An Agent-Based Modeling Approach to Evaluate Protective Action Strategies in a Water Distribution Contamination Event

Mohammadmehdi Shafiee[1] and Emily M. Zechman[2]

[1]Ph.D. Student – Graduate Research Assistant, Environmental and Water Resources Engineering, Zachry Department of Civil Engineering, Texas A&M University, 205-R Wisenbaker Engineering Research Center, 3136 TAMU, College Station, TX 77843-3136, shafiee@tamu.edu.
[2]Ph.D. – Assistant Professor, Environmental and Water Resources Engineering, Zachry Department of Civil Engineering, Texas A&M University, 205-M Wisenbaker Engineering Research Center, 3136 TAMU, College Station, TX 77843-3136; PH (979) 845-2875; FAX: (979) 862-1542; ezechman@civil.tamu.edu.

ABSTRACT

Water distribution systems are vulnerable to both intentional and accidental contamination, which endangers public health and erodes public trust in municipal services. Appropriate protective actions should be selected by public officials or utility managers as the contaminant propagates through the network to best protect public health. Response actions typically attempt to control hydraulics in the network or the water consumption of the public, and decision-makers may be made aware of a security threat through consumer complaints or public health services. Consumers can be influenced to reduce their water consumption through, for example, boil water orders and drinking water restrictions. The interactions and information exchange between the utility managers and consumers will dynamically influence the system hydraulics, increasing the complexity of the decision-making process for the utility managers. An agent-based modeling framework was developed to simulate the dynamic and adaptive actions and reactions in a contamination event. Utility managers and consumers are modeled as agents, and the agent-based model was coupled with a water distribution system simulator to predict the emergent public health for diverse protective action strategies. The modeling framework is applied to a virtual case study, Mesopolis, to investigate the significance of the interactions among consumers and utility managers in water distribution system threat management.

Keywords: Agent-Based Modeling, Water Distribution System, Contamination Event, Complex Adaptive System, Threat Management

INTRODUCTION

Water distribution infrastructure systems are vulnerable to accidental and intentional contamination events. Pathogens may enter the infrastructure through weak points in the system. In addition, toxic chemicals can be intentionally injected into the system to create a public health threat. Propagation of contaminants through the network exposes consumers to threats and endangers public health.

The water distribution contamination event is a dynamic event, and the public health outcomes unfold as actors in the system respond to information. Consumers behave dynamically and adaptively as contamination moves through a water system. Consumers who are sickened due to water consumption may change their demands as they adopt protective actions, such as boiling water or not using water for contact uses. Meanwhile, other consumers may reduce water demands as they are informed about the threat to the water distribution system. Therefore, the number of sickened consumers in an event depends on the propagation of contaminant in a water system, which will fluctuate as consumers select options for changing their water demands. An Agent-Based Modeling (ABM) simulation approach has been used to integrate the dynamics of consumer behaviors with a water distribution system in a single simulation model (Zechman, 2007 and 2008). Zechman et al. (2011) used ABM to couple consumer agents for a mid-sized water distribution system, Mesopolis.

In addition to residential consumers, other actors impact hydraulic conditions and contaminant propagation, directly and indirectly, through decisions and actions. The media, public health officials, and utility managers will impact contaminant propagation and behavior of consumers. During the contamination of a water distribution system, utility managers might be notified about possible contamination in a water distribution system from contamination warning system or public health officials. In order to mitigate the consequences of the contamination event, the utility managers might initiate a range of actions which can be categorized in general as social or hydraulic protective actions. The social protective actions are taken to convince consumers to change their water uses, whereas hydraulic actions are taken to control the movement of contaminant. This study develops new modeling of public officials in a water distribution contamination event and incorporates new modeling into an existing agent-based modeling framework (Shafiee and Zechman 2010). The analysis provided by this study can be used to evaluate the response protection strategies in water distribution contamination events.

AGENT-BASED MODELING

The modeling framework couples a water distribution system, EPANET (Rossman, 2000) with an ABM software, AnyLogic (XJ Technology 2010). In the ABM simulation, agents represent both individual actors (consumers) and organizations.

Consumers

Each individual consumer is simulated as an agent. Consumers are exposed to contamination in a water distribution system based on their water consumption behaviors, which are determined by a set of characteristics, including demographics, volume and timing of water ingestion, exposure and demand decisions, mobility, and communication among consumers (Zechman et al. 2011).

Organizations

Organizations, including public health officials, utility operators, utility manager and emergency response units, are represented as single collective agents. Interactions among these collective agents, individual agents, and the water distribution system are shown in Figure 1.

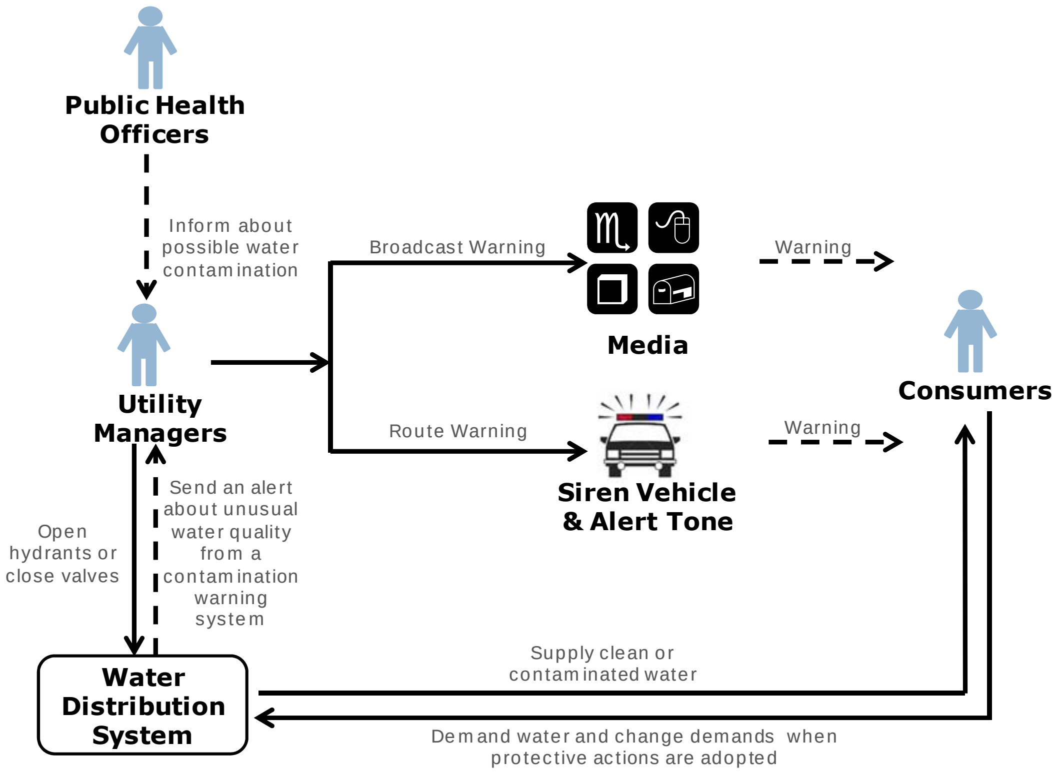

Figure 1. In a contamination event, information (represented by solid lines) is passed between agents and the water distribution system. Actions (represented by dashed lines) are exerted by agents on other agents or the water distribution system.

Public Health Officials

Public health officials receive consumer complaints about waterborne illnesses and will inform utility officers about potential threats to a water distribution system. Public health officials recognize waterborne illnesses from unusual consumer complaints. An increase in complaints will increase the likelihood of identifying a threat and reduce delays in taking actions. A joint probability distribution is developed to simulate threat identification by a public health official, and is based on the time to action, and the rate of complaints. The notification time is the time that passes from when a public health official first receives a complaint and protective actions are taken; the rate of complaints is the number of complaints received per unit time. The two parameters are assumed as statistically independent, and the joint probability of threat identification by a public health official depends on the product of these two random variables.

To develop a probability of threat identification, twenty-nine actual events are reviewed to collect the data (Hurdey and Hurdey, 2004), including the number of confirmed cases of sick consumers, the number of sick consumers at the notification time, the total estimated cases of sick consumer, and the notification time. An exponential distribution function is fitted to estimate the number of cases of sick consumers at health clinics (Figure 2).

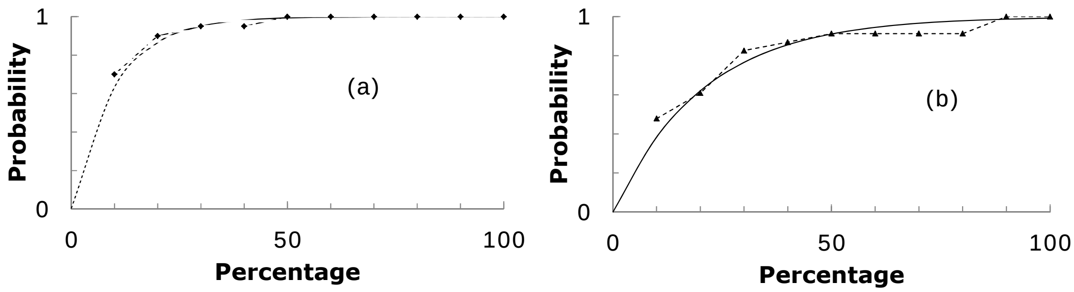

Figure 2. (a) Percentage of sickened consumers at clinical places in a water contamination event, (b) Percentage of sickened consumers at clinical places at time of notifying, Empirical graph is represented by dashed line and Mathematical graph is represented by solid line

Contamination Warning System

The contamination warning system is an ensemble of sensors which is installed in the system to detect contamination in the water network. Different sets of sensors are tested in this study to investigate significance of sensor placement in early warning of contaminated system.

Utility Managers

Utility officers may also receive warnings from a contamination warning system about unusual water quality. After receiving an alert through either of these pathways, the utility officer will choose social or hydraulic protective actions. Social protective actions include broadcasting warnings through the mass media, informing consumers face-to-face, and alerting consumers by using sirens or tone-alert devices. Hydraulic protective actions directly change the hydraulics of the water distribution system to flush the contaminated system by opening hydrants or confining the contaminant by closing valves.

Once a utility manager receives sensor data indicating unusual water quality or is contacted by a public health official about a potential threat, the threat should be verified, which will delay the time of implementation for any response actions. Data from 29 actual events have been surveyed, and the results indicate that the average response time of utility manager to a warning message is 1.54 days.

Use of Media by Consumers

Utility managers use both television and radio broadcasts to alert consumers. Data about the time usage of consumers for watching television and listening to radio are available for simulating how consumers will receive alerts. Rogers and Sorensen (1991) conducted a survey to determine the timing of residents for viewing television, listening to the radio, and sleeping (Fig. 3). Lindell et al. (submitted) surveyed respondents to determine when residents watch TV and listen to radio broadcasts in a college city (Fig. 4). A warning time window is simulated as the time during which an alert is being broadcast through television and radio. During this time window, if a consumer agent uses media, he or she will respond by taking protective actions and alerting other consumers about the threat.

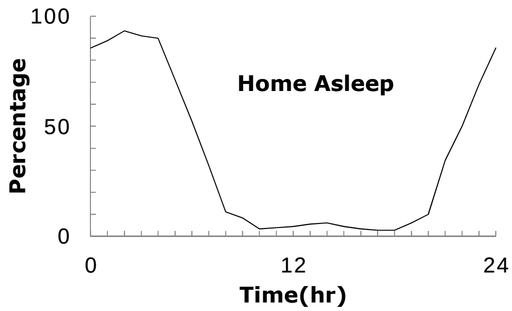

Figure 3. Percentage of residents who are asleep at different times during a day

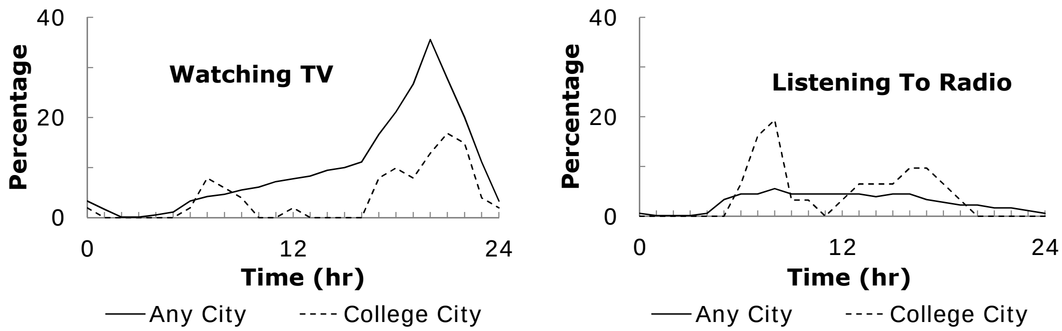

Figure 4. The percentage of consumers who watch television and listen to radio for two different types of cities (Rogers and Sorensen 1991; and Lindell et al. submitted).

A WATER DISTRIBUTION SYSTEM: MESOPOLIS

The new modeling is demonstrated here for an illustrative case study to explore the interactions of collective agents, consumers, and hydraulics during a contamination event. Mesopolis is a mid-size virtual city, with a population of 150,000 residents, developed to provide a model of a realistic city for research in water distribution system planning and security. The water distribution system is modeled with 2994 nodes, 151 valves, 3426 pipes, 69 pumps, one reservoir, and 13 tanks. Demands are exerted at 1418 nodes, characterized as residences, industries, restaurants, airport, university and commercial or institutional users. The diversity in demand patterns and the topography of the system provides an excellent case study for examining a set of scenarios, assessing the impact of contamination on public health, and evaluating different management strategies. IN0150, IN0459, and IN0855 are simulated as nodes for placing sensors (Fig. 5).

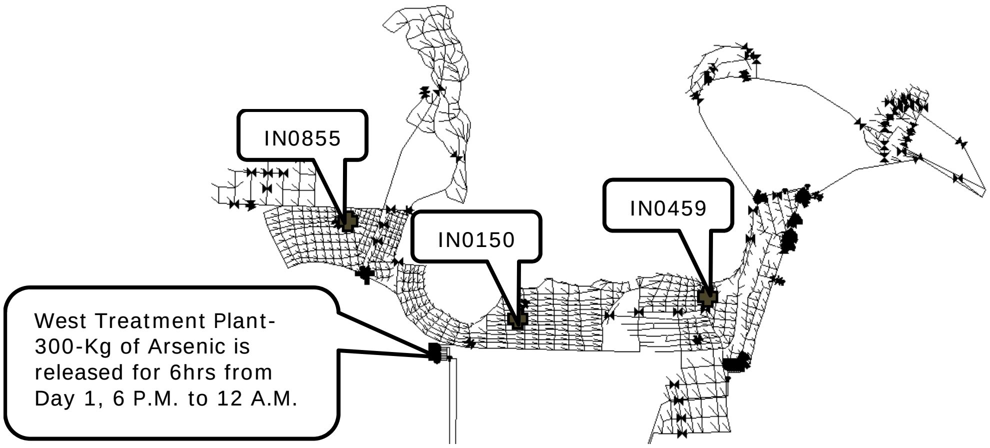

Figure 5. Mesopolis hydraulic network layout. Location of three sensors and a contamination scenario at West Treatment Plant.

PRELIMINARY RESULTS

The simulation is executed to evaluate the number of sickened consumers in a water distribution system event. An injection of 300 kg of arsenic is introduced to the Mesopolis system at the West Treatment Plant. The time of injection, duration, and the location of the attack are shown in Fig. 5. The water distribution system contamination event is evaluated for two scenarios. A scenario simulates five days of the water distribution contamination event, and for each scenario, the simulation is executed 15 independent times to assess the influence of stochasticity on the model results. For both scenarios, the utility manager is alerted to the threat at time step 34 of the simulation (10:00am, Day 2) by the sensor placed at IN0855.

The first scenario simulates the event when no mitigation strategies are implemented by the utility manager. The average over 15 runs is a total of 32,133 consumers who become sick. In the second scenario, the utility manager broadcasts a warning message. The utility manager is simulated with a random value in the time of delay to verify a threat, and 15 runs of the simulation result in different times of response by the utility manager. In Fig. 6, the effect of the delay on the number of sickened consumers in the water distribution event is shown for random values for the time of delay. The number of sickened consumers increases as the utility manager takes additional time to recognize a threat. In addition, there is a significant increase in the number of sickened consumers if the utility manager delays past time step 45 (9:00pm, Day 2). This is due to the behavior of consumers, as a significant number of consumers are asleep after this time and not watching television or listening to the radio; therefore, fewer consumers receive messages about the threat. Further simulations will explore the impact of improving broadcasting systems and response readiness for water utilities.

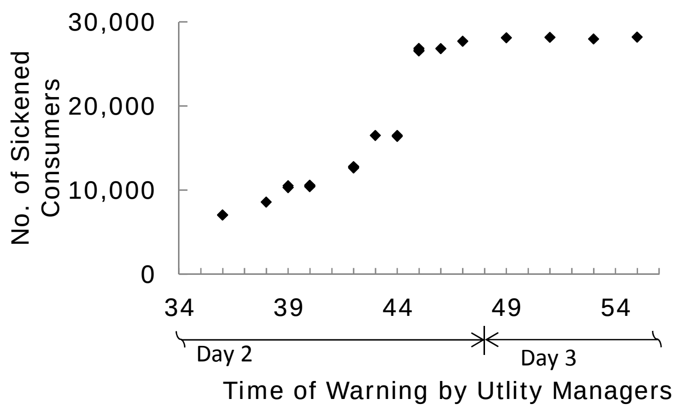

Figure 6. Number of sickened consumers as utility manager takes time to respond to warning of a threat.

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