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Actuator network design to mitigate contamination effects in Water Distribution Networks

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ABSTRACT

Water Distribution Networks (WDNs) are vulnerable to accidental or deliberate contamination. Such contamination can be detected and identified by deploying a network of sensors. If the sensor network detects the presence of a contaminant, it is also very important to take corrective response actions to minimize the effects of contamination on the population being served. One possible mitigation option is to prevent the contaminated water from reaching any customer, by shutting down the distribution network using shut-off valves placed in the WDN. The design problem considered in this work is to determine pipes where the shut-off valves can be optimally located such that it is possible to prevent the contaminated water from reaching any demand point, regardless of the source node from where the contamination has originated. We refer to this problem as the actuator network design problem. We map the problem of actuator design into a graph partitioning problem and the minimal set of actuators are identified for ensuring the total shutdown of the network.

Nomenclature

A_j	actuators obtained for sensor response j
D	demand nodes
D'	contaminated demand nodes
D''	uncontaminated demand nodes
D'_j	contaminated demand nodes that have directed path from S_j
D''_j	uncontaminated demand nodes with respect to S_j
S	source nodes
S'	maximum possible contaminated nodes
S_j	attacked vulnerable nodes for sensor response j
S'_j	contaminated nodes for sensor response j

1. Introduction

Water Distribution Networks (WDNs) are composed of a large number of interconnected pipes, reservoirs, pumps, valves and other hydraulic elements. The primary purpose of a WDN is to deliver water from sources such as reservoirs, rivers, lakes, and tanks to the consumers for different purposes. The topology of the network, number of consumer nodes, loading conditions, hydraulic elements, etc. make the control of a water distribution system a difficult task and makes it highly vulnerable to contamination (Kessler et al., 1998). WDNs are often susceptible to either accidental or intentional contamination. Accidental contamination occurs due to system deficiencies (e.g., cross connections, pipeline breakage) and intentional contamination occurs as a result of deliberate acts of chemical or biological intrusions. Introduction of chemical or biological agents in aWDN can damage public health. After 9/11 attacks in United States, the concern over possible terrorist attacks on WDNs has increased and can be considered as the most serious threat to WDNs (Ostfeld et al., 2008). In order to respond to such attacks, it is necessary to design a sensor network, which is capable of detecting and identifying contaminants as quickly as possible. The contamination events are detected by deploying sensors that monitor water quality parameters at appropriate locations in a WDN. Once the deployed sensors detect the presence of contaminants it is necessary to take corrective response action in order to mitigate the contamination effects.

The problem of contaminant detection in WDNs and appropriate response to a contamination event has been addressed in literature. Numerous procedures are available in the literature for the contamination detection problem. However, very few studies are

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available with respect to the problem of response to contamination events. Several optimization algorithms have been proposed for the problem of sensor placement for contamination detection in WDNs. Single objective optimization problems (Kessler et al., 1998; Lee and Deininger, 1992; Berry et al., 2005; Kumar et al., 1997) are solved by considering objectives for maximizing the demand coverage, maximizing the likelihood of detection and minimizing the elapsed time between the injection and detection of contaminants. Further, multi-objective optimization problems (Ostfeld et al., 2008; Rico-Ramirez et al., 2007; Preis and Ostfeld, 2008; Watson et al., 2004) have been solved by considering objectives for minimizing the time of detection, minimizing the contaminated volume consumed prior to detection, population at risk, etc. The problem of contamination source identification based on deployed sensor measurements has been reported (Mann et al., 2012; Laird et al., 2005). Recently, the problem of sensor placement, which ensures observability and identifiability conditions has also been studied by Palleti et al. (2016).

Although, design of a sensor network to detect and identify intentional contamination of a WDN is important, it is also necessary to consider the potential action that one can take to mitigate the effect of the contaminant. Once the sensor network detects the presence of a contaminant, U.S. Environmental Protection Agency's (USEPA) response protocol toolbox (USEPA, 2004a) provides recommendations for implementation of specific responses to minimize the effect of contamination event. This protocol includes the detection, source identification followed by consequence management strategies. Various researchers have developed methodologies related to the detection and source identification problems as described earlier. Once a contaminant has been detected, water utilities must evaluate the response to the contamination so that potential impact to the public can be minimized. These consequence management strategies may include: (1) public notification, (2) isolation and containment of a contaminant through valve operations (USEPA, 2004a), (3) flushing the contamination system, and (4) combinations of isolation, notification, and flushing (USEPA, 2004b). Very few studies are available with respect to the mitigating actions that would be taken after detecting the presence of contaminant in the WDN (Poulin et al., 2008, 2010; Preis and Ostfeld, 2008; Guidorzi et al., 2009; Alfonso et al., 2010). Heuristic procedures are proposed for isolating a contaminated area through the simultaneous closure of a number of valves in the system, assuming an unlimited number of response teams and subsequent removal of the contaminant by unidirectional flushing (Poulin et al., 2008, 2010). Preis and Ostfeld (2008) proposed a multi-objective approach with the aim of minimizing the number of operations to be performed and to reduce the consumption of contaminated water by consumers for a given specific contamination event. Such an approach is useful only when complete knowledge of the contaminant history is known (in terms of intrusion location, duration and quantity of contaminant injected). Similarly, multi-objective procedures were proposed to identify the minimum number of operations that minimize the contaminated water consumption (Guidorzi et al., 2009; Alfonso et al., 2010). These approaches (Guidorzi et al., 2009; Alfonso et al., 2010) have not considered the characteristics of the contamination event (i.e., location, duration and quantity of contaminant introduced). Later, the problem of optimal scheduling of device activation in order to minimize the consumption of contaminated water after the detection of a contaminant has been studied by Alvisi et al. (2012).

The previous studies focused on operational strategies to be implemented in the event of a contaminant detection assuming that valves are already present in the network. The design problem of optimal valve placement to minimize the effects of contamination events has not been reported in the literature. The design problem considered in this work is to determine the pipes where shut-off valves (the term 'actuators' is used interchangeably with valves in this work) can be optimally located such that it is possible to prevent the contaminated water from reaching any demand point, regardless of the source where the contamination has originated from. Naturally, the shut-down action can be initiated only after one of the sensors detects that the WDN is contaminated. For the purpose of actuator network design, we assume that the sensor network design has already been carried out and locations of sensors are known *a priori*. The objective of this paper is to determine the minimum number of shut-off valves to be used and their appropriate locations for a given sensor network design. We refer to this problem as the actuator network design problem for a WDN. Although the actuator design problem has been well reported for different domains (Padula and Kincaid, 1999; Chmielewski et al., 2002), a technique for identifying actuator locations in WDNs is not yet available. These actuators can be used to enforce a shutdown of the network by isolating the source nodes from the demand nodes following a sensor response so as to prevent further spread of the contaminant. Graph theoretic approaches have already been demonstrated to be useful in the instrumentation of networks, be it process or water (Nguyen and Bagajewicz, 2008; Bhushan and Rengaswamy, 2000; Chang et al., 2012). Here the actuator placement problem is mapped to a graph partitioning problem such that all source nodes are in one set (partition), and all demand nodes are in another set. Specifically, graph partitioning has been extensively studied to meet different objectives in other applications (Bichot and Siarry, 2013). We formulate an integer linear program of the graph partitioning problem specific to our design problem, whose solution gives the pipes where actuators have to be located. By activating these valves, it is possible to shut-down the network and prevent water from being supplied in the event of an alarm raised by any sensor.

The organization of this paper is as follows. Section 2 describes the mathematical formulation for the actuator network design problem. In this section, a binary integer linear program (BILP) is formulated by mapping the actuator network design problem into a graph partitioning problem. Section 3 explains the methodology for the design of actuator network based on two different assumptions on the flow of contaminated water after a shutdown of the valves is implemented. In Section 4, the design of actuator network for the different assumptions is demonstrated on a real urban WDN. The conclusions and future research directions are discussed in Section 5.

2. Problem formulation

A water distribution network can be represented as a graph, $G = (V, E)$, where E represents the edges, and V represents the vertices or nodes. Nodes are used to represent sources, such as reservoirs or tanks, from where water is supplied, as well as demand points where water is consumed. Nodes are also used to represent fire hydrants. The points where two or more pipes meet or where a pipe divides into several branches are represented as nodes. Pipes, valves and pumps are represented as edges in the graph. A real life WDN can consist of several hundred nodes and pipes. Typically, nodes representing sources or fire hydrants are potentially vulnerable sites for intentional contamination, whereas unintended chemical or biological contamination can occur at any point in the WDN. In the current work, we consider main or intermediate reservoirs, tanks, valves, deep wells, water treatment plants, pumping stations and fire hydrants as potential sites of intrusion. The above sites in a WDN are the most vulnerable and can be accessed relatively easily and contaminated by deliberate acts of terrorism.