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A dynamic simulation–optimization model for adaptive management of urban water distribution system contamination threats

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ABSTRACT

Urban water distribution systems hold a critical and strategic position in preserving public health and industrial growth. Despite the ubiquity of these urban systems, aging infrastructure, and increased risk of terrorism, decision support models for a timely and adaptive contamination emergency response still remain at an undeveloped stage. Emergency response is characterized as a progressive, interactive, and adaptive process that involves parallel activities of processing streaming information and executing response actions. This study develops a dynamic decision support model that adaptively simulates the time-varying emergency environment and tracks changing best health protection response measures at every stage of an emergency in real-time. Feedback mechanisms between the contaminated network, emergency managers, and consumers are incorporated in a dynamic simulation model to capture time-varying characteristics of an emergency environment. An evolutionary-computation-based dynamic optimization model is developed to adaptively identify time-dependant optimal health protection measures during an emergency. This dynamic simulation–optimization model treats perceived contaminant source attributes as time-varying parameters to account for perceived contamination source updates as more data stream in over time. Performance of the developed dynamic decision support model is analyzed and demonstrated using a mid-size virtual city that resembles the dynamics and complexity of real-world urban systems. This adaptive emergency response optimization model is intended to be a major component of an all-inclusive cyberinfrastructure for efficient contamination threat management, which is currently under development.

1. Introduction

Safe and reliable drinking water is vital to every community. Approximately 90% of the US population receives water from one of 170,000 public water utilities. These drinking water distribution systems (WDSs) are inherently vulnerable to natural or malicious contamination because of their ubiquity, multiple points of access, the aging infrastructure, and the increased risk of terrorism. Chemical or biological contaminates may be introduced to a water distribution systems accidentally through treatment plants malfunction, backflow events, cross-connections, etc. or intentionally via the acts of malevolence, vandalism, etc. [1]. The plethora of past contamination incidents and foiled attempts further demonstrates the vulnerability of municipal water supply systems [2,3]. Title IV of the Public Health Security and Bioterrorism Preparedness and Response Act of 2002 [4] mandates all community water systems that serve more than 3300 people to prepare or revise emergency management plans.

WDS contamination emergency management is based on risk assessments and includes four major phases of hazard mitigation, emergency preparedness, emergency response, and disaster recovery [5]. This study is particularly more focused on emergency response phase. A contamination emergency response phase is initiated when an actual (or potential) injection of contaminant is propagated (or will propagate) over a WDS, and it extends until the situation is stabilized (e.g., when the risk of health consequences has returned to normal conditions). Emergency response decision aid tools have been devised in previous studies to assist water utility operators in making better decisions for public health protection against contamination events. Genetic algorithms (GA), decision trees, and heuristic approaches have been used for guiding contaminant containment and flushing operations [6–8]. Agent-based models have been developed and coupled with a GA to optimize

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routing of siren vehicles to best warn and protect consumers from exposure [9,10]. Multiobjective simulation–optimization has been applied to help utility operators achieve conflicting response objectives such as health protection and WDS service interruption prevention [11–16].

Previous studies have generally applied static optimization approaches to find optimal response protocols on the implicit assumption that the optimization problem is fixed during the course of an emergency. From an optimization perspective, this assumption implies that the response optimization fitness functions (e.g., minimization of ultimate health impacts) are temporally constant. In other words, fitness of a particular response protocol is not changing during the optimization process once it is started. In reality, however, the fitness functions are feedback-influenced by many uncertain and dynamic factors, i.e., projected spread of contaminant and actions taken by the utility operators and consumers [17,18]. Under the effect of these unpredictable factors, the search domain may repeatedly change over time, and the current best response protocol might be no longer optimal moments later. The decision support model should thus explicitly account for this unpredictably time-varying system behavior to accurately reproduce the reality and identify best contamination impact reduction decisions in a timely manner.

Dynamic optimization has been successfully applied in different disciplines for solving optimization problems in changing environments. Dynamic optimization methods methodically exploit and transfer useful knowledge from older environments and maintain adaptability to guide and speed up the exploration in emergent environments [19,20]. Some recent successful applications include products pricing [21], contaminant source characterization [22], vehicle routing [23], military mission planning [24], electric power supply optimization [25], video-based face recognition [26], and dynamic traveling salesman problem [27]. Despite this rich record of successful applications, however, dynamic optimization has not been employed to solve the crucial problem of dynamic water contamination emergency management yet. This study focuses on this unexplored research area and develops dynamic simulation–optimization models for adaptive management of drinking water networks contamination emergencies.

We investigate the application of dynamic modeling for adaptive emergency response to disasters in the scope of drinking WDS contamination events. A dynamic simulation–optimization scheme is developed to identify and track time-dependant optimal response protocols to provide emergency managers with adaptive decision support in real-time. The adaptive simulation model accounts for multiple uncertainty factors that contribute to the unpredictable time-varying system behavior, including time-dependant perceived contamination source attributes, consumers' actions, and emergency response operations. This dynamic optimization scheme uses an evolutionary-computation-based multiobjective approach, which methodologically preserves diversity in the search process for enhanced adaptation against the effect of changes.

In what follows, the structure and elements of the dynamic simulation model developed to simulate the dynamic emergency environment are first described. These comprehensive descriptions are mainly intended for readers with insufficient background on WDS hydraulics and security. This is followed by the formulation of the time-varying optimization fitness function and decision variables and a brief overview of existing dynamic optimization techniques. The evolutionary-computation-based algorithm used here for the dynamic optimization of health protection response protocols is then described. The proposed adaptive simulation–optimization model is then evaluated and discussed on a virtual city, Mesopolis, which possesses the spatial and temporal complexity of real-world cities. The results are analyzed to illustrate the system behavior during an emergency and investigate model performance. The paper concludes with a number of recommendations for enhancing applicability and efficiency of the proposed decision support model in the future.

2. Dynamic emergency environment simulation

A WDS contamination emergency threat starts with an actual (or potential) release of contaminant that propagates across the network, and it extends until the risk of health impacts has returned to pre-event levels. Under an unfolding contamination threat, the system might exhibit an uncertain and irregular behavior that could radically deviate from normal operation conditions. Knowledge of contaminant source attributes that dictate emergency response decisions evolves as more information streams in over time. As the event progresses, emergency managers take response actions based upon their current knowledge of the state of the system and these actions change the state of the contamination in the WDS and alert consumers. Alerted and exposed consumers may subsequently alter their water consumption choices, which consequently affect network hydraulics and contaminant plume spread [17]. Conceptualizing and modeling these different sources of variability is crucial for realistic simulation of system behavior and effective reduction of contamination impacts.

This section first defines a contamination scenario and how the emergency managers' perception of an occurred scenario evolves as more information streams in over time. Then, it describes the two particular emergency response mechanisms considered in this study (i.e., contaminant flushing through opening hydrants and public warning through food-grade dye injection) and how their implementation contributes to the system dynamics. It is followed by a description of consumers' behavior during a contamination emergency and its influence on the state of the contamination and health consequences. The last part of this section describes the hydraulic model used in this work to simulate WDS hydraulics and contaminant propagation during a contamination event.

2.1. Perceived contamination scenario updates

A contamination scenario is defined by a set of attributes (e.g., contaminant injection location and duration) and corresponds to a specific level of ultimate consequences [28]. The attributes of a contamination scenario are estimated through integrated assessment of different system observations and evidence. This information may stream from physical security alarms, supervisory control and data acquisition (SCADA) system, and consumers' complaints. Bayesian and optimization models can be applied to process the streaming data in real-time and update estimated scenario attributes using existing and incoming information [22,29–32]. Helpful guidelines and information on WDS sensor technology and networks can be found in [33,34].

Since the perceived contamination scenario dictates the effectiveness of the health protection strategies taken, the optimization process needs to adapt to scenario updates to be capable to continuously track the optimum in a time-varying search space. Perceived scenario attributes are thus treated here as time-varying parameters opposed to past studies that assume the perceived contamination scenario is fixed while the optimization is being performed. It should be emphasized that the *true* contamination scenario has already occurred and is thus not time-varying, but it remains unknown to the emergency managers. During the course of an emergency, the streaming data is processed adaptively at every stage and perceived contamination scenario is updated to better estimate the true scenario.