Using TEVA to Assess Impact of Model Skeletonization on Contaminant Consequence Assessment and Sensor Placement Design

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1.0 INTRODUCTION:

Drinking water systems are known to be vulnerable to contamination by toxic substances, whether the contaminants are introduced intentionally during a terrorist attack, or unintentionally through accidental cross-connections or backflow incidents. Understanding the vulnerability of drinking water distribution systems to contaminant intrusion is currently a major research focus within the federal government and across the water community. The EPA's National Homeland Security Research Center (NHSRC) developed the Threat Ensemble Vulnerability Assessment (TEVA) Research Program to analyze the vulnerability of drinking water distribution systems to contaminant threats and develop a methodology to design Contamination Warning Systems (CWS). The TEVA Research Program, the NHSRC and its collaborators at the University of Cincinnati, Argonne National Laboratory, Sandia National Laboratories developed software that accomplishes this task. The software tool uses quantitative health impacts data from probabilistic or exhaustive consequence assessments to optimally locate and evaluate CWS designs for a drinking water distribution system.

Both the characterization of the potential impacts from contaminant attacks and the designing of CWS rely on calibrated hydraulic models developed by the water community for modeling and simulating contaminant transport. Distribution system models, however, vary widely in detail and, therefore, their representation of the actual system also varies. A complete representation of the distribution system model, especially given any large or even medium-sized city, can be enormously complex and very difficult to model. As a result, "s*keletonization"* is the process most often used to select the most significant attributes of the hydraulic network that accurately represent the behavior of the system. The underlying assumption is that those portions of the network that are not modeled are accounted for within the parts of the system that are represented by the model. The level of detail of a distribution system model can be described by the number of junctions and pipes in the model as compared to their numbers in the actual system that the model represents.

The TEVA model for assessing the spatial and temporal distribution of health impacts in a distribution system has been previously described [Murray et al., 2006(a)]. Furthermore, the strategic placement of sensors in a distribution system to monitor water quality as part of a CWS has been well studied [Berry et al., 2006] and described [Murray et al., 2006(b)].

The purpose of this paper is to evaluate the effects that varying levels of model detail (degree of *skeletonization*) have on estimating potential health impacts from an intentional contamination event, on a water system community. Additionally, the performance of sensor monitoring designs developed for six *skeletonized* models are compared to designs developed for an "all-pipes-model". Mean and maximum, or worst case, health impacts for each of the sensor designs from the *skeletonized* models are compared to the performance of the sensor designs developed for the "all-pipes-model". Given that most distribution systems are represented by models that are *skeletonized* to some degree, this paper examines the effectiveness of sensor designs developed for *skeletonized* models to protect public health.

2.0 METHODOLOGY

In this section the methodology is described beginning with a description of the water system used, including its distribution system model and the *skeletonization* process used, followed by the consequence assessment and sensor placement design approaches.

2.1 Water Distribution System

The results presented here are for an "all-pipes-model" of a large city distribution system. The distribution system model has approximately 12,000 nodes, an average daily demand of approximately 20 million gallons, and a census population of approximately 260,000 people. The municipal water system has customer service accounts which total approximately 80,000. Each node in the model represents a connection where pipes join together and where water leaves the network due to demand. Given there are approximately 12,000 nodes and 80,000 service connections, results in about 7 service connections per node in the model.

The system contains two reservoirs, no tanks, and approximately 1,100 miles of pipe. The mean node demand is approximately two gallons per minute (gpm) while the maximum node demand is 200 gpm. The median node demand is one gpm.

Populations at each node were estimated using the Geographical Information System (GIS) thiessen polygon method to assign a population at each node of the "all-pipes" model and separately for each of the *skeletonized* models, ensuring that the total population for the system, across all the models, remained constant. Hydraulic and water quality simulations were run for 192 hours. Water age analysis using EPANET (Rossman, 2000) indicates the mean water age is 30 hours while the median water age is 23 hours.

"Skeletonized" models from the "all-pipes-model" were created by trimming pipes and associated junctions at 2-inch pipe diameter intervals to a maximum of 12-inches using a commercially available software program (MWH Soft H20MAP, 2004). Table 2-1 provides the diameter specifications and resulting pipe totals, by diameter, for each *skeletonized* model. By repeatedly defining a database of pipes by diameter, the *Skeletonizer Tool* in the H20MAP Suite was used to perform *Reduce and Trim* operations successively, starting with the "all-pipes-model" to produce the resulting "reduce and trim" *skeletonized* models. Figures 2-1a and 2-1b provide pictures of a portion of the network for the "all-pipes-model" and the 12 inch *skeletonized* model, respectively, to illustrate the *skeletonization* process and the changes that occur with respect to the removal of pipes and nodes. Table 2-2 provides model specifications (i.e., junctions, reservoirs, pipes, and total system demand in gpm) for the "all-pipes-model" and the *skeletonized* models. Table 2-3 provides a measure of the degree of *skeletonization* (as compared to the "all-pipes-model") for each *skeletonized* model as well as the population density for each model.

2.2 Chemical Contaminant Consequence Assessment

Consequence assessments of contamination events were developed by applying the TEVA consequence assessment methodology to the "all-pipes-model" and the six *skeletonized* network models (Murray, et al., 2004). The TEVA contaminant consequence analyses considered two approaches for modeling public health impacts. First, attacks were simulated at every node of the "all-pipes-model" and each of the *skeletonized* models. Separately, attacks were simulated at a set of nodes that was common to all the models. This common set of nodes corresponded to the all-nodes set of the 12 inch *skeletonized* model. Table 2-4 provides the number of threat scenarios (attacks) that were simulated for each model for the two contaminant consequence assessment approaches.

To simulate a contamination event, numerous parameters must be specified, including characteristics of the contaminant, the contaminant-introduction scenario, and the consumption patterns of the population. In order to take into consideration the range of possible parameter values, the TEVA software uses simulation to vary parameters such as contaminant type, quantity, and concentration, as well as injection location, rate, or duration, to generate threat ensembles (collections of many threat scenarios) which collectively can be analyzed for health impact statistics.

For the analyses presented here, chemical contaminant releases lasted one hour. The chemical contaminants were modeled as conservative tracers, i.e. free of the effects of hydrolysis or other reactions within the bulk water matrix or with pipe wall materials, which may increase or decrease the contaminant's effectiveness in causing harm to public health. Contaminants were modeled using a mass injection rate, zero volume added, which consequently does not influence the network hydraulic solution.

Health impacts are affected by such factors as the contaminant-specific dose-response relationship, dose received, time before onset of symptoms, time for effective treatment, and the time delay between contamination event determination and implementation of mitigative measures to stop further exposures. Considering these factors, modeling and simulation analyses are performed on a contaminant specific basis. Not surprisingly, health impacts to a population increase with an increase in the time required to implement an effective response. For these analyses, a zero response time delay was assumed.

The public health consequence assessments were performed using a chemical contaminant. The chemical contaminant chosen has a 50% lethality rate when an adult (70 kg) individual ingests approximately 3,000 mg of the chemical. The time period for onset of injury for the chemical contaminant is estimated to be 1 hour. A sigmoidal dose-response curve was assumed for each contaminant consistent with the above assumptions. The chemical contaminant had an untreated fatality rate at 100%. Exposure is assumed to occur only through ingestion. Each person is assumed to consume two liters of water per day. The probability that an individual at a node consumes water at a certain time is assumed to be proportional to the ratio of the demand at that time to the average demand over the simulation time.

Each contaminant release was simulated to occur at time zero (12:00 am) and the start of the simulation. Statistically analyzing the approximately 6,000 to 12,000 nodes as release points or threat scenarios, depending on the model, provide an estimate of the hypothetical health impacts in terms of both average health impacts (in this case fatalities) and maximum impacts. Average impacts could be expected to result if the terrorist or saboteur had no knowledge of where best to attack and simply randomly chose a node location for contaminant injection. Maximum health impacts correspond to a relatively small set of injection node locations (threat scenarios) that maximize health impacts to the associated receptors.

2.3 Sensor Placement

A number of researchers have developed approaches to place sensors and design CWS (Ostfeld, 2004; Watson, 2004; Uber 2004). The Sensor Placement Optimization Tool (SPOT) (developed by Sandia National Laboratories) used in this analysis has been described in numerous publications (Berry, 2006). SPOT can find sensor placement solutions for a variety of objectives, and prove that these solutions are optimal with respect to the modeling assumptions. Recently, SPOT has been integrated with TEVA in a JAVA-based graphical user interface with the resulting, integrated, software program called TEVA-SPOT. The TEVA-SPOT program is flexible enough to allow for exploring the trade-offs of selecting one objective as compared to another, minimizing worst cases measures, and allowing for multiple constraints. Furthermore, the TEVA-SPOT software program has the capability to develop numerous sensor placement designs for a variety of threat ensembles and determine which sensor design performs best overall.

For the analyses presented here, sensor designs were developed using TEVA-SPOT for the “all-pipes-model” and the six *skeletonized* models. Sensor locations were selected to minimize mean public health impacts. Sensor designs were developed for 5 sensor set sizes, i.e., 5, 10, 15, 20, and 25 locations. Further discussion of the sensor placement methodology is described by Murray in the paper titled, “Sensor Network Design for Contamination Warning Systems: Tools and Applications,” (Murray, et al., 2006b).

3.0 RESULTS

In this section results are presented for the chemical contaminant consequence assessments and the sensor placement designs. Mean and maximum health impacts (fatalities) are presented for the “all-pipes-model” and the *skeletonized* models for the baseline (no sensors case) and the CWS sensors case. For the analysis of the sensor design’s ability to reduce public health impacts, each *skeletonized* sensor design, for a given sensor number, was evaluated in the “all-pipes-model” of attacks.

3.1 Contaminant Consequence Assessment

Table 3-1 provides the mean and maximum fatalities for the baseline case for the “all-pipes-model,” and each of the *skeletonized* models. Figures 3-1 and 3-2 provide plots of the average and maximum fatalities, respectively. As the degree of *skeletonization* increases, mean fatalities increase. However, the estimate for maximum health impacts remains relatively constant across the range of *skeletonized* models, except for the 12 inch *skeletonized* model. The increase in mean fatalities indicates an exaggeration of health impacts proportional to the level of *skeletonization*. In reality, average fatalities increase because lower impact contaminant release nodes, e.g., dead-end nodes, are eliminated in the skeletonization process so that the average threat scenario’s impact is increased.

Table 3-2 provides the mean and maximum fatalities for the “all-pipes-model” and the *skeletonized* models considering the threat ensemble is composed of only those nodes common to all the models, i.e., determined by the 12 inch *skeletonized* model containing 6,691 release nodes. Figures 3-3 and 3-4 provide plots of the average and maximum fatalities, respectively, for this common node set. As shown in Figure 3-3, mean fatalities do not increase until the level of *skeletonization* reaches the degree exhibited by the 8 inch, 10 inch, and 12 inch models, resulting in an exaggeration of fatalities from approximately 5 to 10 percent above the estimate provided by the ”all-pipes-model". This increase is likely due to the aggregation of larger numbers of people to nodes where they can be exposed. Although there is a decrease in maximum fatalities for the 2 inch through 10 inch *skeletonized* models, the "all-pipes-model" and the 12 inch *skeletonized* model have comparable maximum fatalities. It is not clear the reason for the decrease in maximum fatalities for the 2 inch through 10 inch *skeletonized* models.

3.2 Sensor Placement Designs

Tables 3-3 and 3-4 provide mean and maximum health impacts, respectively, by sensor set design. These results were developed by determining the health impacts resulting from each *skeletonized* sensor design given the threat scenarios associated with the "all-pipes-model," i.e., attacks from 12,624 nodes. Comparing each *skeletonized* model's health impacts with the blue shaded results from the "all-pipes-model" illustrate the effectiveness of a sensor design developed based on a *skeletonized* model to perform as well, in most cases, as the design developed for the "all-pipes-model". Figure 3-5 illustrates for a portion of the network and a subset of sensor locations the nearly identical selection of sensor locations between the "all-pipes-model" (red circles) and the 12 inch *skeletonized* model (red squares). Figure 3-6 provides a plot of percent increase in mean fatalities versus sensor set size between the 12 inch *skeletonized* model's sensor design and the "all-pipes-model" sensor design. These results illustrate that even for the most *skeletonized* model, the performance of the sensor designs is within approximately 5 to 15 percent of the performance of the sensor designs developed by the "all-pipes-model".

4.0 CONCLUSIONS

In summary, this paper presents results illustrating the effect that model detail has on estimating public health impacts given an intentional release of contamination and designing contamination warning systems. Using the TEVA methodology for contaminant consequence assessment and sensor placement design, intentional releases of a chemical contaminant are simulated, modeled, and evaluated for a real drinking water distribution system. The results indicate that mean and maximum health impacts can be predicted fairly well using *skeletonized* models and sensor designs developed for such models perform very well in comparison to their "all-pipes-model". These results support the application of the TEVA methodology to water systems represented by less detailed models. This work is based on only one distribution system network model, additional distribution systems will be evaluated in the future.

With increasing levels of skeletonization the exaggeration of health impacts could become an issue. Although, for this model after removing nearly half the nodes, the results still prove favorable. There is more uncertainty surrounding the health impact results.

5.0 REFERENCES

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Figure 2-1a: Portion of network model for the “all-pipes-model”

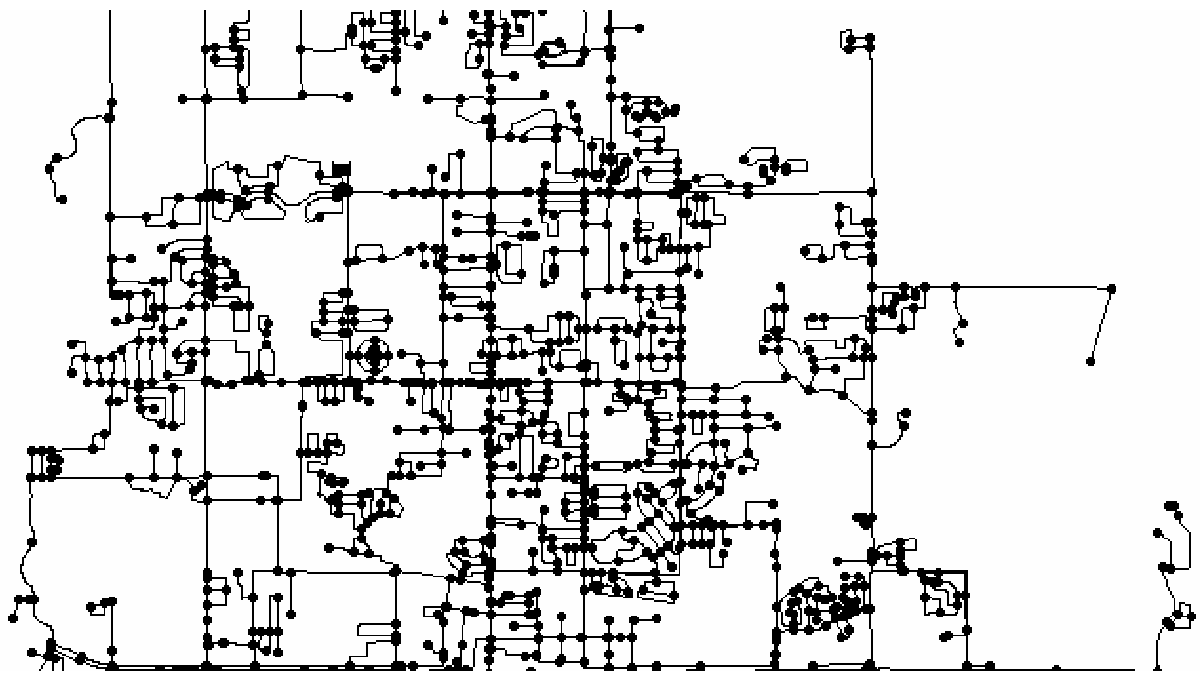

Figure 2-1b: Portion (same portion as Figure 2-1a) of network model for the 12 inch *skeletonized* model to illustrate the effect of *skeletonization* with respect to the removal of model junctions and pipes.