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ENERGY LOSS MODELING OF WATER MAIN BREAKS: A HYBRID SYSTEM DYNAMICS-AGENT BASED MODELING APPROACH

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Abstract: According to the United States Government Accountability Office Energy-Water Nexus Report, the water pipeline infrastructure system is nearing the end of its service life. Up to 50 percent of water is lost, as evidenced by the 240,000 water main breaks that occur each year, estimated by the American Society of Civil Engineers (ASCE). Water loss in the distribution system leads to additional expenditures for extracting water from natural resources, treatment, pumping, and transporting water into the distribution pipeline network system. Minimizing water losses has the potential to curb the increase in operating costs throughout the distribution system. This paper describes a conceptual System of Systems (SoS) framework for estimating the energy footprint resulting from water main breaks that considers the full cycle of providing drinking water to customers. The paper focuses on the interactions between the water loss in the distribution system and the energy-intensive operational components of the water infrastructure. This paper contributes to the body of knowledge and practice by developing a methodology to quantify the impact of water main breaks on energy consumption and by creating a tool that assists the water utilities as decision-makers in their assessment of the effects of water main breaks on the satisfaction of customers and the revenue loss of water utilities.

1 INTRODUCTION

A 2013 study by the Center for Neighborhood Technology of the Great Lakes states revealed that 6.5 billion gallons of drinking water are lost annually from 63,000 leaking pipes in this region; enough water to meet the demand of 1.9 million consumers for a year (CNT 2013). Water losses cascade into energy loss due to the interdependencies of the infrastructure systems, and leads to additional energy expenditures for extracting water from natural resources and treating, pumping, and transporting water to the end users. Approximately four percent of all electricity generation in the U.S. is used to move and treat drinking water and wastewater (Electric Power Research Institute 2003). For example, the water sector in California consumes 19 percent of the state's electricity per year (California Energy Commission 2005). Nationwide, the energy bill comprises 40 percent of operation cost for water utilities to provide a clean supply of drinking water for customers (WaterRF 2013). Therefore, minimizing water main breaks through an effective asset management program has the potential not only to reduce the operating and social costs associated with disruption of services to the communities, but also to reduce the energy and carbon footprint resulting from water main breaks.

This paper develops and demonstrates a framework for quantifying the energy footprint resulting from water main breaks that considers the full cycle of providing drinking water to customers. In this study, the energy footprint is a measure of total amount of energy loss in water distribution and supply systems resulted from water main breaks. This framework will investigate the impact of water main breaks on the water supply and distribution system, and assess the interdependencies of the water and energy sectors.

1 BACKGROUND

Extraction and conveyance of water requires a significant amount of energy to transport usable water for the treatment plant. For example, in Southern California, water agencies have to import water from the Colorado River Aqueduct, which requires 2000 kW/h electricity for pumping (Nuding 2011). In water treatment facilities, the amount of energy used for the treatment process depends on the quality of the water received and the applicable quality standard required for drinking water. Drinking water quality regulations have become more stringent in recent years, requiring advanced water treatment processes, such as UV disinfection systems, which are energy-intensive. Drinking water is then pressurized and pumped through the pipeline distribution network for delivery, which requires additional energy. Figure 1 represents the energy consumption of water supply and distribution components.

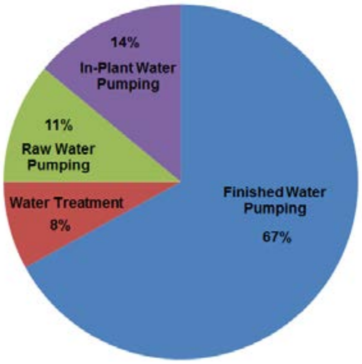

Figure 1: Energy consumption of water supply system (WaterRF 2013)

Prior research in the water-energy nexus area that addressed the energy needs for water (e.g., American Water Works Association Research Foundation 2007; WaterRF 2011; EPA 2013; WaterRF 2013; U.S. Department of Energy 2014) focused on macro-level analysis of water and energy interactions, including the energy and water demands related to population growth, the development of technology to reduce the energy footprint of the water and wastewater treatment processes, the energy consumption during the rehabilitation and renewal processes, and the improvement of the energy optimization of pumping stations. Additional work has included the quantification of the energy loss of water pipes based on head loss, friction loss, and hydraulics equations (Pelli and Hitz 2000; Colombo and Karney 2002; Filion et al 2004). Cabrera et al. (2010) not only considered the effect of water leakage in distribution systems, but also assessed the energy audit from the resource (reservoir) to the end user. The Reynolds transport equation and integral energy equation were used to develop a mathematical model to evaluate the energy input/output for a water distribution system. These integral energy equations led to calculating the energy loss indicator using leakage; however, it measured only the energy loss in the closed loop of water distribution, not from the water supply systems (extracting and treatment). In addition, the current state of the literature is limited to macro-level analysis of water distribution and supply systems (in the delta level shown in Figure 2), and has not addressed the energy-intensive components of water distribution system in cases of main breaks.

2 METHODOLOGY

In order to better understand the complexity and boundary of the water infrastructure system, a multi-level hierarchal framework for water infrastructure system was developed using the System-of-Systems framework (see DeLaurentis and Callaway 2004), as shown in Figure 2. The alpha (α) level is the base level system and further decomposition does not take place in this context, the beta (β) level is collections of α-level systems, the gamma (γ) level is collections of β-level systems in a network, and the delta (δ) level is collections of γ -level systems. This bottoms-up assesses the interaction between entities in each level, as well as interdependences across levels.

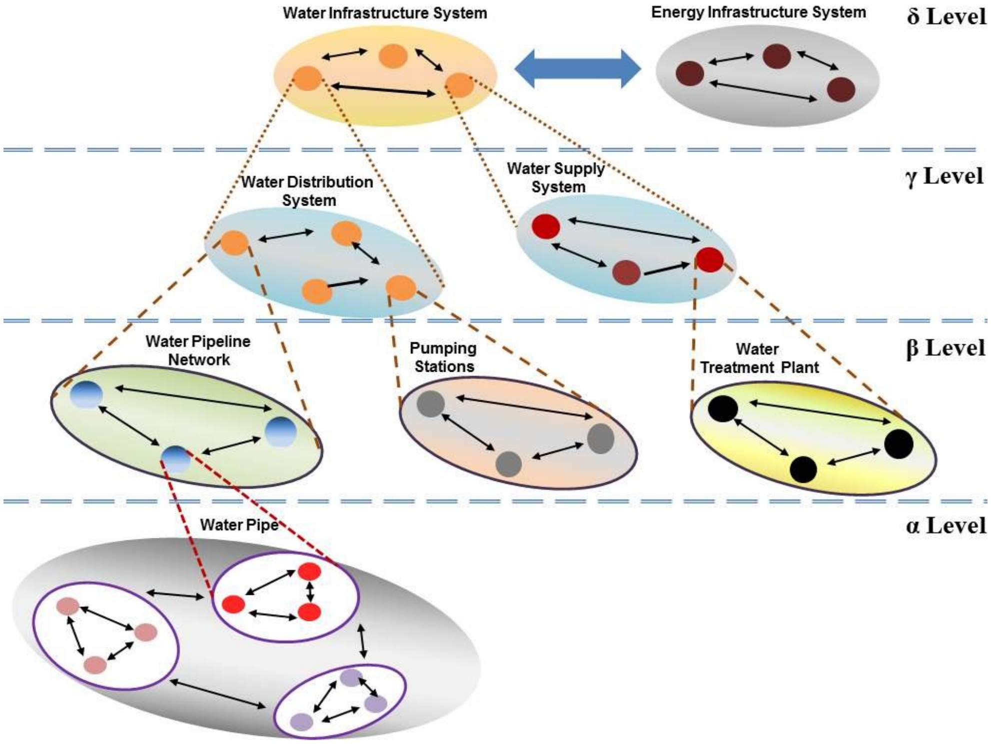

Figure 2: Water and energy infrastructure interdependencies

Investigating the dependencies and interdependencies of a complex system requires a theoretical framework including three phases: definition, abstraction, and implementation (DeLaurentis and Callaway 2004). In the forthcoming paragraphs, a discussion on each of the three phases is provided to highlight the purpose of each phase as well as the processes and tasks conducted within each phase.

The first phase, namely definition, intends to ensure that the current problem fits within the overall system characteristics by defining the operational context, status quo, and barriers. In this study, the existing interactions between water and energy infrastructures are defined in order to improve water utilities' capability by addressing the water and energy loss in water supply and distribution system. Barriers to the possible interactions between water and energy infrastructures can be counted as different managerial and operational dependencies and lack of appropriate communications.

The abstraction phase defines the key entities and their roles. Four main entities can be defined in this phase, which can be grouped under two entity-descriptors, specifically, explicit-implicit and endogenous-exogenous. The four entities that are addressed in this phase are: resources, stakeholders, drivers, and disruptors. Infrastructure resources are the physical entities which are managed, operated and maintained by utilities and acquired by end users. In this study, these resources include water pipes at the alpha level, and the water pipelines network and pumping stations, water treatment plants at the beta level. These resources have an impact on stakeholders. Stakeholders are those who are impacting or are impacted by decisions. Stakeholders include public/private agencies (i.e. water and energy utilities), and users (i.e., water consumers and utility managers). In this study, the drivers are the operation cost (such as energy, cost repair cost, etc.) and the level of service of water infrastructure. Drivers influence the decisions of utility companies to maintain the infrastructure to a certain level of performance. Disruptors are severe events that will reduce the efficiency of the system; in this case, water main break events.

The implementation phase builds upon the definition and abstraction phases. To assess the impact of water main breaks on water and energy infrastructure interdependencies, a number of mathematical models (see Cabrera et al. 2010) must be integrated. Due to the complexity of system, difficulty of integrating these mathematical models, and the level of uncertainty represented by this problem, system dynamic modeling was chosen for conducting the study and to uncover emergent patterns of system behavior. System dynamics is a methodology that can be applied to analyze the behavior of complex systems with a series of stocks, flows, and feedback loops (Forrester 1991). In this research, the system dynamics component focuses on the interactions between the water loss in the distribution system and the energy-intensive operational components of the water infrastructure. The advantage of using system dynamics modeling to assess the interdependencies is that it allows explaining the endogenous structure of the system, from water main breaks and pipeline characteristics to pumping stations, water treatment, water extraction, and water conveyance, as well as how the different components of the system interact. The closed boundary of the system structure does not imply that the system is unaffected by outside events, such as, traffic load, external corrosion. However, the dynamic behavior is created by interactions within the boundary (Forrester 1999). Figure 3 identifies the boundaries of the system dynamics model and depicts the interactions between system components.

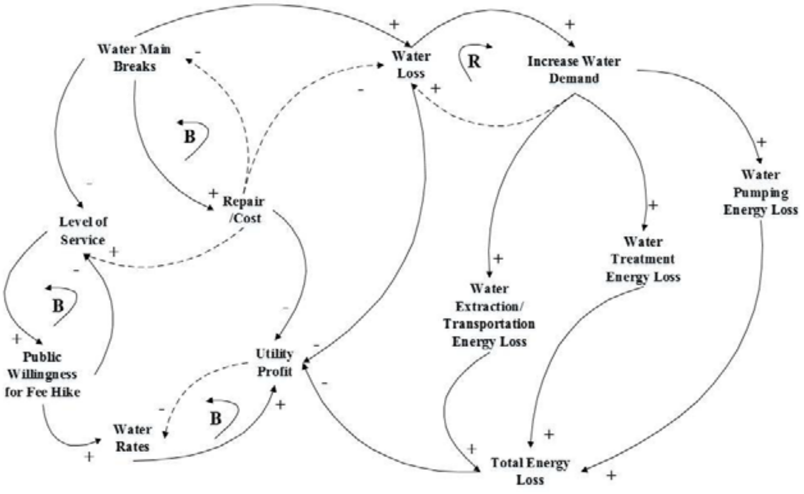

Figure 3: Causal loop diagram for the system dynamics model

The research methodology was applied to water distribution system in U.S. City A to demonstrate the framework. City A is a Midwestern city with an approximate population of 853,000 in 2013 with an area of 372 square miles and water supply capacity of 79 million gallon per day (US Census 2014; CEG 2013). Water pipeline installation was initiated in 1848 with cast iron pipe (CIP) materials. According to the City GIS database, the current water pipes range in diameter from 0.75 inches to 60 inches. CIP comprises the majority of the installed materials, followed by ductile iron pipe (DIP), polyvinyl chloride (PVC) pipe, steel pipe, asbestos cement (AC), high density polyethylene (HDPE).

AnyLogic 7.0, an object-oriented program, is used to demonstrate the modeling and simulation of the water and energy footprint, as well as the modeling of the interdependent micro-behaviors of the agents toward water main breaks, water loss, and energy loss. The primary components of the system dynamics model include:

- Stocks, which represent the variables of the system that change or accumulate over time. Examples of stocks are number of water main breaks, amount of water loss, amount of energy loss, amount of revenue.
- Flows represent rates that produce changes in the value of the stocks. These elements introduce changes in the flows to and from the stocks. Examples of flows are frequencies of water main breaks, water loss rates, energy consumption rates.
- Causal or feedback loops that represent the dynamic behavior of a system and the causality relationship between the variables and determines the flow of resources from the stocks.

The relation between stock and flow in system dynamics modeling is defined by Equation 1 (Sterman 2001):

[1] Stock (t) = $\int_{t_2}^{t_1}[\mathrm{inflow}\ (s) - \mathrm{Outflow}\ (s)]\,ds$

Where, t_1 is the initial time, t_2 is the current time, and the difference between inflow and outflows is the flow rate.

The amount of water loss from water main breaks is based on the AWWA M36 Manual (AWWA 2009). The water loss equation is a function of number of breaks in distribution system, the average flow rates of leaks, duration of leaks, and the average pressure in distribution system, shown in Equation 2 as:

[2] Annual Loss (MG) = $(BR \times (AFR \times 60 \times 24 \times TD\ (AP \div 70)^{0.5}) \div 1{,}000{,}000)$

Where, MG is million gallons, BR is the number of annual breaks reported by agencies, AFR is the average leak flow rate at 70 psi (gpm), TD is the total duration is days (= awareness duration + repair duration), and AP is the average system pressure (psi).

2.1 Data Analysis

The model input, such as the number of breaks, flow rates, average system pressure, and response time to the water main breaks were retrieved from City A's GIS database and from literature sources, including AWWA M36 manual, Water Research Foundation, and Environmental Protection Agency (WaterRF 2013; AWWA 2009; EPA 2009). The input variables are the characteristics of three common types of pipe materials, CIP, DIP, and PVC, and three categories of pipe diameters, 6" diameter, 12" diameter, and higher than 16" diameter. The model output variable includes the energy footprint of water main breaks based on the characteristics of the distribution and the main breaks. The average pressure is assumed to be 70 psi for entire water distribution system, based on the City A requirements. The average flow rate for water main breaks is estimated using the pipe diameter and the AWWA M36 Manual as shown in Table 1 (AWWA 2009). The total duration of water loss (awareness duration + repair duration) is retrieved from the GIS database of the City A.

Table 1: Water distribution characteristics for City A

#	Pipe Diameter	Average Flow Rate	Average Pressure	Average Failure Duration[1]
1	6 Inch	46 gpm	70 psi	4 days
2	12 Inch	111 gpm	70 psi	4 days
3	>16 Inch	111 gpm	70 psi	4 days

The water loss from main breaks affects the water supply system in order to extract, transport, treat, and pump extra amount of water to customers. The energy rate for extracting water (ground water or surface water) depends on pump efficiency (WaterRF 2013). In this study, it is assumed that the source of water is surface water with the pumping efficiency of medium and production of 20 million gallons per day (MGD), based on the water production rates in City A. The estimated energy consumption of this source water pumping is 2,898 kW/day (WaterRF 2013). Equation 3 is used to calculate the energy consumption of extracting water from resources in the system dynamics model as flows.

[3] Energy Loss of Extracting & Conveyance = Initial Value + $\frac{d(Energy\ Loss\ of\ Extraction\ \&Conveyance)}{dt}$

The amount of energy used for the water treatment process depends on quality of raw water and the quality standard required for drinking water. Drinking water quality regulations have become more stringent in recent years, requiring advanced water treatment processes, which are energy intensive (WaterRF 2013). The types of treatment plant needs to be considered for energy footprint analysis because traditional treatment plants energy consumption is different from advanced treatment plans. This study considered the conventional water treatment plant as a process of treating raw water through rapid mixing, flocculation, sedimentation, filtration, and chlorine stages with the approximate energy intensity of

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[1] Time of identification of failure to repair of failure

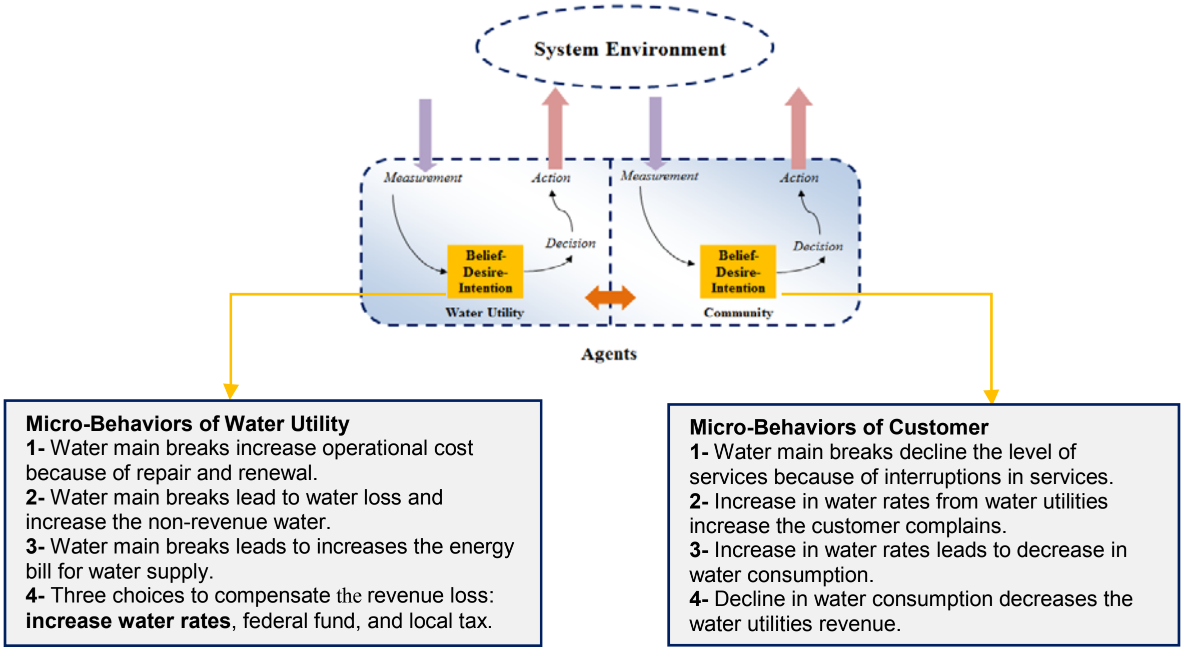
25,605 Kwh/day (WaterRF 2013). Equation 4 is used to calculate the energy consumption of water treatment plant in the system dynamics model as flows.

$$[4]\ \text{Energy Loss of Water Treatment Plants} = \text{Initial Value} + \frac{d(\mathit{Energy\ Loss\ of\ Water\ Treatment\ Plants})}{dt}$$

Energy consumption of pumping stations is a function of the flow, an assumed distribution system pressure head, and assumed pumping efficiency (a measure of pumping system efficiency). In the study, the average pressure of the distribution system is assumed to be 70psi and the efficiency of pump is considered as 65%, based on the commonly observed practice in the water industry (AWWA 2009). Based on these values, the approximate energy consumption of finished water pumping with the pumping efficiency of medium and production of 20 MGD is 21,563 kWh/day (WaterRF 2013). Equation 5 is used to calculate the energy consumption of pumping stations in the system dynamics model as flows.

$$[5]\ \text{Energy Loss of Pumping Stations} = \text{Initial Value} + \frac{d(\mathit{Energy\ Loss\ of\ Pumping\ Stations})}{dt}$$

Water main break events affect both the water utilities and communities in several ways, such as the social cost for communities and the financial loss for water utilities in repairing breaks. Agent-based modeling (ABM) is used in this study to capture the micro-behavior and emergent behavior outcomes from the activities and interactions between the water utility and consumer agents. ABM models the stakeholders (water utilities and customers) as autonomous agents in order to understand their behaviors toward water main breaks and to assess the potential increases in costs that may be passed on to the users from non-revenue water and energy loss. Figure 4 shows the beliefs, knowledge, and information (BKI) of the water utility and customer agent.



Micro-Behaviors of Water Utility

1- Water main breaks increase operational cost because of repair and renewal.
2- Water main breaks lead to water loss and increase the non-revenue water.
3- Water main breaks leads to increases the energy bill for water supply.
4- Three choices to compensate the revenue loss: **increase water rates**, federal fund, and local tax.

Micro-Behaviors of Customer

1- Water main breaks decline the level of services because of interruptions in services.
2- Increase in water rates from water utilities increase the customer complains.
3- Increase in water rates leads to decrease in water consumption.
4- Decline in water consumption decreases the water utilities revenue.

Figure 4: Representation of environment and agents interactions

2 RESULTS & DISCUSSIONS

The proposed methodological framework is used to assess the energy footprint of water main breaks and evaluate the stakeholder's interactions from the main breaks. This section focuses on the assessment of interdependencies between water and energy infrastructure systems resulting from water main breaks in water distribution system. Figure 5 shows the energy footprint for City A due to water main break events based on different types of pipe materials. This energy footprint includes the energy loss in the water supply system. The energy loss due to breaks in CIP pipes is higher compared to that in DIP and PVC pipes. This may be related to the aging CIP pipes, which were installed more than 100 years ago in North America. (McKim 1997), and hence show higher rate of breaks. PVC pipes have a lower energy footprint, because of the material's high resistance to corrosive environments and longer life expectancy (Folkman 2012; Davis et al 2007; Moser et al. 1994).

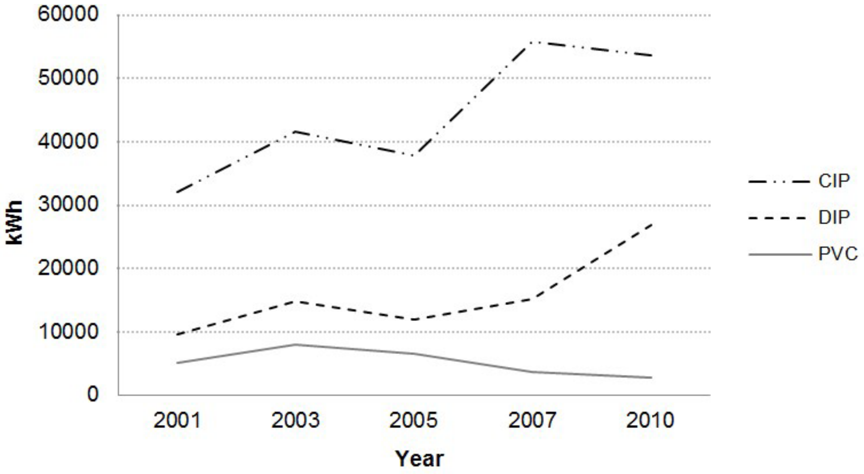


Figure 5: Energy footprint of water main breaks for each pipe material

Figure 6 shows the energy footprint estimates of water main breaks based on the three different categories of pipe diameters: 6" pipe, 12"pipe, and higher than 16" pipe. 6" diameter pipes in water distribution system have higher rates of energy loss, three times higher than 12" diameter pipes and five times higher than larger than 16" diameter pipes. This is mainly because of higher length of installation and smaller diameter. The small diameter pipes, such as 6" pipes, have a smaller thickness and they are more likely to be affected by the corrosive soil environment and the number of breaks rates for the small diameter pipes are higher (Kettler and Goulter 1985; Loganathan et al 2002).

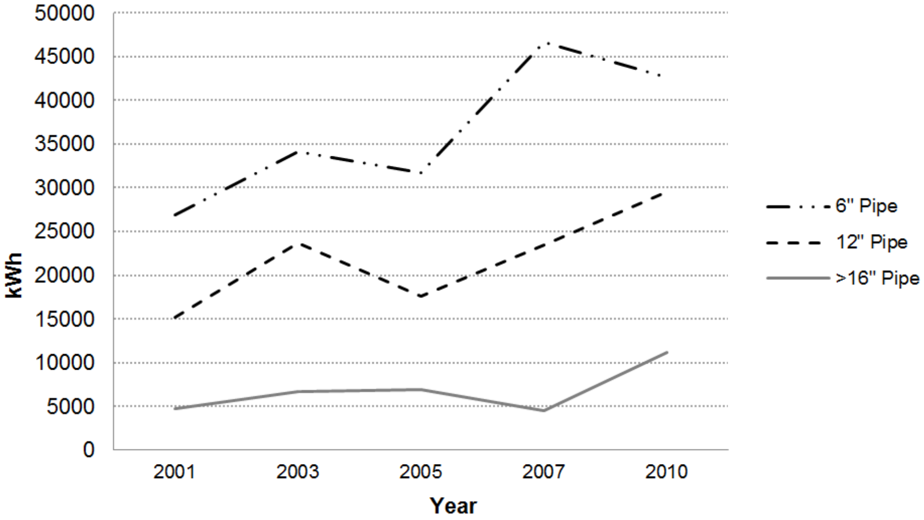


Figure 6: Energy Footprint of Water Main Breaks for Three Categories of Pipe Diameter

The analysis of this study revealed that as the diameter of the pipes increases (and the thickness increase), the energy footprint decreases. For example, the 6" pipes have a 1523 miles installation in the City A in compare with 12" pipes, which have 936 miles though the city.

Single factor sensitivity analysis was conducted to observe the impact of the different parameters on the energy footprint of the water main breaks. The variable with the highest uncertainty spans the largest range in the tornado diagram. Figure 7 shows the tornado diagram for the citywide energy footprint from water main breaks in City A. The tornado diagram captures the impact of water pipeline characteristics on energy loss of water supply and distribution system. Smaller diameter pipes with the oldest materials types as well as the higher installation lengths have higher energy footprints. PVC pipes with diameters higher than 16” have lower energy footprint rates. 12” PVC pipes and 6” PVC pipes have approximate similar energy footprints.

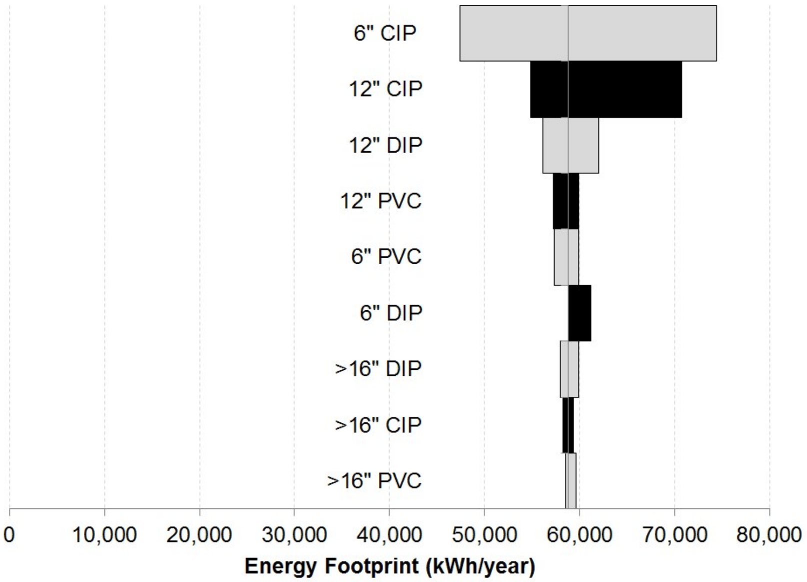


Figure 7: Tornado diagram for citywide energy footprint of water distribution system

3 CONCLUSION

This paper presented a framework to assess the energy loss of water main breaks to assist in decision making by water utilities in areas of energy cost and operation cost. A hybrid system dynamics-agent based modeling was proposed to evaluate the interaction between water main breaks and energy infrastructure system, as well as the micro-behavior of stakeholders toward water main break events. A system dynamic simulation framework was created and analyzed to estimate the water energy footprint of water main breaks based on the water distribution characteristics. Single factor sensitivity analysis was conducted to identify significant factors affecting the energy footprint of water supply and distribution system in a citywide case. For the case study, 6” CIP pipes were found to be energy-intensive components of water distribution system in case of water main break events, followed by 12” pipe material pipes. Large diameter pipes (greater than 16”) were also found to experience lower energy loss due to breaks in water distribution and supply system. The next stage of this research is implementing the agent based modeling to capture the stakeholders behaviors and potential increases in costs that may be passed on to the consumers from non-revenue water and energy loss.

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