Exploring Spatial and Temporal Demand Aggregation on Transport Characteristics in Distribution System Modeling

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1. A progress report containing Problem and Research Objectives, Methodology, and Principal Findings and Significance

Problem and Research Objectives

Drinking water distribution system network models have traditionally been used to evaluate the ability of the network to provide adequate water quantity to the consumers. More recent applications of network models (e.g., selecting regulatory sampling locations, and protecting public health) have resulted in an increase in the use of these models for water quality analysis. In addition to performing more detailed analysis, utilities have also been moving towards the development of "all-pipe" network models (due to the proliferation of geographic information systems). Unfortunately, as the industry has begun to use these models more progressively, the assumptions that most of these models are based have not been thoroughly evaluated. Typical modeling approaches assume that consumptive demands are constant over a 1-hour time frame, which was sufficient when utilities were only modeling transmission or large diameter distribution pipes. The use of "all-pipe" models have resulted in the same modeling assumptions being applied to areas with only 8 consumers. While the greater spatial detail can provide additional information, the usage of water at such a scale begins to behave in a stochastic manner that cannot be adequately represented by current modeling techniques. The objectives of this study are to explicitly evaluate the impacts of demand variability, aggregated at different temporal and spatial scales, on the underlying hydraulic and transport characteristics.

Methodology

The study will be performed by integrating a common distribution system network hydraulic and water quality solver (EPANET) with a computational framework capable of representing stochastic demand behavior (PRPsym). Two different size network models will be utilized to evaluate the impacts of spatial and temporal aggregation of demand on the underlying hydraulic and transport characteristics. Demands will be temporally aggregated at 1-min, 10-min, and 1-hour time intervals, and spatially aggregated through the use of commercially available algorithms capable of reducing the network model size and redistributing demands. Monte Carlo simulation will be utilized to generate multiple realizations of stochastic demands and used to simulate both the hydraulics and water quality aspects associated with the two models.

The analysis of the hydraulic data will be focused on exploring the impacts of the different scales of demand aggregation on flow rate variability. This information will ultimately be linked with water quality metrics to determine if there is a specific level of underlying flow variability that has a deleterious impact on water quality variability. The water quality analysis will first be focused on evaluating the impact of demand aggregation on the simulated hydraulic residence time, which can be used as a surrogate for water quality. Additional water quality simulations will be performed to assess the potential variability associated with exposure to 1) disinfectant by-products, which are ubiquitous in distribution systems, and 2) a short-duration contamination event, which would be more susceptible to hydraulic uncertainty. All of these simulations will be utilized to understand the potential impacts of various spatial and temporal aggregation scales on different distribution system network modeling objectives. These results will be compiled into a guidance document for the industry, and result in guidance for future research efforts aimed at improving distribution system network modeling.

Principal Findings and Significance

The first part of the research was focused on evaluating the impacts that temporal aggregation of consumptive demands had on pressure and flow rate variability. The results from the hydraulic analysis are qualitatively the same of both the small and large networks. With respect to pressure, decreasing the temporal aggregation from 1-hour to 1-minute time steps had little impact on pressure variability. However, decreasing the temporal aggregation generally increased the flow rate variability with the relative differences being more important as the average flow rate decreased. The decrease in relative demand variability at higher flow rates is expected, by the law of large numbers, as the larger flow rates are typically dependent on many more downstream demands that ultimately average out towards the expected values (i.e., similar to the deterministic case). Also, as the temporal time scale decreases, the probability of a node having no "arrivals" (i.e., no water usage) increases. Thus, between increased variability at the hydraulic edges of the system and an increased probability of no demands, which could increase stagnant flow conditions, we hypothesize that for short-duration water quality events (e.g., (un)intentional intrusion) the decreasing temporal aggregation will increase water quality variability. The increase in water quality variability can impact the use of drinking water distribution system models to perform, for example, system vulnerability and risk assessment.

To evaluate the impacts that temporal aggregation of consumptive demands had on water quality simulations, a conservative tracer signal was simulated by performing a 2-hr or 3-hr "injection" for the small and large network model, respectively. The small model was a more highly skeletonized model (i.e., less spatial detail) and, as such, did not have many nodes with zero consumptive demands (stagnant conditions) and had very few interconnections to impact transport. However, even with such a model, decreasing the temporal scale of the consumptive demand modeling: 1) increased the water quality variability throughout the system; 2) impacted the hydraulic residence times and travel paths (relative to a "deterministic" model); and 3) illustrated that the temporal scale could alter exposure assessments in distribution system analysis.

Similar behaviors were observed for the larger, all-pipes network model. To further study the potential impacts of temporal demand aggregation on hydraulic residence time and transport path, additional analyses on the large-scale network model were performed to investigate: 1) the time to first arrival of the conservative signal at a node, 2) the time required for half of the total mass to reach a node, and 3) the total mass consumed by an individual at a node by using the assumptions of Murray et al (2005). In general, the research team has observed the following results with respect to decreasing temporal aggregation scale: 1) increased time to first arrival and 2) increased time to reach the "half-max" concentration [the exposure assessments are still being performed]. The preliminary analyses of these results suggest that, in general, incorporating demand variability has a greater impact on the metrics of interest than the specific temporal aggregation scale. Additional analysis will be performed to further explore the significance of general demand variability versus the temporal aggregation scale. Regardless of the outcomes, the results will be an important first-step in characterizing the types of variability important within drinking water distribution system modeling.

2. Publication citations

MS Thesis

X. Yang (2010) "A Full-Scale Simulation Study of Stochastic Water Demands on Distribution System Transport." MS Thesis, University of Cincinnati. (in preparation)

Conference Proceedings

Yang, X. and Boccelli, D. L. (2010). "A Full-Scale Simulation Study of Stochastic Water Demands on Distribution System Transport." 2010 Water Distribution Systems Analysis Symposium, Tucson, AZ (accepted).

Yang, X. and Boccelli, D. L. (2009). "The Impacts of Demand Variability on Distribution System Water Quality and Transport." Proceedings, Computing and Control in the Water Industry 2009, Sheffield, UK.

3. Number of students supported by the project (MS/PhD) as well as their majors

Xueyao Yang (MS Student), Major: Environmental Engineering (Xueyao will be continuing in to his PhD after completing his MS degree)

4. Awards or Achievements

None.