Comparison of EPANET and Experimental Tests for Water Quality Modeling of Pipe Networks with Transient Storage

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Abstract

Threats to water distribution systems from accidental or intentional release of contaminants require improved understanding of how these contaminants move through the distribution system. As part of a 3-year research program, Sandia National Laboratories has performed numerous flow and transport experiments consisting of single-joint, multi-joint small-scale pipe networks, and storage tanks for the purpose of understanding the hydrodynamic behavior of solutes moving through a pipe network. Experiments were performed to gather data to further support improvements to the existing EPANET code.

This paper will discuss experiments and models developed to elucidate transient mixing processes in a small-scale pipe network with a storage tank. Previous models and tests have been performed on steady-state systems involving individual pipe junctions or small-scale networks. This work is unique in that it combines a pipe network with a storage tank and investigates transient mixing processes within the network as a result of dynamic filling and draining of the tank. Models and experimental results are presented that show the impact of mixing assumptions (complete or incomplete) at pipe junctions on the model predictions of transient concentrations throughout the network and in the tank.

1. INTRODUCTION

Water distribution systems are comprised of complex networks of pipelines, pumps, tanks, water reclamation, and treatment stations. Threats to water distribution systems from accidental or intentional release of contaminants are poorly understood due to a lack of understanding of how these contaminants move through the distribution system. The source of contamination can be intractable or inaccurately determined; this is evident in recorded historical outbreaks (Clark, 1996). Understanding how solutes move and mix through a network of pipes and junctions is critical for developing mitigation plans should a contamination event occur.

Previous work on single-joint and idealized network geometry reveal experimentally and theoretically incomplete solute mixing at cross junctions (Orear *et al*., 2005; van Bloemen Waanders, 2005; Ho *et al*., 2006; Webb and van Bloemen Waanders, 2006; Romero-Gomez *et al*., 2006; and McKenna *et al.*, 2007). Such behavior is contrary to the complete and instantaneous mixing model in pipe junctions employed by water-distribution network models. The software EPANET (Rossman, 2000), sponsored by the U.S. Environmental Protection Agency, is a standard for modeling hydraulic and water-quality behavior in water distribution piping systems. EPANET solves solute transport in a distribution network in a sequential fashion from the upstream-most junction where the concentration boundary conditions are prescribed to downstream sections. The flow rate in each pipe is calculated based on prescribed boundary conditions of pressure and/or flow rates and/or concentration.

Recently, Ho (2008) proposed an analytical model to account for incomplete solute mixing in pipe junctions. The bulk-advective mixing (BAM) model honors conservation of mass and more accurately represents momentum transfer of the fluid flow within each junction. The new bulk advective mixing (BAM) model is being distributed as an open-source software known as EPANET-BAM (Ho and Khalsa, 2008). EPANET-BAM allows the user to define an additional scalar mixing parameter, *s* (between 0 and 1) for each junction in the network, that linearly scales the mixing results between the lower-bound results of the bulk advective mixing model (s = 0) and the upper-bound results of the complete-mixing model (s = 1). Using s = 0.5, EPANET-BAM has shown good agreement with single joint and idealized 3x3 network experiments.

While incomplete mixing is shown to be evident in pipeline junctions, how it impacts dynamic mixing with storage tank is yet to be realized. This work studies the impact of incomplete mixing with network that includes a storage tank and focuses on dynamic fill and drain cycles. Unlike solute mixing in a single joint and pipeline networks, experimental and theoretical studies that involve dynamic mixing in storage tanks have been developed and well documented (Mays, 2000; Grayman et al., 1999, Roberts, 2005). Mixing considerations in storage tanks have been important in the designs of water distribution systems because the potential variability in water quality. Poor mixing that does not allow sufficient disinfection of water will result in non-compliance and health threats. There have been numerous correlations and dimensional analyses to describe mixing times based on geometries of the tank and the momentum of inlet fluid.

2. EXPERIMENTS

Single-Tank Characterization

The dynamic mixing experiments that involve both storage tanks and pipeline network are designed in two stages. The first stage focuses on a model-scale tank dynamic mixing without a network, and the second stage combines the tank with a 3x3 network. For our study, a 100-gallon tank is checked for dynamic mixing time at various flow conditions. Figure 1 shows the schematic for the mixing-tank experiments. Inside of the mixing tank, there are three hanging conductivity probes that are attached and wired into a data logger. This is similar to the set up described previously by Grayman (1999). The data logger used in all the dynamic experiments is made by Campbell Scientific CR23x Micrologger. Additionally, there are three redundant hanging handheld conductivity probes that are situated right next to a data logger probe to verify data acquisition system. The bottom pair of probes hangs 1 ½" from the bottom of the tank (i.e. probe 13), the next pair hangs 7" from the bottom of the tank (i.e. probe 14) and the highest probe hangs 13" from the bottom of the tank (i.e. probe 18). The two lowest handheld probes are Hach SensION 5 handheld probes and the highest probe is the Orion Model 150 handheld probe. All of the data logger probes are Orion CDE1201 electrodes.

The inlet and outlet pipes are situated 180 degrees from each other; each end is equipped with an in-line flow meter, a conductivity meter, and a series of regulating valves. The inlet and outlet flow are powered by a Dayton 4TU19 pumps and regulated by the valves. The same data logger used to record internal conductivity also records flow and conductivity at the inlet and outlet pipes.

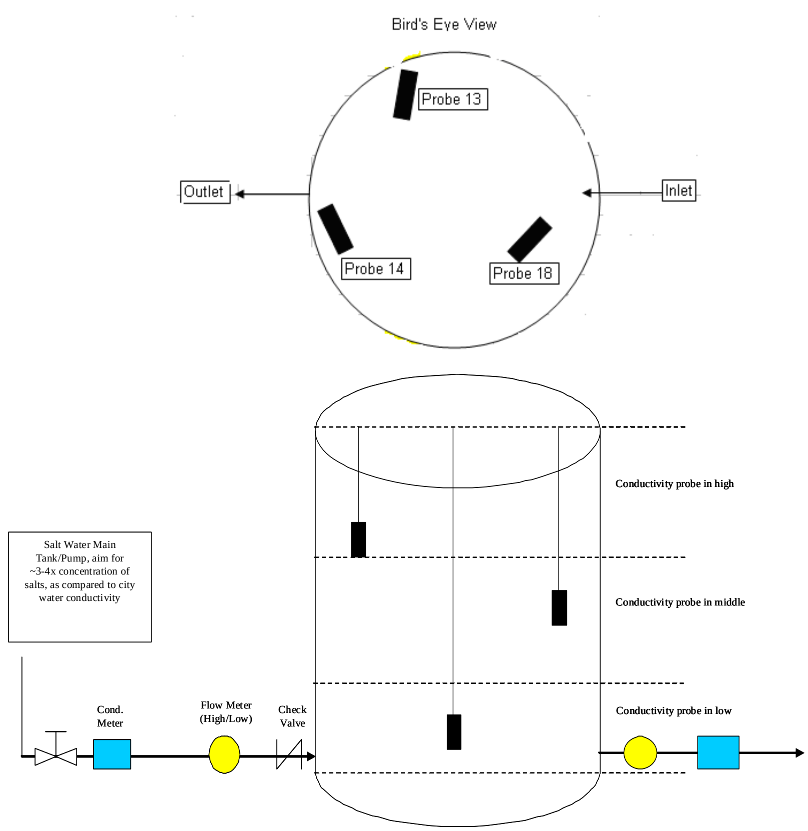

Figure 1 – The 100-gallon mixing tank configuration. A 12 mm pipe diameter is used for both inlet and outlet pipes.

Not shown in Figure 1, a tracer tank is located upstream from the inlet pipe. At the start of the each experiment, the tracer tank is spiked with NaCl until it reaches between 1750µs and 1800 µs. The mixing tank is filled to clear water with a background NaCl concentration of around 800 µs. These initial concentrations are necessary to consistently start at known conditions. All of the fluids are equilibrated at room temperature and ambient pressure. The initial tank level at the start of dynamic mixing experiments is 200 mm when the inlet flow is higher than the outlet flow and 900 mm when the outlet flow is greater than the inlet flow. Mixing characteristics are recorded at different relative inlet and outlet flow conditions.

Figure 2 shows a typical conductivity response as a function of time for the three probes and relative inlet to outlet flow ratios. Probe 18 responded partially in experiments where the level of fluid did not reach the probe until later in the filling experiments. During the draining experiments, the same probe did not react to varying concentration either.

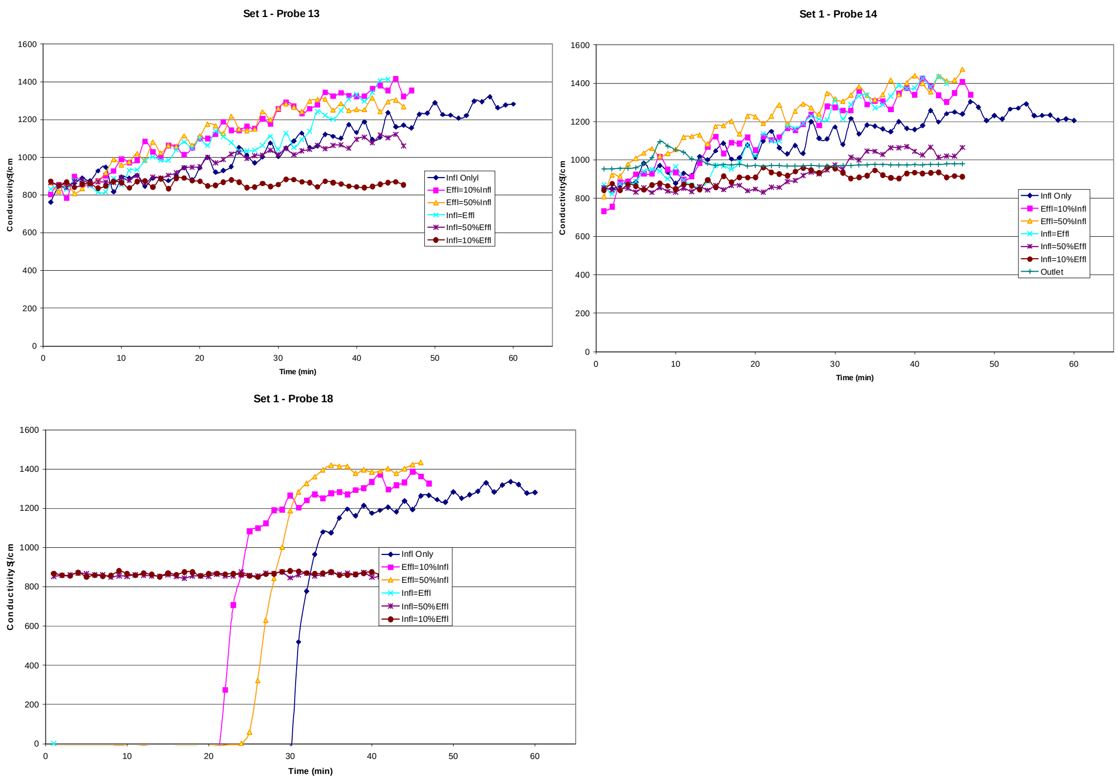

Figure 2 – Set 1 experiments showing the conductivity response of all three probes in the storage tank. Set 1 refers to influent volumetric flow of 2 liter/min.

Single-tank Extent of Mixing

Two types of data are collected for the storage tank experiments to understand its mixing characteristics: extent of mixing as a function of ratios of inlet-to-outlet flows and coefficient of variance (for fill experiments only). The time required to reach one and half times the tank's initial concentration is plotted in Figure 3 for inlet flow of 2 liter/min (Set 1) and 6 liter/min (Set 2). This shows a drastic increase in mixing time for draining experiments at low inlet flow condition. The dynamic response of mixing in the model tank experiment has enhanced our understanding and anticipated response of transient solute mixing.

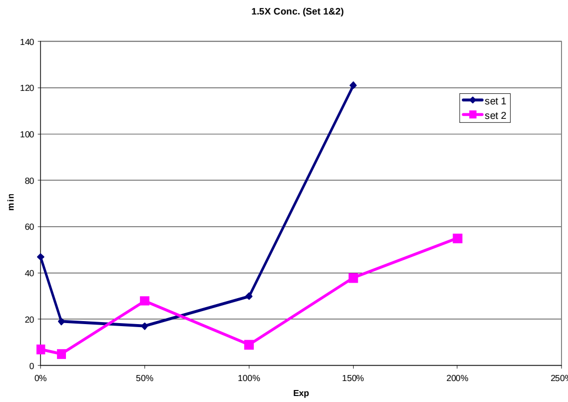

Figure 3 – Time required to reach 1.5 times the initial concentrations in storage tank experiments as a function of Qin/Qout (%). Set 1 refers to inlet flow of 2 liter/min and set 2 refers to inlet flow of 6 liter/min.

The coefficients of variance is defined as the ratio of standard deviation of the recorded conductivities from probes 13, 14, and 18 to the average conductivity (Grayman, 1999). A criterion for fully mixed system is when the coefficient is less than 0.05. The coefficient of variance plotted as a function of time for one experiment is shown in Figure 4. Qualitatively, the coefficients do decrease as a function of time; however, the values remain fairly low throughout the experimental periods, indicating little stratification in the tank. This is consistent with the previous plots showing little variations amongst all three probes.

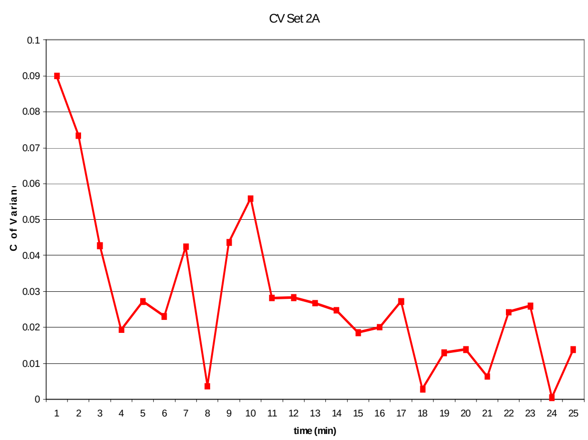

Figure 4 – Coefficient of Variance for Tank filling. Inlet flow is 2 liter/min..

Design of Coupled Storage Tank – 3x3 Network

The coupling of a single storage tank with a 3x3 pipeline network is graphically represented in Figure 5. Two supply tanks and one demand tank are set up to dynamically alter the inflow and outflow conditions of this coupled system. The storage tank, identical to the one characterized in the last section, is located at one vertex of the 3x3 network that fills and drains accordingly. One of the supply tank is spiked with up to 1800 μs of NaCl solution before the start of experiments.

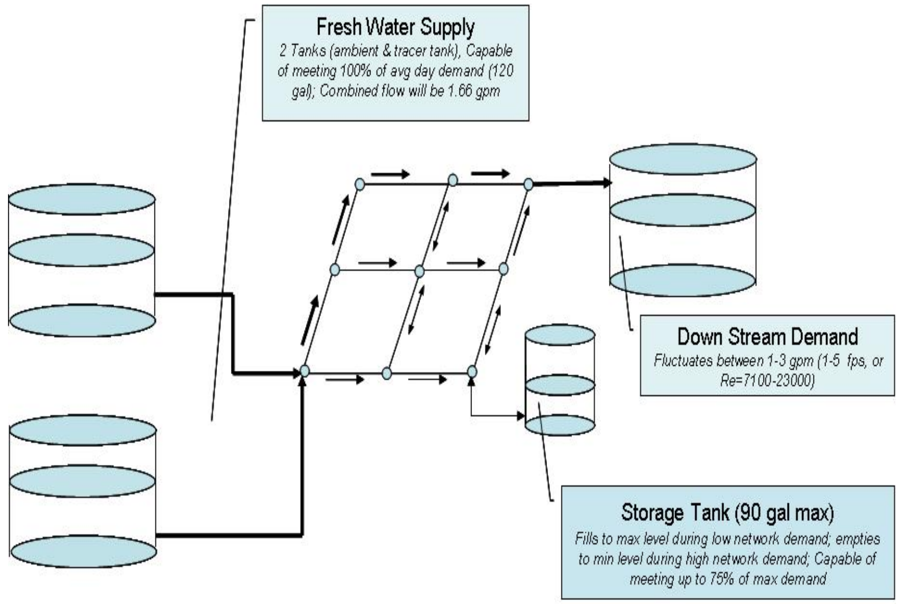

Figure 5 – Coupled storage tank with a 3x3 pipeline network.

The instrumentation diagram for the coupled system is illustrated in Figure 6**.** Flow meters and conductivity probes are installed in every segment of the network as well as all pipes leading to and from the tanks. The same in-line probes and data logger used in the single tank study are used in this study.

The feed flows are estimated by scaling back a typical municipality supply and by the capacities of holding tanks. **Table 1** summarizes the scaling applied to this set of experiments, reflecting consistency in velocities between the laboratory scale and full scale distribution systems.

Table 1 - Full Scale & Lab Scale Flow Comparison

	Lab Scale			Full Scale			ratio
Mean Velocity (ft/s)	2.05	3.43	4.9	2.05	3.43	4.9	1
Pipe diameter (in)	0.5	0.5	0.5	10	10	10	20
Flowrate (gpm)	1.25	2.10	3.00	502	840	1200	400
Time (s)	0.020	0.012	0.009	0.407	0.243	0.170	20
Mean Velocity (m/s)	0.625	1.046	1.494	0.625	1.046	1.494	1
Reynold's number	8882	14861	21230	8882	14861	21230	1

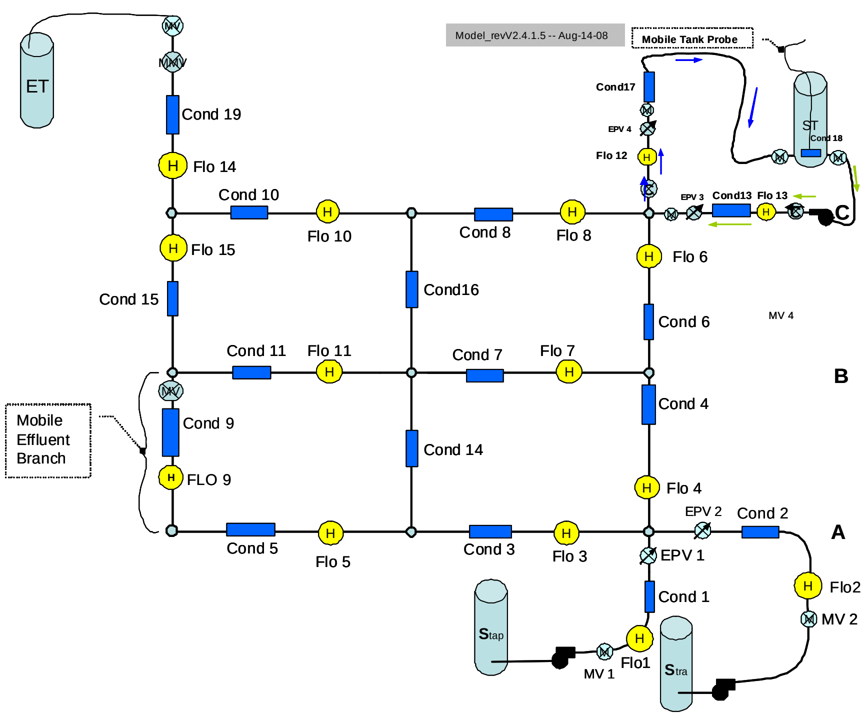

Figure 6 Combined Network-Tank Dynamic Experiment Set-up.

A sequence of valve opening and closing actions is orchestrated to mimic diurnal demand pattern. Figure 7 shows the flow fluctuations recorded for the experiment. The two supply tanks (tracer and ambient) maintain constant flow while the inlet and outlet flow rates of the storage tank reflect the opposite cycle relative to demand curve. This is accomplished by manually adjusting the valves to match that of demand curves. As shown in Figure 7, given a constant supply of tracer and clear fluids from the two supply tanks, the cycles in the storage tank work in opposite directions. The experimental design has been scaled back to a 70-minute cycle to represent a full-day period. Based on Figure 7, the initial demand is low from midnight to early AM, then it peaks during the full morning period. This is followed by another decline until the evening period, where demand rises again.

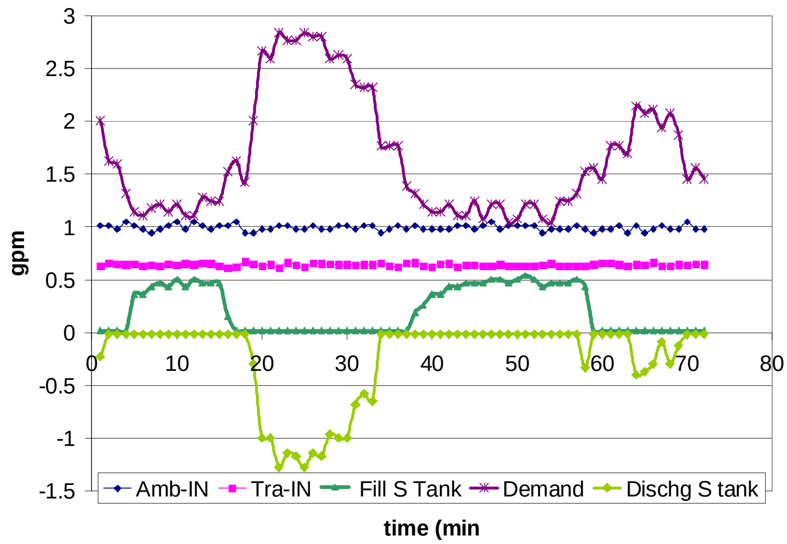

Figure 7 – Experimental flow data during an entire scaled day which spans over 70 minutes. Q_{Tracer}=0.66 gpm, $Q_{Ambient}$=1.0 gpm. Demand ranges from 1.15 to 3 gpm, and the initial tank level is 25 gal.

3. MODELING

Storage Tank Mixing in EPANET-BAM

The storage tank experiment are modeled in EPANET-BAM to check for the type of mixing model that best represents the one used in the experiment. We have found that in most cases the original EPANET *2-component* tank mixing model with the ratio near 0.7 to be the best mechanism, and in others the well-mixed representation best fit the experimental observations. Figure 8 shows one of the EPANET-BAM simulation against validation data. They are plotted against other tank mixing models, such as different 2-compartment constants or Last-In-First-Out (LIFO) or First-In-First-Out (FIFO). Unlike solute mixing in the pipe network, the different theoretical models that exist in the original EPANET software adequately provide mixing mechanisms in storage tanks.

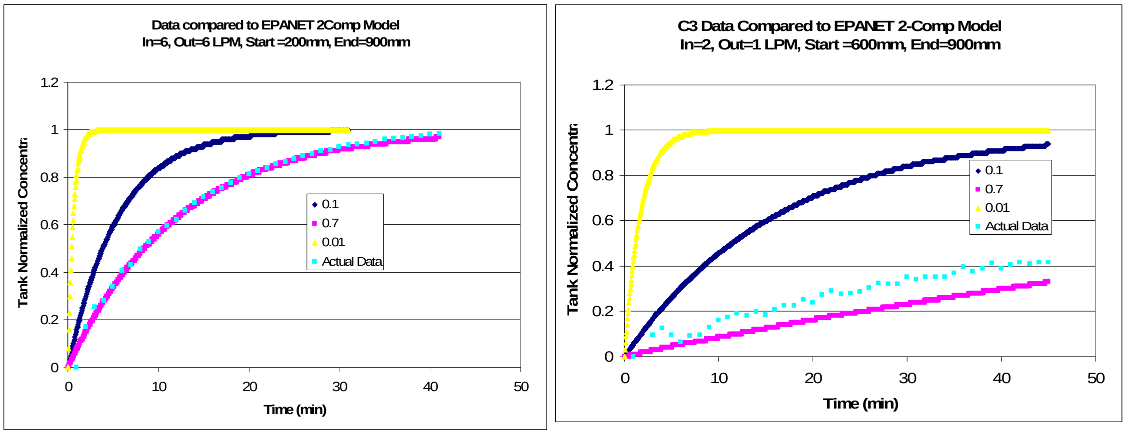

Figure 8 – Selected comparison of storage tank dynamic mixing data to EPANET tank mixing models.

Network-Storage Tank Mixing in EPANET-BAM

A comparison between experimental data and EPANET-BAM model predictions is performed for coupled tanks-network experiments. A diagram of the EPANET-BAM model is shown in **Figure 9**. The conductivity reading, normalized between 0 and 1 are plotted in Figure 10. Along with the experimental reading, there are three simulated EPANET-BAM mixing parameters. The EPANET-BAM results with a mixing parameter of 0.5 match the dynamic mixing data quite well, which is similar to the findings of previous comparisons with steady-state pipe network tests.

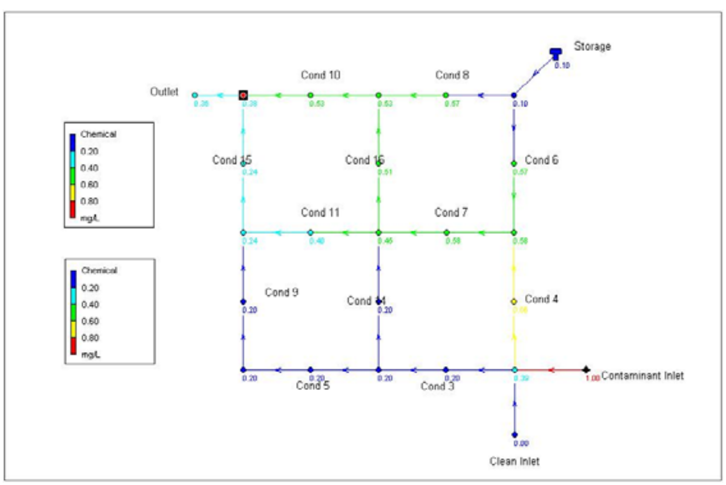

Figure 9 – EPANET-BAM model for the combined network-tank experiments.

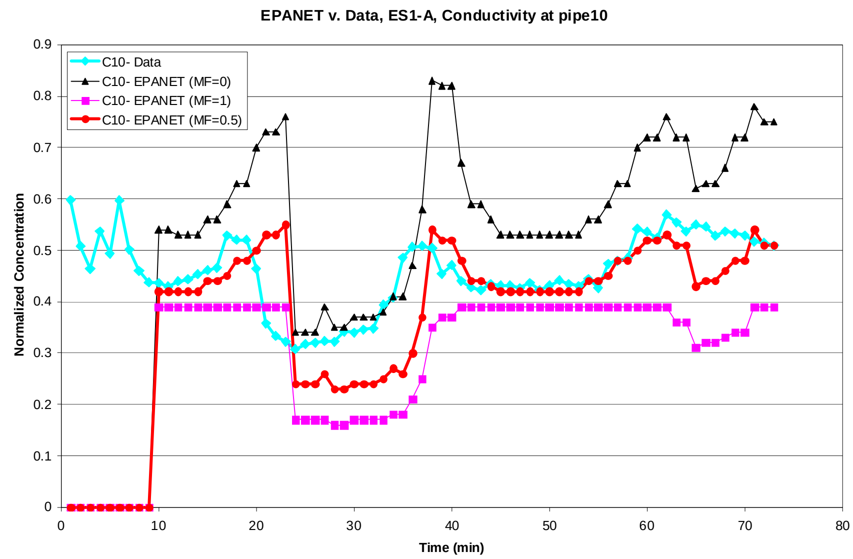

Figure 10 – Comparison of Experimental data and EPANET-BAM model at node C10 (refer to Figure 6 for keys).

4. DISCUSSIONS

The experiments and modeling results yielded valuable hands-on expertise and insight for dynamic mixing in a coupled 3x3 network with storage tank experiments.

- The dynamic experiments differ from steady-state experiments since temporal variations are to be monitored and recorded. The single-tank characterization shows better mixing when the tank is filling as opposed to draining. The mixing time for our storage tank is shorter than those described by the literature.

- The expertise gained from individual unit testing made the combined network-tank experiments easier to set up and monitor. We have scaled a network-tank demand and supply flow that is comparable to a daily diurnal cycle. The results of EPANET-BAM of the combined network still show consistent improvement using the incomplete mixing model in EPANET-BAM with a mixing parameter of 0.5.

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