | 10%   | 36%   | 46% | 100%   |

Nature of Water Distribution Systems

Large network of interconnected pipes, pump stations, and storage facilities:

• 1,000s of miles of pipe distributed often over many square miles
• Finished water storage facilities distributed throughout the network – often million of gallons in size

Systems are designed to be accessible:

• Water for use by customers and industries
• Water for fire fighting

The distributed nature and accessibility make water distribution systems vulnerable to contamination attack:

• There are 1,000s of effective targets in any city’s water distribution system
Feasibility of Intentional Contamination of WDS and Historical Experiences
According to a report by the General Accounting Office released in 2004:

The *distribution system* is the top vulnerability of drinking water systems:

“...the distribution of a chemical, biological, or radiological agent via the distribution system could be difficult to detect until it is *too late* to reverse any harm done.”

**Distribution systems are vulnerable to:**

- Insider, physical, and cyber threats
- Intentional or accidental contamination (e.g., injection at fire hydrant or cross-connection)
- Contamination might not be detected until people are sick or in the hospital
“Al Qaeda prisoner interviewers and confiscated documents suggest other possible attacks ranging from blowing up gas stations to poisoning water supplies to using crop dusters to spread biological weapons to detonating radioactive dirty bombs.”

Contamination incidents in Water Distribution Systems

• Contaminant injections can occur anywhere in the distribution system.

• Health and economic impacts can vary widely depending on the threat, e.g., contaminant used.

• Significant consequences can occur miles from the injection location.

Area shown above is about 10 x 10 km
Potential Water Contamination Problems

Actual contamination incidents provide the best examples for demonstrating the potential consequences from contamination incidents.

Tracer studies allow a controlled investigation of potential contamination spread through a distribution system.
Here are just three examples:

• 1993, Milwaukee, WI: Unintentional *Cryptosporidium* contamination incident. 403,000 of the 880,000 served by the treatment plant became ill with 104 deaths (Fox et al. 1996).

• 1980, Pittsburgh, PA: Intentional contamination with the pesticide chlordane. 10,500 people affected. One month without service and 9 months of flushing and cleanup. Cleanup costs exceeded $200K (Welter et al. 2009)

• 2014, Charlestown, WV: An industrial spill results in 300,000 customers and many business not having tap water to use for any purpose – drinking, flushing toilets, food prep, etc), some for over a week. Weeks later, many still do not trust the tap water’s safety. (Scientific American online, Feb. 05, 2013)
Tracer Study: Illustration

- Tracer: calcium chloride
- Bulk Volume: 666 L
- Injection Duration: 6 hrs
- Injection Rate: 1.89 L/min
- Injection Concentration: 421 g/L
Conductivity monitoring at fire hydrants...
Tracer Profiles

Branch Line 0.75 Miles Downstream
Tracer Spread in Water Distribution System

Legend
- Tracer Injection Location
- Roads
- Boundary of Tracer Spread
Role of EPA and EPA’s National Homeland Security Research Center
EPA’s Role in Protecting Critical Infrastructure

• The Bioterrorism Act of 2002
• PPD 21-Critical Infrastructure Security and Resilience-designates EPA the lead federal agency for water and wastewater infrastructure (February, 2013).
• HSPD-9 (Defense of U.S. agriculture and food) directs EPA to develop a surveillance and monitoring program for early detection of contamination (January, 2004).
• Water is considered as both critical infrastructure and food threat.
Need for quantitative models for predicting adverse health effects from drinking water contamination incidents
Need for Quantitative Models

Characterizing and understanding the adverse consequences that could be associated with contamination events in water distribution systems (WDSs) is necessary for:

- Performing consequence and vulnerability analyses
- Performing comparative risk analyses
- Implementing surveillance and monitoring activities
- Designing contamination warning systems
- Preparing and responding to emergencies, including disruptions and contamination events
- Supporting policy decisions
Example: Using Consequence and Vulnerability Assessments to Support Policy Decisions

Department of Homeland Security (DHS) develops consequence and vulnerability assessments to support policy and resource decisions:

- Chemical Threat Risk Assessment (CTRA)
- Biological Threat Risk Assessment (BTRA)
Example: Support Contamination Warning Systems Design

Drivers:
- Presidential Homeland Security Directives
- Utility responsibility to provide safe drinking water

Goals:
- Detect a broad range of contamination events in drinking water distribution systems
- Detect *rapidly* to allow for utility and public health intervention that reduces public health and economic impacts
- Achieve multiple benefits to water utility, increasing sustainability

Design principles:
- Spatial coverage: entire distribution system service area
- Contaminant coverage: all contaminant classes posing a threat
- Timing of detection: in sufficient time to allow for effective response
- System reliability: information sufficient to make response decisions
- Deployable at water utilities of all sizes and types
Design of Contamination Warning Systems (CWS)

CWS Components

Water Quality Monitoring:
- Online monitoring
- Sampling and analysis

Consumer Complaint Surveillance

Contamination Warning System

Public Health Surveillance:
- 911 calls / EMS data
- ED visits
- OTC medication sales

Enhanced Security Monitoring:
- Video
- Alarms
- Intelligence

Optimization of Sensor Placement
(circle size is a measure of # of contamination events detected)

Cost-Benefit Analysis
(Benefit is reduction of public health impacts)

ED: Emergency Department
Detection of contamination using water quality sensors:

• Comprehensive report comparing sensor technologies.
• Evaluates multiple sensor platforms.
• Demonstrates ability of water quality sensors to indirectly detect a wide range of contaminants.
• EPA/600/R-09/076, www.epa.gov/nhsrc
• Our approach is agnostic to sensor/detector type, i.e., better detection will only improve the performance of the CWS.
Two Approaches For Assessing Adverse Health Effects of Contamination Events in Water Distribution Systems
Flexible Analysis Framework

• **Detailed Model Approach**: Estimate magnitude of adverse effects using network infrastructure models and detailed system information.

• **Simple Approach**: Using a bounding approach, estimate upper bounds on adverse effects for water systems based only on the population served by the system. Simple approach can be used when little information about the water system is available.
Detailed Model Approach
Assessing Consequences

What do we want from a detailed model for assessing the consequences from a water contamination event?

- Ability to accurately estimate exposures, doses, and adverse health effects to the population served by the water system.
- To be empirically-based using state-of-the-art methodologies.
- Flexible, able to be refined with new or better data and information.

Contamination injection location (red square) and downstream locations (blue and light blue nodes) with receptors receiving a dose above some level. Node coloring is a measure of the number of receptors at particular node receiving some dose.
Software for Detailed Model Approach

Define Water System:
- Thorough understanding of water system
- Network infrastructure model that accurately reflects water system operations

Determine Design Basis Threat:
- Threat ensemble (injection locations)
- Contaminant and quantity released, duration of release, time of release, etc.

Identify Exposure Input Parameters:
- Exposure parameters, e.g. water consumption pattern
- Population distribution
- Simulation duration

Perform Simulations:
- Independent injection of a contaminant at each node
- Transport of the contaminant in the network after injection
- Simulations were performed using TEVA-SPOT/EPANET software.

TEVA-SPOT (Threat Ensemble Vulnerability Assessment – Sensor Placement Optimization Tool): A software tool for assessing consequences from contamination events in water distribution systems (TEVA) and a tool for determining the optimal locations for placing monitoring stations (SPOT) in order to reduce consequences.
Defining Contamination Event and Injection Locations

- Contamination incident, e.g., 8,330 mg/min for 60 min or approx. 0.5 kg.
- Ensemble of contamination injection locations, e.g., injection of contaminant at all non-zero demand nodes.
Determining Adverse Health Effects

Exposure pathways from contaminated tap water:

- *Ingestion*
- Inhalation
- Others?

Adverse health effects to water users can be quantified as the numbers of illnesses and fatalities:

- Estimating number of illnesses or fatalities from contamination event requires model relating contaminant dose to endpoint, e.g., illness
- Dose response models involve considerable uncertainty for types of contaminants possibly present in contamination events and vary from contaminant to contaminant

Restricting results to contaminant doses:

- To reduce complexity
- To avoid added uncertainties with modeling actual health impacts
Use of Dose Levels to Determine Impacts

Impacts (consequences) defined by:
- Size of the population receiving a dose above a given level (or dose level) due to ingestion of contaminated tap water.

Dose level can be related to an endpoint reached following ingestion of contaminant:
- A dose level could correspond to median lethal dose (LD\textsubscript{50}).

A wide range of dose levels can be considered:
- Equivalent to a wide range of contaminants.
- Dose levels specified by user.

Doses in units of mg/kg:
- Divide dose by 70 kg (adult body weight)
- Assumes body mass of all exposed individuals is the same.

2. ANALYSIS FRAMEWORK

The following terms related to the analysis framework have the definitions given below:

**Dose.** A dose is the total quantity (mass in milligrams) of a contaminant ingested by consumption of tap water.

**Dose Level.** A dose level is a quantity of ingested contaminant for which we quantify adverse effects. For a particular contaminant, it can be related to a health-effect level. For example, a dose level could correspond to the median lethal dose (LD\textsubscript{50}) or the no-observed or lowest-observed-adverse-effect level (NOAEL or LOAEL). Lower dose levels can be related to a particular health-effect level for more toxic contaminants and higher dose levels can be related to the same health-effect level for less toxic contaminants.

**Impact.** Impact is the size of the population that receives a dose of a contaminant above some specified level by ingestion of contaminated tap water. It is an integrated measure of all downstream adverse effects resulting from a contaminant injection at a particular location and is our measure of adverse effects associated with a contamination event.

Flexibility of Dose Levels Given Different Injection Masses

- Use of dose levels allows modification of impacts for cases of different injection masses.
- For example, increasing injection mass by $M$ will yield results identical to those in the figure at right but with the dose levels on the horizontal axis multiplied by $M$:
  - Each person’s dose would increase by same factor as injected mass increased.
  - Number of people with a dose above some level $L$ would be the same as the number of people with a dose above the level $M \times L$ after the injected mass is increased by the factor $M$.


*Fig. 1. Impact versus dose level for Network 12 (injection mass = 0.5 kg).*
### Probabilistic Ingestion Timing and Volume Models

<table>
<thead>
<tr>
<th>Name</th>
<th>Model Type</th>
<th>Description</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>D24</td>
<td>Timing</td>
<td>Demand based, every hour (24 events)</td>
<td>Historical use</td>
</tr>
<tr>
<td>F5</td>
<td>Timing</td>
<td>Ingestion based, fixed times (5 events)</td>
<td>Time-use studies</td>
</tr>
<tr>
<td>P5</td>
<td>Timing</td>
<td>Ingestion based, probabilistic (5 events)</td>
<td>Time-use studies</td>
</tr>
<tr>
<td>M</td>
<td>Volume</td>
<td>Mean volume per day (1 L)</td>
<td>Mean volume, tap water</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>Variable volume per day (probabilistic)</td>
<td>U.S. EPA (2000)</td>
</tr>
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</table>

Contaminant Classes

<table>
<thead>
<tr>
<th>Class</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Petroleum products</td>
</tr>
<tr>
<td>2</td>
<td>Pesticides (chlorine reactive)</td>
</tr>
<tr>
<td>3</td>
<td>Inorganic compounds</td>
</tr>
<tr>
<td>4</td>
<td>Metals</td>
</tr>
<tr>
<td>5</td>
<td>Pesticides (chlorine resistant)</td>
</tr>
<tr>
<td>6</td>
<td>Chemical warfare agents</td>
</tr>
<tr>
<td>7</td>
<td>Radionuclides</td>
</tr>
<tr>
<td>8</td>
<td>Bacterial toxins</td>
</tr>
<tr>
<td>9</td>
<td>Plant toxins</td>
</tr>
<tr>
<td>10</td>
<td>Pathogens causing diseases with unique symptoms</td>
</tr>
<tr>
<td>11</td>
<td>Pathogens causing diseases with common symptoms</td>
</tr>
<tr>
<td>12</td>
<td>Persistent chlorinated organic compounds</td>
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</table>

Contaminant Behavior in Water

<table>
<thead>
<tr>
<th>Substance</th>
<th>Decay Mechanism</th>
<th>Reaction Conditions</th>
<th>Half Life</th>
<th>k (d⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyprazineb</td>
<td>H</td>
<td>g</td>
<td>254 d</td>
<td>0.003</td>
</tr>
<tr>
<td>Atrazineb</td>
<td>H</td>
<td>g</td>
<td>130 d</td>
<td>0.005</td>
</tr>
<tr>
<td>Chlorfenvinphosc</td>
<td>Cl</td>
<td>h</td>
<td>&gt;100 d</td>
<td>&lt;0.007</td>
</tr>
<tr>
<td>Chlorpyrifosd</td>
<td>H</td>
<td>g</td>
<td>78 d</td>
<td>0.009</td>
</tr>
<tr>
<td>Diazinont</td>
<td>H</td>
<td>g</td>
<td>52 d</td>
<td>0.01</td>
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<td>Malathionb</td>
<td>H</td>
<td>g</td>
<td>7 d</td>
<td>0.1</td>
</tr>
<tr>
<td>Phorateg</td>
<td>H</td>
<td>pH 5.7</td>
<td>52 h</td>
<td>0.3</td>
</tr>
<tr>
<td>Botulinum toxinf</td>
<td>i</td>
<td>pH 7.9</td>
<td>24 h</td>
<td>0.7</td>
</tr>
<tr>
<td>Phosmetg</td>
<td>H</td>
<td>g</td>
<td>7.1 h</td>
<td>2.3</td>
</tr>
<tr>
<td>Chlorpyrifosc</td>
<td>Cl</td>
<td>h</td>
<td>15 min</td>
<td>70</td>
</tr>
<tr>
<td>Diazinonf</td>
<td>Cl</td>
<td>h</td>
<td>&lt;15 min</td>
<td>&gt;70</td>
</tr>
<tr>
<td>Botulinum toxinsf</td>
<td>Cl</td>
<td>h</td>
<td>8 s</td>
<td>8,000</td>
</tr>
</tbody>
</table>

a H = hydrolysis; Cl = chlorine oxidation.
c Acero et al. (2008).  
e Hong and Pehkonnen (1998).  
f Notermans and Havelaar (1980).  
g Approximately pH 7 and 20 °C.  
h 0.5 mg/L Cl.  
i Not given in reference.

Table 3. Examples of Pseudo-First-Order Decay Rate Constants

Cryptosporidium

Conservative tracer: Or single species, e.g., first-order decay.

Multi-Species Analysis: TEVA-SPOT-GUI/EPANET-MSX software can be used for complex water quality modeling of contamination events:
- Adsorption/desorption to pipe walls
- Attachment/detachment to biofilms
- Reaction with chlorine
Results can be applied to biological contaminants by adjusting for injection quantity:

- If $5 \times 10^9$ organisms were injected (instead of 0.5 kg of chemicals), dose levels in figures would be multiplied by $10^4$ organisms/mg.
- $5 \times 10^9$ organisms/0.5kg = $10^4$ organisms/mg, which would change the range in dose levels from $10^{-4}$ to 100 mg to a range of 1 to $10^6$ organisms.
Case Study Application of Detailed Model Approach
Description of Case Study

12 networks examined:

- Diverse range of system sizes and populations served.
- Range of model detail (skeletonization levels).

Input Parameters:

- Probabilistic exposure and volume models.
- Population distribution assumed constant and based on water usage.
- Simulation duration of 1 week or more.

Simulation:

- Injection of contaminant (0.5 kg) at each non-zero demand node.
- Transport and decay of contaminant after injection.
- Exposure and dose assessment for individuals who ingest contaminated tap water.

Results: Impacts (measure of consequences)

- Dose level of 1 mg could correspond to an LD_{50} of about 0.01 mg/kg.
## Descriptions of 12 Real Systems

<table>
<thead>
<tr>
<th>Net</th>
<th>Pop. ($10^3$)</th>
<th>Area (km$^2$)</th>
<th>Mean pop. density (#/km$^2$)</th>
<th>No. of nodes</th>
<th>No. of NZD Nodes</th>
<th>NZD Mean pop.</th>
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<tr>
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<td>160</td>
<td>410</td>
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<td>2</td>
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<td>3,200</td>
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<tr>
<td>3</td>
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<td>130</td>
<td>1,000</td>
<td>6,800</td>
<td>6,700</td>
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<tr>
<td>4</td>
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<td>500</td>
<td>310</td>
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<td>1,600</td>
<td>94</td>
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<tr>
<td>5</td>
<td>190</td>
<td>260</td>
<td>740</td>
<td>3,000</td>
<td>1,800</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>250</td>
<td>490</td>
<td>520</td>
<td>13,000</td>
<td>11,000</td>
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<td>7</td>
<td>590</td>
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<td>260</td>
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<tr>
<td>8</td>
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<td>7,400</td>
<td>5,900</td>
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<td>9</td>
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<td>1,500</td>
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<td>1,200</td>
<td>43,000</td>
<td>28,000</td>
<td>51</td>
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<td>11</td>
<td>1,500</td>
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<td>1,100</td>
<td>14,000</td>
<td>8,700</td>
<td>170</td>
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<tr>
<td>12</td>
<td>1,800</td>
<td>3,700</td>
<td>480</td>
<td>3,100</td>
<td>1,400</td>
<td>1,200</td>
</tr>
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</table>

Note NZD: Non-zero demand
Approach to Contaminant Decay

• First-order decay (rate = $k[A]$, where $[A]$ is the concentration of the contaminant A and $k$ is the decay rate constant.

• Decay only assumed to occur in bulk flow, i.e., neglect influence of tanks and pipe walls.

• First-order decay is an approximation (reasonable if conditions in system are constant, e.g., chlorine).

• Results expected to be conservative since depletion of chlorine would be expected and would result in reduced decay.
Case Study Results

Impacts determined for:

- 12 system models
- Injection of contaminant at all non-zero demand nodes
- 7 dose levels (contaminant types or toxicity levels)
- 11 decay rates (ranging from 0 to 128/day)

Injection locations ranked by impact ($N\%$ of impacts are smaller; $100^{th}$ percentile defined as worst case)

Impacts compared across networks, decay rates and dose levels

Figure taken from “Assessing Potential Impacts Associated with Contamination Events in Water Distribution Systems: A Sensitivity Analysis,” EPA/600/R-10/061.
Defining Significant Impacts

- Significant impacts (those similar to worst case) occur from contaminant injections at a minority of locations.
- Median impacts range from less than 1/1000 (Network 6) to about 1/10 (Network 7) of the respective network’s worst-case impact.

Influence of Toxicity

High toxicity (low dose level) contaminants:
• Magnitude of impacts can vary substantially for different systems
• Magnitude of impacts is sensitive to population served by the water system

Low toxicity (high dose level) contaminants:
• Impacts concentrated near injection location
• Magnitude of impacts not sensitive to network population

Figure modified from Davis, M. J., and Janke, R. (2010). “Patterns in potential impacts associated with contamination events in water distribution systems.” Journal of Water Resources Planning and Management, (16 March 2010), 10.1061/(ASCE)WR.1943-5452.0000084
High toxicity contaminants:
- Magnitude of impacts less sensitive to mass of contaminant injected.

Low toxicity contaminants:
- Magnitude of impacts sensitive to mass injected.

Results for the given LD$_{50}$ obtained for a low quantity (mass) of contaminant injected:
- Similar impacts can be achieved for higher LD$_{50}$ values by injecting more mass.

Influence of Contaminant Decay on Impacts for Network 12

- Impacts vary by percentile, decay rate, and dose level.
- Significant impacts result primarily from injections at high percentile node, e.g., 95th.
- Notice logarithmic vertical scale.

Figure 1. Impact versus dose level for Network 12 (injection mass = 0.5 kg).

How are population impacts influenced given contaminant decay or loss?

- A $k$ less than about 1 $d^{-1}$ will produce noticeable reduction in impacts (10%) for impacts associated with high percentile injection nodes.
- A $k$ of 40 $d^{-1}$ or more is sufficient to eliminate 99% or more of the estimated impacts resulting from injections at high percentile nodes.
- Decay or loss tends to have a larger influence on reducing impacts for higher toxicity contaminants.

Simple (Bounding) Approach
Simple (Bounding) Model Approach

• Impacts are constrained by:
  - Mass of contaminant injected
  - Population of network

• Injected mass limits the number of people who can ingest contaminant above some level.

• Population of network provides absolute upper bound on magnitude of impacts.

• Given the ingested mass for the population, the upper bound on impact for a particular dose level is the \textit{ingested mass divided by dose level}.

• Useful when limited information is available on the system.
Quantity of contaminant mass ingested ($M_i$) is determined by the fraction of contaminated water ingested multiplied by the mass of contaminant injected:

- $M_i = (v/V) \times M$, where $v$ is volume of contaminated water ingested; $V$ is total volume of contaminated water.
- Assumes contaminant concentration is the same in water that is ingested and water that is withdrawn for other uses.

Assuming a constant per capita ingestion rate ($q$), constant per capita withdrawal rate ($Q$), population ($P$) using water, and time period ($T$) when contaminated water is used:

- $V = qPT$ and $V = QPT$, therefore
- $M_i = qM/Q$
Maximum number of people (N) who can receive an ingested dose d equals the mass ingested divided by the dose:

\[ N = \frac{qM}{Qd}, \text{ with } N \leq P. \]

This gives the mass-based bound on impacts for any dose.

**Figure 5.** Bounds on impact for Network 2 (injection mass = 0.5 kg).

- Per capita ingestion rate = 1 L/d
- Per capita water usage rate = 429 L/d (average for Network)
Figure at right provides comparison of 100th percentile impacts with upper bound estimates (0.5 kg injection mass) determined for the 12 networks.

Simple upper bound does not completely apply for one very small system, but with minor deviation:

- i.e., Network 1 for dose levels of 1, 10, and 100 mg
- Ingestion and usage rates vary diurnally, and are not constant as assumed in the simple bounding approach

Fig. 6. Comparison of 100th percentile impacts for 24-h injections with bounds based on mass. Results are shown for 12 networks for an injection mass of 0.5 kg; some points overlap.

## Descriptions of 12 Real Systems

<table>
<thead>
<tr>
<th>Net</th>
<th>Pop. (10³)</th>
<th>Area (km²)</th>
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<th>No. of NZD Nodes</th>
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Note NZD: Non-zero demand
Next Steps, Summary, and Further Reading and References
Next Steps for Detailed Model Approach

Flexible analysis framework described can be improved with better network models and contaminant reaction dynamic models:

• Network models that better reflect actual operations (EPANET-RTX).

• Better representation of contaminant interaction with chlorine, organic matter and pipe walls (EPANET-MSX multi-species modeling).
Summary

Threat and Consequences from Contamination Incidents in Drinking Water Distribution Systems (WDS):

• Threat of intentional WDS contamination is real
• Adverse consequences can be significant

Organizational Roles to Help Make Water Systems Safer:

• EPA’s role
• EPA’s National Homeland Security Research Center role
Need for Quantitative Models to Assess Consequences:

- Consequence vulnerability assessment
- Risk analysis
- CWS design
- Surveillance and monitoring
- Supporting policy decisions

Two Approaches for Assessing Adverse Consequences:

- Detailed model approach
- Simple (bounding) model approach
Further Reading and References

For More Information

- Robert Janke (janke.robert@epa.gov)
- Mike Davis (mike_davis@anl.gov)
- Matthew Magnuson (magnuson.matthew@epa.gov)