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Drinking water distribution systems contamination management to reduce public health impacts and system service interruptions

Amin Rasekh*, Kelly Brumbelow

Zachry Department of Civil Engineering, Texas A&M University, 3136 TAMU, College Station, TX 77843-3136, USA

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ABSTRACT

Decisions on protecting public health against drinking water systems contamination threats should be made with careful consideration of credibility of threat observations and adverse impacts of response on system serviceability. Decision support models are developed in this study to prepare water utility operators for making these critical decisions during the intense course of an emergency. A pressure-dependent demand model is developed to simulate the system hydraulics and contaminant propagation under pressure-deficit conditions that emerge after the response actions are executed. Contrary to conventional demand-driven models, this hydraulic analysis approach prevents potential occurrence of negative pressures during the simulation and may identify better response protocols through exploring a larger search space. Response mechanisms of contaminant containment and discharge are optimized using evolutionary algorithms to achieve public health protection with minimum service interruption. Sensitivity analyses are conducted to assess optimal response performance for varying response delay, number of hydrants, and intrusion characteristics. Different methods for quantifying impacts on public health and system serviceability are explored and the sensitivity of the optimal response plan to these different formulations is investigated. The simulation-optimization schemes are demonstrated and discussed using a virtual water distribution system.

1. Introduction

Aging drinking water infrastructure and increased risks of terrorism have intensified concerns for vulnerability of water distribution systems (WDS) to accidental and intentional contamination. A contamination event may cause health and sociopolitical impacts, erode public trust, and interrupt system operation. To effectively cope with these threats, there is a need to prepare contamination emergency management plans that describe the actions a drinking water utility should take in preparation for and in response to a contamination threat or incident. An emergency management plan should be based upon careful risk assessments and cover the four phases of hazard mitigation, emergency preparedness, emergency response, and disaster recovery (Lindell et al., 2006).

A contamination emergency response phase is initiated with an actual (or potential) release of contaminant that spreads across a WDS, and it extends until the situation is stabilized (i.e., when the risk of health impacts has returned to pre-event levels). An emergency response protocol explains actions that managers may take in response to the perceived state of the system after the emergency begins, and it considers how best to achieve managers' multiple objectives. These response actions can be classified as "assessment," "preventive," or "protective" actions, depending on whether they collect information about the state of the system, operate on the system to decrease impacts, or require action by the public to reduce exposure, respectively (Perry and Lindell, 2007).

Title IV of the Public Health Security and Bioterrorism Preparedness and Response Act of 2002 (United States Congress, 2002) requires all community water systems serving a population greater than 3300 in the United States to prepare or revise emergency response plans. The Response Protocol Toolbox (RPT) has been prepared by the United States Environmental Protection Agency (USEPA, 2003) to help water utilities meet this requirement. It provides general guidelines on how response decisions should be made at the various stages of a contamination event as more information is collected. Because this toolbox is essentially a qualitative document, however, it does not provide specific guidance on how appropriate response strategies should be devised for a particular WDS. This study develops quantitative simulation-optimization models to prepare emergency response protocols that specify functional

* Corresponding author. Tel.: +1 979 739 9652; fax: +1 979 862 1542.
E-mail addresses: aminrasekh@tamu.edu (A. Rasekh), kbrumbelow@civil.tamu.edu (K. Brumbelow).

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contaminant containment and flushing operation rules for the achievement of conflicting response objectives.

2. Problem statement and solution approach

Emergency response is a progressive, interactive, and adaptive process that includes parallel activities of assessing unusual contamination observations and making appropriate emergency response decisions. As more information is obtained about contamination, emergency management progresses through three threat stages of “possible,” “credible,” and “confirmatory” (as described in RPT) accompanied by an increase in seriousness of the threat impacts and magnitude of response decisions. While public health protection is the primary response focus, emergency management should carefully consider other potential consequences on infrastructure serviceability due to response implementation, specifically in the early stages of the process where the attack credibility level is relatively low. At this stage, a multiobjective response plan is useful to identify the balance between actions taken to protect public health against a potential threat and limiting overaction that adversely impacts the ability of the system to meet multiple aspects of its overall mission. Nevertheless, if streaming threat information and observations corroborate occurrence of a contamination event, minimizing potential health impacts becomes the sole primary objective that should be sought for. Under these circumstances, the large size of multiobjective optimization results may not be decipherable for making timely emergency decisions and use of a single-objective model may become preferable.

To date, limited research has addressed this multicriteria nature of the contamination emergency response problem (Preis and Ostfeld, 2008; Alfonso et al., 2010). Multiobjective frameworks proposed so far have only considered hydrant and valve locations as decision variables and have not optimized the operation timing. While these studies have considered the number of operational actions as an emergency response criterion, the important criterion of system service interruption has not been explicitly addressed. Moreover, previous single and multiobjective studies have used demand-driven analysis (DDA) to simulate WDS behavior, and this assumption inevitably limits the optimization search space to response protocols that do not cause excessively low pressure in the WDS. This may unfavorably filter out many possible response protocols with a high potential for reducing the health impacts.

In the light of these needs, this study develops and integrates a hydraulic pressure-dependant demand model (PDDM) and evolutionary optimization schemes to find the optimal emergency response protocols with explicit consideration of two important response criteria: (1) public health impacts, and (2) system service interruption. Emergency response is treated as both single and multiobjective optimization problems to address utility managers’ needs under different conditions. Operational rules for contaminant containment and discharge locations and timing are explicitly treated as optimization decision variables. Sensitivity analyses are performed to provide insight into effective response protocols and assess sensitivity of optimal protocols to different parameters such as response delay. Different formulations for quantifying impacts on public health and service availability are examined with the help of the PDDM and an exposure model. Performance of the proposed schemes is investigated using the WDS of Mesopolis virtual city, which resembles the interdependency and interconnectedness of real—world complex water distribution networks.

3. Model development

Contamination scenario and the simulation and optimization models will be described in this section. Different attributes of a contamination scenario which is treated as a model input here are explained and a series of existing contaminant source identification methods are introduced. This is followed by a detailed description of the pressure-dependant demand and exposure models for the simulation of contamination events under pressure-deficit conditions. Optimization objective functions and decision variables are then explained along with an overview of the evolutionary-computation-based optimization algorithms used in this study.

3.1. Contamination scenario

Optimization of emergency response protocols needs to be performed for a given WDS contamination scenario, which is defined by a set of attributes including: (1) site(s) of contaminant intrusion, (2) contaminant type, (3) contaminant mass, (4) time of year, (5) the time of day the contamination event is started, and (6) the intrusion duration (Rasekh and Brumbelow, 2013). The simulation-optimization models developed here treat the contamination scenario as input information. This scenario could be a potential critical and base scenario for which the response protocols need to be optimized before an emergency occurs (Perelman and Ostfeld, 2010; Rasekh and Brumbelow, 2013). Alternatively, it can be a scenario that is occurring and being characterized by applying a contaminant source identification model (Preis and Ostfeld, 2006; Zechman and Ranjithan, 2009; Hart et al., 2009; Liu et al., 2011a; Rasekh and Brumbelow, 2012; Gugat, 2012; Shen and McBean, 2013) linked with the sensor network (Ostfeld et al., 2008; Janke et al., 2009). Therefore, the simulation-optimization models developed here can be employed after the potential critical or design basis scenarios have been characterized during the emergency preparedness phase or a real contamination scenario has been identified during a contamination emergency.

3.2. Hydraulic simulation under pressure-deficit conditions

Behavior of a WDS under normal operating conditions is most commonly simulated using standard DDA models like EPANET (Rossman, 2000) for design, operation, and rehabilitation purposes. DDA models are formulated on the premise that nodal water demands are known and completely met during the simulation period so that nodal pressure and pipe flows can be calculated by solving a system of quasi-linear equations (Wu et al., 2006). Projections of network behavior that are based on DDA are reasonably accurate under normal conditions when pressures are sufficiently high. Under abnormal pressure-deficit conditions caused by emergency response actions, however, DDA may illustrate a distorted image of the true system behavior.

A standard DDA solves a system of energy and continuity equations to calculate unknown nodal heads and pipe flow rates (Todini and Pilati, 1988; Rossman, 2000). This system of equations may be extended to include pressure-dependant demand functions (PDDF) as well to relate pressurized water availability to existing nodal head under pressure-deficit conditions (Laucelli et al., 2012). Full pressure-driven analysis approaches solve this extended system of equations simultaneously to determine unknown nodal demands, nodal heads, and pipe flow rates (Laucelli et al., 2012). Alternatively, the standard DDA model may be iteratively run and nodal demands are updated sequentially after each iteration using the PDDFs until a satisfactory convergence is achieved (Liu et al., 2011b; Jun and Guoping, 2013; Kanta and Brumbelow, in press). This modeling approach is used in this paper. A major advantage of this approach is that it allows benefiting from the computational efficiency and robustness of hydraulic and quality simulators of the well-established EPANET software. The fact that many existing