Agent-Based Modeling to Simulate Contamination Events and to Analyze Threat Management Strategies in Water Distribution Systems

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Abstract

In the event of contamination of a water distribution system, decisions must be made to mitigate the impact of the contamination to protect public health. Making threat management decisions while the contaminant is spreading through the network is a difficult process due to uncertainty and lack of monitoring data. This is further complicated by the response actions taken by the utility managers and water consumption choices made by the consumers as they all will affect the hydraulics, thus the spread of the contaminant plume, in the network. A modeling framework that allows the simulation of a contamination event under the effects of actions taken by utility managers and consumers will be a useful tool for the analysis of alternative threat mitigation and management strategies. The complex interactions between the managers' network operation decisions and consumers' water consumption choices, and the response of the hydraulics and contaminant transport in the water distribution system will be simulated using an agent-based modeling approach. Agent-based models are simulated individuals that are formulated as interacting autonomous entities. Each agent selects actions based on a set of rules that represent an individual's autonomy, goal-based desires, and reaction to the environment and the actions of other agents. This paper presents a multi-agent modeling framework that will combine agent-based, mechanistic, and dynamic methods. As actions taken by agents affect demands and flows in the system, dynamic approaches will update the mechanistic model and the identification of the contaminant source to supply the "utility manager" agents with the latest information as it becomes available. The framework will be designed to consider the typical issues involved in water distribution threat management and will provide valuable analysis of threat containment strategies for water distribution system contamination events.

Introduction

Public utilities managers must be prepared for threatened and actual contamination of the drinking water supply, as contamination in a water distribution system will potentially result in wide-spread adverse public health consequences. Contamination can propagate rapidly through a system. Thus, once a contaminant has been introduced to the system, actions must be taken quickly to protect and minimize impacts on public health. Initial decisions, however, must typically be made with incomplete information concerning the credibility of the threat or spatial and temporal characteristics of the contamination. With these uncertainties, decisions-makers should act prudently to avoid false alarms and unnecessary interruption of water supply to fire departments and critical care facilities. Additionally, the management of a threat scenario is an interactive and continuous process (EPA, 2003). Decisions made to contain the contamination or influence the consumer's water usage will change the hydraulic conditions in the network, and a decision-maker must adapt a strategy to as the contaminant plume fluctuates with changing hydraulics.

Given these difficulties in making real-time decisions during a contamination incident, it would be beneficial to develop a priori a strategy for managing contamination threats. A strategy may be realized as a set of rules that prescribe actions corresponding to time-varying threat levels and sensor information. For example, EPA's Response Protocol Toolbox suggests that for a threat that is deemed "possible," appropriate response actions, such as site characterization or immediate operational response, e.g., such as hydraulic isolation of a tank (EPA, 2003), must be carried out. A threat management strategy may be constructed as a set of appropriate response actions corresponding to escalating levels of threat and system observations.

A threat management strategy can be evaluated through simulation and analysis of a set of contamination threat scenarios to assess its effectiveness in achieving objectives such as protecting public health and providing a safe supply of water for sanitation, consumption, and firefighting. This paper describes the concept of an integrated dynamic modeling framework to enable the identification of efficient threat management strategies for contamination of a water distribution system.

Problem Description

Under an unfolding contamination event, the interactions among the many key players in the system collectively influence the state of the contamination in the network, which recursively affects the reactions and responses of all the players. For example, Fig. 1 depicts the interaction of individuals, such as a perpetrator, water utility operations staff, utility manager, media, public health services, and consumers with a water distribution network during a potential contamination event. Each player receives information from others, takes actions that affect the hydraulics of the water distribution network, and passes on information to other parties. Utility managers receive information of a threat from, for example, the utility operations staff, public health services, or the media, and make decisions toward the protection of consumers by contacting the media or instructing utility operators to isolate portions of the system or control the flows in the network. Water usage will fluctuate significantly from typical levels due the reactions of consumer in response to, for example, a "do not drink" notice. As the hydraulics in the system is dictated by the demands of consumers, the spread of the contaminant plume will dynamically change with the varying demands. The shift in the contaminant plume may warrant reconsideration of management decisions about flow controls in the network, which will in turn affect the behavior of consumers. Additionally, more information, such as public health notifications and water quality sampling, will become increasingly available as time progresses. To more realistically evaluate management strategies that must be inherently adaptive, dynamic simulation between the actions and reactions of the different players and the propagation of the contaminant can be enabled through an integrated dynamic modeling framework. One approach to enable dynamic simulation is the use of a modeling framework that provides mechanistic modeling of the water distribution system and agent-based modeling of the influencing actors in the system.

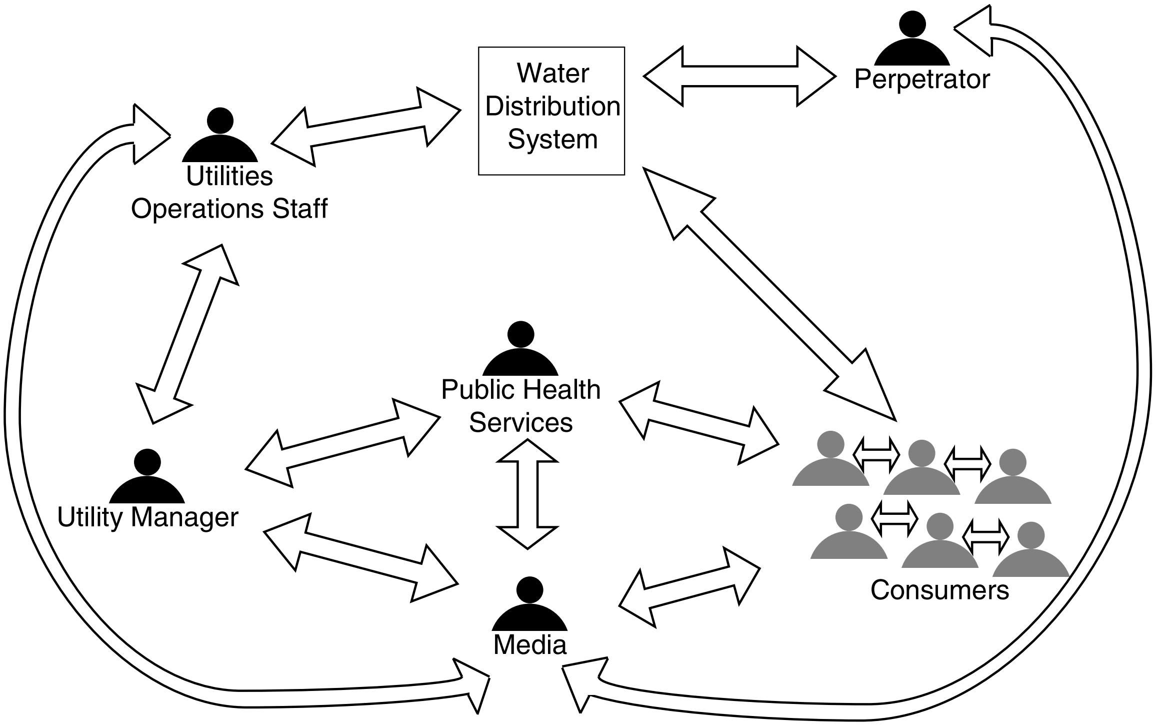

Figure 1. Water distribution system and the actors who interact with each other and the system to impact the effects of a contamination incident

Agent-based Modeling

Agent-based modeling is an approach to represent individual actors in a system for analyzing the emerging phenomena that result from the aggregate behavior of a population (see Wooldridge, 2002). An agent-based model (ABM) is typically a computer program that simulates a single actor that is situated within an environment. An agent receives information about its environment, has goals and is capable of taking action to change its environment and meet goals. Additionally, an agent can receive information from other agents and interact with them. ABM has been used in social sciences to represent individual people and simulate the behavior of human societies (Gilbert and Troizit, 1999). More recently, ABM has been applied in problems associated with managing natural resources (Hare and Deadman, 2004). For example, agents are used to model individual farmers to investigate viability of irrigation practices.

A few applications have demonstrated the use of agent-based modeling to simulate the interactions in a water distribution system. One study modeled households in a city as agents, and analyzed how the interaction among neighbors impacts the aggregate demand patterns after severe droughts (Edmonds and Moss, 2005). Other investigations used ABMs to simulate the engineer or manager of a water system. A water engineer was modeled as an agent who makes decisions based on demands to increase capacity of a water supply (Tillman, et al. 1999, 2001, and 2005). A second investigation modeled both a water manager and the consumers using ABM. The manager agent received demand data from consumers and meteorological data to determine water prices. Consumers received information from other consumers and economic information from the water supplier to adjust their demands for the future (Athanasiadis et al., 2005). These studies will provide insight into the effect of interactions among consumer agents on the emerging demand pattern of a community and will assist in building the modeling framework, as they provide examples of rules for utility manager and consumer agents.

Modeling Framework

A modeling framework is being developed to provide coupling of agent-based models with mechanistic models. Agent-based models are developed for the human actors, and a mechanistic model is used for simulating the water distribution system. The framework can be implemented, for example, using an object-oriented paradigm, in which each model will serve as an object that can communicate with other objects as appropriate. The framework also supports further development and inclusion of event detection algorithms, source identification algorithms, and optimization techniques for identifying optimal management strategies.

Illustrative Example

A specific instance of the modeling framework is described here for demonstration purposes. This instance provides the simulation of the interactions among a utility manager, consumers, and the water distribution system, as shown in Fig. 2. One utility manager agent and one water distribution system agent will be instantiated. A large number of consumer agents will be instantiated, where each agent represents one consumer or a collection of consumers.

An ABM for representing a utility manager consists of a set of rules that specify the next step of action for input. The rules for the utilities manager agent will be designed to achieve his goals, which are to protect the population from harmful contamination and avoid excessive shut-down of the water distribution system. Inputs to for utility manager agent will be information from the water distribution system, such as concentration of contaminants at sensors in the network, and complaints of illness from consumers. The output of the utility manager agent corresponds to the action of a typical utility manager, such as isolating a portion of the system or releasing a public health notification to consumers. An example of a rule for the utility manager agent is as follows: if the number of consumer complaints is greater than a pre-determined threshold, or if the severity of the health impacts of consumer sickness is greater than a pre-determined threshold, then additional water quality samples will be collected at nearby nodes in the water quality network.

An ABM will also be used to represent each individual consumer, such as a household or a neighborhood. Each consumer agent is associated with a spatial location or node in the network where demands are withdrawn, and, similar to the utility manager, the consumer will be modeled using a set of rules. The goals of the consumer are to avoid illness from contamination and expect a regular withdrawal from the water network. The consumer agent will receive inputs, such as information from public officials, information from neighboring consumers, or incidents of poisoning from the drinking water system. Upon receiving any combination of these inputs, the output of the agent will be actions such as refusing consumption of water, continuing to withdraw from the system, or complaining to the utility manager agent. As two consumers may react differently to the same information or receive different amounts or types of information during a scenario, the actions of consumer agents will be modeled probabilistically to represent the unpredictability of human decision-making.

Mechanistic models are readily available for simulating the hydraulics and chemical transport in a water distribution system. Pipes, hydraulic characteristics, and typical demand patterns will be specified in the water distribution model before a contamination event is simulated. The outputs of the water distribution model will be used as the simulated contaminant concentration values at sensor locations and nodes.

Threat Scenario Simulation. To initiate a contamination event simulation, a contaminant is simulated as entering the system that is operating under typical system operation and demand conditions. The simulation will proceed in discrete time intervals corresponding to the hydraulic time steps as specified in the water distribution model description. At the end of the first time step, the consumer agents and the utility manager agent request information from the model. For example, the utility manager agent may query the water distribution model for water quality measurements at sensors. A consumer agent that has a non-zero demand for that time step will receive information of the quality of the water that has been consumed and will assess its own level of health. The consumer agent will pass complaints of sickness to the utility manager agent. Upon receiving either complaints from the consumer agent or alarming water quality observations from the water distribution model, the utility manager agent may issue directives to control the flow through actions such as system isolation through valve closure or bypassing a segment of the network. These changes will be written to update the inputs of the water distribution network model for simulating the conditions in the subsequent time step. The utility manager agent may also communicate information of a contamination event to consumer agents. A consumer agent that receives information such as a “do not drink” notification from the utility manager agent would change its consumption, affecting the demand, which will be updated in the subsequent time step to the input of water distribution model. This process will iterate until the contaminant has been flushed from the system.

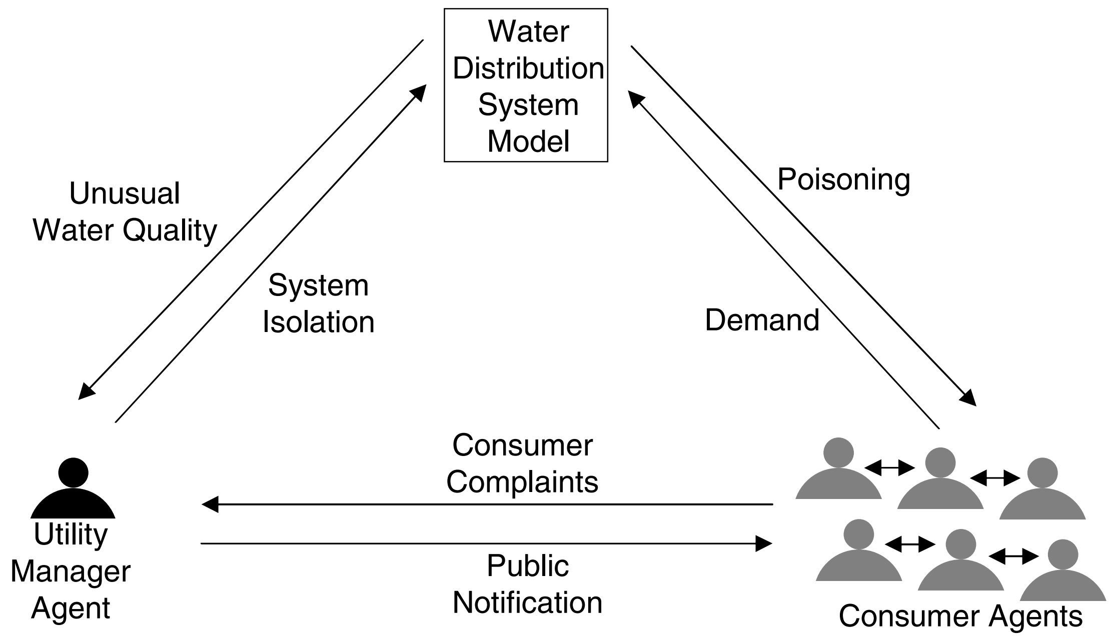

Figure 2. Interactions among a decision-maker, consumers, and the drinking water system.

Threat Scenarios and Metrics. A set of metrics will be defined to evaluate a threat management strategy. In a contamination incident, the primary objective of public officials and utility managers is to protect public health. EPA (2003) has suggested metrics for consequence analysis, such as the number of individuals affected, which is related to the spread of the contaminant and the population exposed to the contamination. An alternative metric for health protection is the severity of the health impacts due to the type and concentration of the contaminant. As the overall mission of a drinking water utility is to provide safe drinking water for a range of purposes, we will use a second metric that will measure the impact of a strategy on the normal water usage of consumers. A metric can be defined to capture the amount of service outages and reductions in pressure. Metrics for both health protection and the interruption of normal water delivery will be included in the analysis to evaluate the overall effectiveness of alternative strategies.

Additionally, to evaluate a management strategy, a set of threat scenarios should be simulated to represent the range of threat levels. Contamination sources should be simulated in different locations in the network and at various times of day. A range of threat levels and false alarms should also be simulated. A conservative strategy is expected to perform well to protect public health for scenarios of high threat levels; however, if the strategy were analyzed for a false alarm, it would unnecessarily impact the delivery of water without achieving incremental health protection. As there is some randomness in the actions of consumers and decision-makers, each threat scenario should be executed for a number of random seeds. The overall or average performance for a set of random trials for a set of threat scenarios will be used to determine the effectiveness of a threat management strategy.

Discussion and Framework Extensions

The modeling framework described above will provide the ability to evaluate management strategies under simulation of more realistic interactions. To fully simulate a contamination incident, additional algorithms will be integrated into the modeling framework, as utility operations staff will likely use event detection algorithms and utility managers would use source identification techniques in reacting to a contamination event.

While the described framework will provide the ability to evaluate and compare a set of alternative strategies, future work will incorporate optimization methods to search for and identify optimal management strategies. Optimization techniques will be developed and applied to identify management strategies that will perform robustly for a range of contamination threats. Evolutionary computation-based methods for symbolic searches will be used to evolve a set of rules as a management strategy to optimize the different performance metrics.

Additional work will specify the perpetrator as an ABM whose contamination strategy would be interactive and composed of a set of rules to achieve the perpetrator's goals. Co-evolutionary algorithms would be used to evolve the perpetrator's strategy simultaneously with the utility manager's strategy in a competitive co-evolutionary experiment. A simulation of the arms race between the utility manager and the perpetrator would allow the emergence of increasingly sophisticated and complex strategies for threat management.

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