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Incorporating operational uncertainty in early warning system design optimization for water distribution system security

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Abstract

Incorporating a system of monitoring stations to insure high quality water is being delivered to consumers has been acknowledged a crucial component required by any public water distribution system (WDS). Extensive studies have acknowledged the risk posed to large populations by an accidental or intentional contamination intrusion within a WDS; failure of an early warning system (EWS) to report a contamination event carries profound economic and public health consequences. Dynamic, stochastic conditions exist in municipal WDSs and a monitoring system needs to be designed according to a robust protocol that incorporates the inherent uncertainty in WDS operation, including: demand variability, and contamination event characteristic variability. This work composes the problem of locating the best junctions within a WDS to place fixed monitoring stations, and the best junctions to input innovative inline mobile sensors, in a multi-objective framework that incorporates uncertainty in the network's demands and EWS operation. Mobile sensors are carried by flow within pipes sampling and monitoring water quality in real time, and wirelessly uploading data to fixed transceiver beacons, providing an implicit preference towards demand dense regions. A multi-objective noisy messy genetic algorithm is structured to the problem at hand and employed on a small, medium, and large-scale model WDS to calculate near-optimal solutions from the large solutions space. This multi-objective framework provides high performing trade off (Pareto) sets comparing an EWS's system cost to numerous performance objectives incorporating non-deterministic objective functions to provide a high performing and resilient EWS. Results show a large trade off surface between the cost and the respective system's performance, with large diminishing returns. Although implementing a more expensive solution may provide little to no benefit from a traditional performance standpoint, implementing a system of higher cost can increase the systems resiliency, highlighting the importance of incorporating proper objective measures in optimization procedure.

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1. Introduction

1.1 Problem Statement

Operational characteristics of a water distribution system (WDS) are inherently uncertain. Variability in consumer demands propagates variability in network pressure distributions, and thus network flow rates. Variability in pressures requires robust design of network infrastructure to accommodate uncertain network pressure distributions. In the event that a harmful contaminant is introduced in to a network, an early warning system (EWS) needs to be designed to protect consumer demands according to uncertainty in the operational characteristics of the network. Uncertain demands may be caused by an abnormal number of consumers present at a given node, out of date network data, or simply model inaccuracy to operating conditions. These conditions make populations vulnerable to a contaminant if an early warning system was designed within a deterministic framework. Larger pipe velocities may transport a portion of a contaminant plume faster through a network than expected and greatly increase adverse effects of a contamination intrusion.

In this work, classical contamination sampling procedure is augmented to be posed in an uncertain framework. In this work contamination events are sampled and for each event sampled, network demands are varied randomly to determine the variability in the population affected by a contamination event. A new evaluation metric is introduced, modified from the previous work of [1] to evaluate an EWS according to the variance in the affected population of a given contamination event. A maximum allowable affected population is assigned to the network, i.e. 1% of the network population, and a safety factor is assigned according to the calculated variance in the network's affected population. The objective function then reports the magnitude of the population affected which violates the maximum allowable population affected, minus a safety factor for any given contamination event. Contamination events especially sensitive to network demand variation yield increased variance and consequently a larger factor of safety is imposed on the allowable population affected.

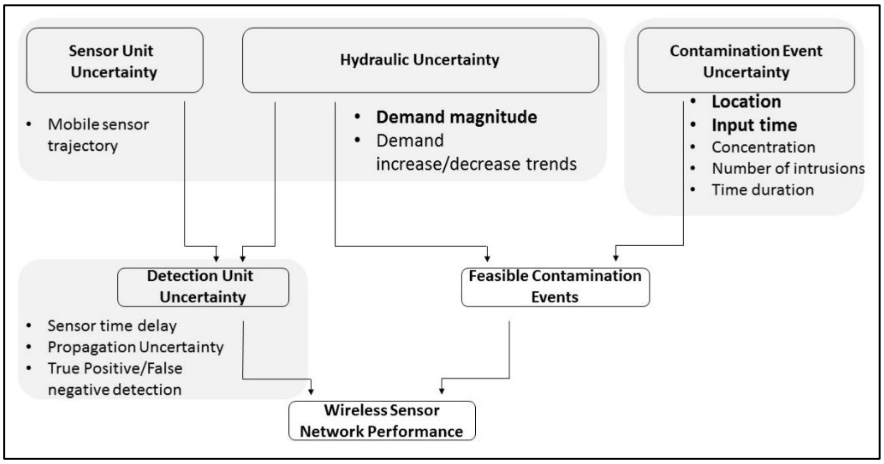

Figure 1: Current uncertainty architecture with in the proposed water security problem. Bold uncertainty sources are addressed in this work.

A multi-objective genetic algorithm is employed to determine the best protocol for: placing fixed water quality sensors throughout a WDS, for input of inline mobile water quality sensors in a WDS, and a degree of network coverage by wireless transceivers to wirelessly communicate with mobile sensors, to minimize a network's population affected violating a network safety factor while minimizing an EWS implementation cost. Multiple sensitivities are analyzed to measure the magnitude of the safety factor, the nodal demand variability, and algorithmic operators. The simulation and optimization are then performed on a case study network.