VULNERABILITY ASSESSMENT OF WATER SUPPLY SYSTEMS FOR INSUFFICIENT FIRE FLOWS

A Thesis

by

LUFTHANSA RAHMAN KANTA

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject: Civil Engineering

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Approved by:

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Committee Members,	Francisco Olivera
	Sergiy Butenko
Head of Department,	David V. Rosowsky

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ABSTRACT

Vulnerability Assessment of Water Supply Systems
for Insufficient Fire Flows. (December 2006)
Lufthansa Rahman Kanta, B.S., Bangladesh University of Engineering and Technology
Chair of Advisory Committee: Dr. Kelly Brumbelow

Water supply systems' vulnerability towards physical, chemical, biological, and cyber threats was recognized and was under study long before September 11, 2001. But greater attention toward security measures for water supply systems was focused after the incidents of September 11, 2001. In response to those events, several acts have been passed by the United States Congress, and numerous vulnerability assessment tools and methodologies for water systems have been developed. Although water supply systems are vulnerable to many forms of terrorist acts, most of the vulnerability analysis studies on these systems have been for chemical and biological threats. Because of the interdependency of water supply infrastructure and emergency fire response, any substantial damage in a water system would be a significant threat towards the community.

In this study, attention is focused toward physical threats on water supply systems during a fire flow condition, and a methodology is developed to determine the vulnerable components of a water supply system during a fire event. The methodology utilizes dynamic programming optimization procedure to determine maximized disruption of fire flows as a function of number of attacks and/or failures in the water distribution system. Disruption is quantified at specific fire hydrants in two schemes using normalized values of (1) available flow and (2) available pressure and distance to the nearest operational fire hydrant. It is found that the pressure-based quantity is inferior to the flow-based one. However, using the flow-based disruption metric, clear functions of disruption versus failure number can be determined that exhibit discernable properties of robustness and resiliency – and the sequential failures in each.

This methodology is applied to the water supply system of Micropolis, a virtual city developed by Brumbelow et al. (2005), and vulnerability analysis is performed with fire at several possible locations. On the basis of the results, three mitigation strategies are proposed to harden specific sets of water mains and more simulations are performed on the hardened water supply system to assess its changed vulnerability. The results from the simulations of the mitigation strategies show that the recommendations on specific mitigation measures reduce the serious consequences from such threats.

DEDICATION

In loving memory of our daughter

Lamiya Zahin

(March 13, 2000 – August 2, 2004)

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1. INTRODUCTION

1.1.Background

Water systems are spatially diverse and are naturally vulnerable to physical, chemical/biological, and cyber threats. These types of threats might be caused by natural disaster and/or malevolent actions such as terrorist attack, vandalism or insider sabotage, and may cause serious consequences. The nature and degree of these threats to water systems vary mostly with the geographical location, population of the region, and accessibility of the system components. These threats towards water systems had been recognized long before September 11, 2001 and the water utility industry had taken some security measures against such threats, but not as many as since September 11, 2001. Water supply infrastructure is also connected to the critical infrastructures of electrical power, transportation, chemical industry, emergency services such as fire response, etc. Thus, any potential damage in water supply infrastructure would be a threat to those infrastructures as well, and vice versa.

In response to the events of September 11, 2001, attention has been drawn to the security issues of water infrastructure throughout the Unites States. Within a very short time after September 11, 2001, a number of acts were passed by the United States Congress such as the Bioterrorism Preparedness Act (P.L. 107-288) and Homeland

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This thesis follows the style of *Journal of Water Resources Planning and Management.*

Security Act (P.L. 107-297) that addressed the nation's water supply and water quality infrastructures and required vulnerability assessments to be performed to evaluate the potential threats towards those systems and to identify the corrective actions that might help to reduce or to mitigate the risk of serious consequences from adversarial actions. These acts also designated the United States Environmental Protection Agency (USEPA) as a lead federal agency to establish security measures and to safeguard water supplies from terrorist attacks and other malevolent actions. In response, USEPA has developed several vulnerability assessment methodologies/tools in association with other partner agencies such as American Water Works Association (AWWA), Department of Energy's Sandia National Laboratories, Association of Metropolitan Sewerage Agencies (AMSA) and various other agencies. Continuous studies and development of vulnerability assessment methodologies have been in progress by various public and private organizations, universities, researchers and students throughout the country since then.

1.2.Motivation of the Current Research

Water supply systems are generally constructed to provide sufficient water to the users with a specified pressure, quantity and quality. These systems consist of various major components like, pipes, valves, junctions, pumps, elevated storage tanks, water treatment plants, etc. The three competing goals for the water supply systems are: (1) reliable delivery of water even in case of emergencies like pipe failures, power outages, and, fires, (2) efficient and economic operation of the system, and, (3) meeting water quality standards mandated by USEPA (Mays 1996). These goals can be achieved by providing security against natural hazards and/or terrorist attacks and also by proper operation and maintenance of the system. The major maintenance activities in the water supply system include maintenance of the pumps, leak detection in the pipes, testing fire hydrants and valves, flushing the water mains, etc. Most of the system components are generally durable and can function for a long period of time without maintenance; but, if a single component fails because of mechanical malfunction or terrorist attack, it can hamper one or more of system's objectives. The repairing or replacing of damaged components generally takes a couple of days, but during this period the system must have adequate supply of water in the storage tanks to consistently provide water to the customers. The reason for this additional storage of water is the emergency services for fire response depend upon the fire suppression capacity of the water supply system. Thus, in case of fire, the system must provide adequate water with sufficient pressure for a certain period of time. If multiple main breaks or leakages occur during fire, the system might not provide water to suppress fire with required flow and pressure.

The present research of vulnerability assessment of the water supply system was inspired by the need to find out the most critical components/pipes of a water supply system during fire events. Using the dynamic programming optimization technique a methodology has been developed to determine the critical components/water mains of the system that maximize the damage caused by fire in the system. Knowing those critical system components a few mitigation strategies have been proposed like hardening those pipes, increasing security measures around those critical components, etc., so that the system can perform adequately when fire occurs in the system.

1.3.Organization of Thesis Sections

The present section has explained the need for vulnerability assessment of the water supply system during fire flow condition. Section 2 explains the concept of critical infrastructures and how the government of the United States addresses protection of those critical infrastructures. Section 2 also reviews various vulnerability assessment tools for the water systems those have developed since last decade.

Section 3 establishes a methodology for vulnerability assessment of the water supply system when fire occurs in the system. This section explains why it is important to identify the most critical pipes in the system during fire event and what techniques can be applied to locate those critical components. A methodology based on dynamic programming optimization procedure is developed to identify the most critical components of the water supply system of Micropolis, a virtual city model, during fire flow condition. The objective function of the optimization model is formulated to maximize damage caused by fire when one or more pipes has destroyed or disrupted. Based on available flow and pressure at the fire location, damage is evaluated and the pipes whose removal from the system caused the maximized damage are identified as the critical pipes for fire at that particular location.

Section 4 presents the results from the optimization model for fire at six selected locations in the Micropolis water supply system. Based on the results, three mitigation strategies are proposed in this section. With these mitigation strategies, more simulations are performed with fire at those selected locations and the results of mitigated and unmitigated conditions are compared. A benefit cost analysis is also performed to evaluate the economically optimum mitigation strategy for each of those selected locations.

Section 5 summarizes the research findings and recommends a new direction for further studies to make water systems even more secure in future.

2. LITERATURE REVIEW

2.1. Water Infrastructure and Its Vulnerability

Water infrastructure is a collection of several independent systems such as the water supply system, waste water system, and urban drainage system, each of which serves within a specific municipality or region (Haimes et al. 1998). In general, water infrastructure include surface and groundwater sources of untreated water, dams and reservoirs, raw water transmission networks, treatment facilities, tanks and reservoirs for storing treated water, water distribution networks, and waste water collection and treatment facilities (Copeland and Cody 2003). The water supply system can be further divided into sub-systems like raw water pumping and transmission systems, raw water storage and treatment systems, and water distribution systems (Mays and Tung 1991). Each of these systems is a collection of some specific components and sub-components; for example, the major components of a water supply system are pumping stations, elevated storage tanks, reservoirs, and a distribution network. Many types of entities own more than 75,000 dams and reservoirs, thousands of miles of water distribution and sewer lines, thousands of drinking water and wastewater facilities throughout the country. Although hundreds of dams and diversion structures are owned and operated by the U.S. federal government, the majority of the water infrastructure is owned and managed by public and private entities (Copeland and Cody 2003).

In 1996 President Clinton established the President's Commission on Critical Infrastructure Protection (PCCIP) which identified the eight nation's critical infrastructures like telecommunications, electrical power systems, water supply systems, gas and oil storage and transportation, banking and finance, transportation, emergency services, and continuity of government (Haimes 2005). The purpose of the PCCIP was to develop a national strategy to protect the critical infrastructures from potential attacks and to assure their continued operation. Later, the White House document of *National Strategy for the Physical Protection of Critical Infrastructures and Key Assets* (White House 2003) cited eleven critical infrastructures: agriculture and food, water, public health, emergency services, defense industrial base, information and telecommunications, energy, transportation, banking and finance, chemicals and hazardous materials, and postal and shipping. This document identified four sectors of water systems' vulnerability including physical, chemical/biological, cyber and interruption by another infrastructure's failure. Thus, the vulnerability of water supply infrastructure had been recognized, studied, and documented long before September 11, 2001. The reason for this attention towards the water supply infrastructure was that these systems must provide adequate supply of water with adequate pressure and required water quality to communities. Any physical damage to the system would interrupt the flow and pressure through the system, and introduction of any chemicals or microorganisms to the system would affect the water quality.

Haimes et al. (1998) recognized the potential threats against water supply systems and proposed a methodology to reduce the vulnerability of the system. The threats towards the water supply system were categorized as physical threats, chemical/biological threats, and cyber threats. The physical threats corresponded to the destruction of the physical components and control structures of the system caused by either natural disaster such as major floods, hurricanes, earthquakes, etc. or by terrorist attacks. Chemical/biological threats referred to the injection or addition of toxins, chemicals, radioactive materials or biological agents to significantly contaminate the supplied water and thereby to endanger the health of the community. Cyber threats corresponded to introduction of software viruses through computer networks to disrupt or disable Supervisory Control and Data Acquisition (SCADA) systems. Generally speaking, SCADA systems are the monitoring and control systems in the utility industries which help in operating the water system components with proper timing and sequence, measuring water quality parameters, etc., without physically accessing the network. Thus, SCADA systems can reduce operating cost for a water utility and thereby increase a water system’s efficiency. The proposed hardening methodology of the water supply system was based on the philosophy of Hierarchical Holographic Modeling (HHM) (Haimes 1981). Using the HHM philosophy, the water supply system was decomposed into fifteen categories representing the physical, temporal, organizational, managerial, institutional, hydrological, water quality, and other aspects of the system. The decision was then made to harden the system against natural disaster or terrorist attack in terms of security, redundancy, robustness and resilience. The security included surveillance, fences, and guards protecting the pumping stations, storage facilities, dams/reservoirs, treatment facilities, etc. Redundancy referred to the duplication and/or multiple means of emergency response for system components. Robustness corresponded to the increased insensitivity of the system to the model inputs of the system. Resilience referred to the state of the system when the system could be operated close to its optimum design criteria. Later Haimes (2002) proposed a strategic plan combined with the hardening of the water supply system by applying a well planned maintenance program and by standardizing the components of water supply and distribution systems. The author also stated that training, education, and technology transfer are essential to the hardening of any infrastructure. Although hardening of the water supply system could result in less vulnerability of the system, absolute hardening is unachievable.

Ezell et al. (2000a) developed the probabilistic Infrastructure Risk Analysis Model (IRAM) and applied this to a small water supply and treatment system (Ezell et al. 2000b). The IRAM consisted of four phases: (i) identifying the risk to the infrastructure, (ii) modeling the risks, (iii) assessing the infrastructure, and, (iv) managing the risk to the infrastructure. The Hierarchical Holographic Modeling (HHM) (Haimes 1981) philosophy was adopted to decompose the system with respect to vulnerability, state, function, and hierarchical structure and the threats to the infrastructure were identified. A risk model was then developed to describe the consequences and to estimate the probability of mitigating events' success and failure. Using the Partitioned Multi objective Risk Method (PMRM) (Asbeck and Haimes 1984) the system's performance was assessed under potential threats. Finally, the risk management was performed by multi-objective tradeoff analysis. Later Ezell et al.

(2000b) demonstrated the applicability of IRAM by applying the model to an actual municipal water distribution system. This approach could also be used in other complex, interconnected infrastructures like electric power and transmission, telecommunications, etc.

Matalas (2005) viewed the probabilistic approach of assessing vulnerability of the water supply systems in a different way. The author stated that the probabilistic measures could be adopted when the future could be predicted. For instance, natural hazards like floods, droughts, storms and earthquakes can be predicted from the past hydrology, recurrence intervals, severity of consequences, etc.; but terrorist attacks are "unique episodes," and it could be questionable to apply strictly probability-based approaches in such cases. However, the author did not recommend any definite approach to such problems as terrorist acts.

2.2. Security Concerns in Response to September 11, 2001

In June 2002, the U.S. Congress passed the Bioterrorism Preparedness Act (P.L. 107-288) which required that all community water systems within the U.S. serving more than 3,300 people needed to complete vulnerability assessments and prepare emergency response plans. In November 2002, Congress passed the Homeland Security Act (P.L. 107-297) and created the Department of Homeland Security to secure the nation's critical infrastructures including the water infrastructure without interfering with the responsibilities of U.S. Army Corps of Engineers (USACE) or U.S. Bureau of

Reclamation (USBR) in protecting their respective dams and with the responsibilities of USEPA in assisting the water and wastewater utilities (Copeland and Cody 2003).

As a lead agency in assisting water infrastructure security, USEPA granted funding to develop several security tools for vulnerability assessment including: Risk Assessment Methodology for Water Utilities (RAM-W), Vulnerability Self Assessment Tool, and Security Self Assessment Guide for Small Systems Serving between 3,300 and 10,000 (Mays 2004). In developing those tools, the American Water Works Association Research Foundation (AWWARF), Sandia National Laboratories, Association of Metropolitan Sewerage Agencies (AMSA), National Rural Water Association (NRWA) and Association of State Drinking Water Administrators (ASDWA) worked with the assistance of USEPA. USEPA also developed a water utility response, recovery and remediation guidance for man-made and/or technological emergencies (Mays 2004).

Ostfeld and Salomons (2004) presented a methodology to detect accidental or deliberate intrusions of harmful chemicals and microorganisms to the water distribution system. This method consisted of finding the optimum locations of a set of monitoring stations, called an early warning detection system (EWDS), throughout the distribution network to reliably identify a contamination event in the system. Assuming that the contaminants could be injected through the water distribution system nodes such as sources, tanks, and consumers, a randomized pollution matrix (RPM) was constructed to provide a stochastic representation of the consequences of a set of randomized contaminant intrusion events applied at the nodes. Selecting a number of candidate monitoring stations, a genetic algorithm (GA) was applied on the RPM for searching a set of monitoring stations which could detect all or most of the pollution events. On the basis of this search result, the optimal locations of the monitoring stations were selected. Because the water distribution systems are vulnerable to potential chemical and biological threats, this real-time pollutants monitoring system could be applied in conjunction with network modeling to detect and to keep track of hazardous contaminants throughout a water distribution system.

Kumar et al. (1997) and Al-Zahrani and Moied (2001) performed similar approaches to identify optimal location of water quality monitoring stations in water distribution networks. In the former study, the optimal locations were identified using Integer Programming; in the later one a Genetic Algorithm was adopted. Bahadur et al. (2003) proposed a methodology to monitor introduced contaminants in water distribution systems using extended period simulation model and GIS data.

Tidwell et al. (2005) proposed an alternative approach of threat assessment of water supply systems using Markov Latent Effect (MLE) modeling. “A latent effect is an occurrence, condition, or behavior that does not necessarily cause an immediate problem but that can subsequently combine with other occurrences, conditions, or behaviors” (Tidwell et al. 2005). In this method, a complex threat system was decomposed into sub-systems or decision elements to track down a particular threat from its origin to the point of consequence. Each of these decision elements subjected to inputs and produced an output; these inputs were the latent effects and external effects. To reflect the strength of the relationship between the decision element and the external effect, each of the external effects were assigned an attribute value mapped onto a scale of 0 to 1 representing very weak to very strong relations respectively. All decision elements were then aggregated and an assessment score was obtained which provided a measure of the credibility of a threat. The authors applied the proposed methodology to a real municipal water distribution system under two different modes of attack: bomb and injection of a toxin and evaluated the level of security of the system under both of those threats.

Lewis (2006) developed a comprehensive method to analyze infrastructure vulnerability in different sectors called Model Based Vulnerability Analysis (MBVA) and thereby suggested a method of allocating limited resources to improve the infrastructure security and to reduce the risks. Applying the “Network Theory” Lewis (2006) modeled different critical infrastructures such as, water system, power, telecommunication, internet, etc., as mathematical graphs containing nodes and links where nodes are connected by links. The network was then tested to see if it was a “scale-free” network or not. Unlike random graphs which follow a Poisson distribution of links, the scale-free networks are generally nonrandom in structure and they follow a power law distribution of links. The scale-free network testing involved counting the “degree” of nodes, which is the number of links connected to each node, and plotting the node frequencies as a histogram. If the shape of the resulting histogram followed a power law then the network would be a scale-free network. From the resulting histogram, the nodes with maximum degree would be identified as the critical nodes. The critical nodes were then modeled as a fault tree, which is a tree structured graph of critical nodes. Each critical node was represented as a component and the root of the tree was represented as the sector, for example, a water supply system can be considered as a sector and a reservoir with highest degree can be considered as a critical component. The fault tree model was then analyzed using an event tree, which is a binary tree that represents all possible combinations of failure events generated by the fault tree. The sector vulnerability was then calculated from the estimate of component vulnerability, which is the probability of a successful attack on the component. Risk at each critical node was then computed as the component vulnerability multiplied by the estimated damage caused by the component failure. The overall sector risk was also computed and the cost of hardening the critical components was estimated as well. Lewis (2006) also proposed four strategies to allocate the limited available resources for hardening the critical nodes and thereby reducing the vulnerability, these are: (1) manual risk reduction, (2) ranked order risk reduction, (3) optimal risk reduction, and, (4) apportioned risk reduction.

Newman (2003) also studied the behavior and characteristics of complex networked systems like the Internet, the World Wide Web, social networks, and biological networks and discussed the degree distribution of complex networks. Because “degree” of a node represents the number of edges connected to that node, removal of nodes from a network will result in loss of connectivity between the nodes and this makes higher degree nodes more vulnerable to deliberate attack/removal. Newman (2003) discussed various stochastic approaches to understand the function and workings of those network systems; however, most of his studies were on information networks and social and biological networks.

A significant number of studies on water infrastructure security have been done in last two decades; with a few exceptions, most of those security studies have evaluated chemical or biological threats even though these systems are vulnerable to physical threats as well. Few water supply systems rely on computer-based operation; thus, the vulnerability of these systems to cyber threats is relatively less than to other threats (Haimes et al. 1998). Various components of urban water supply system offer the greatest opportunities for terrorism because of the relative accessibility of these components: pumps, tanks, pipelines, valves, meters, etc. (Mays 2004). Any physical destruction of these components may result in simultaneous main breaks, loss of water pressure and flow through the network which would result in hindering fire fighting capabilities. In this study an effort has been made to assess the vulnerability of a city's water supply system during fire flow condition when one or more of the system's physical components are destroyed or disrupted.

3. OBJECTIVE AND METHODOLOGY

3.1. Rationale

The urban water supply system is indispensable to any city's daily activity because the system not only ensures safe drinking water to the end users but also provides adequate water to meet domestic, commercial, and industrial needs. To ensure safe delivery to the water users, the water supply system is generally designed to fulfill the base demand with additional capacity for emergency demand conditions such as broken pipes/valves, fire demand, pump and power outages, etc. (Mays 2004). These types of emergency loading conditions might arise because of mechanical failure of the system during a natural disaster or due to terrorist attacks. In such conditions the system might not deliver water to the end users with sufficient flow and pressure. An example of an engineering design standard is that of the cities of Bryan and College Station, Texas, where under normal conditions, a static pressure of 35 psi (pounds per square inch) is maintained throughout the system to meet Texas Commission on Environmental Quality (TCEQ) requirements (Cities of Bryan and College Station [BCS] 2005); but when a segment of a system is damaged it might not maintain the required pressure at certain locations. Moreover, when there is a fire in the system, the demand at the fire location increases instantly and the system needs to deliver a specified volume of water under a required minimum pressure at this fire location. For instance, according to BCS (2005), during a fire event a flow of 1,000 gpm (gallons per minute) is required for single family residential areas and a flow of 2,500 gpm is required for commercial or multi-family residential areas; while these flow rates are provided, a minimum of 20 psi pressure has to be maintained at fire hydrants for fire fighting. This minimum pressure requirement is to overcome the head losses between fire hydrants and fire-engine pumps (Mays 2004). If either or both the flow and pressure requirements are not fulfilled, the fire demand is not satisfied.

To ensure reliable delivery of water for fire fighting, water mains are generally laid in a grid pattern so that if a single section fails, the damaged section can be isolated and the remainder of the system would still provide adequate flows and pressures at different fire hydrants near the fire location. But if multiple segments fail, the water supply system might not provide the security required by the community. In this study, a methodology based on solving a dynamic programming problem has been adapted in order to find out which components of a vulnerable water supply system are most critical during a fire flow condition. Following the vulnerability analysis, recommendations are made for specific mitigation measures such as hardening system pipes and other components, adding new network pipes, increasing security around pump stations and elevated storage tanks, etc.

3.2. Model Formulation

A water supply system can be viewed as a collection of links connected to nodes (Rossman 2000). Typically the major physical components of a water supply system are pipes, pumps, control valves, junctions, tanks, reservoirs, etc. Pipes are those components in the system that convey water from one location to another, and they can be of different length and diameter. Based on whether a particular pipe is directly connected to a user or not, the pipes can be classified as water mains or service lines. In general, pipes with larger diameter conveying water from the sources such as reservoirs, tanks, etc. to different locations of a city are called water mains. Pipes with relatively smaller diameter carrying water from the mains toward the end users are called the service lines, however, a service line can have larger diameter than that of a water main. In a similar manner, a junction node can be named differently depending upon its location in the network: terminal node, intermediate node, fire hydrant, etc. The terminal nodes are laid at the end points of the service lines representing the end users of the network and the intermediate nodes are laid along the water mains where the service lines, pumps and valves are joined with the mains. The fire hydrants are also laid at the end points and are used in connection with a fire-engine pump and a fire hose only during occurrence of fire. Because of the functional interdependency of different physical components of the water supply system, the performance of the whole system depends upon the performance of each component. When a single component of a system is destroyed or disrupted, it causes some damage to the entire system; the severity of damage would depend upon the type of the component destroyed, location and purpose of that component in the system, and also the number of customers who are served by that system component. For example, if a service line fails, only the customers who use that particular segment of the network would be affected; but if the pump station or a tank is destroyed, the entire system can fail, and this might affect the whole community. Because different components of a water supply system cause different levels of damages when destroyed, destruction of specific components can be conceptualized as a form of decision making. Sometimes water mains are more accessible than pump stations or tanks since the mains are laid along the highways, bridges, etc. Simultaneous destruction of multiple mains might cause the same level of damages as caused by destruction of a pump station or a tank. Thus, destruction of multiple numbers of mains/components can be viewed as interrelated decisions or multistage decisions.

There are two general approaches to solve this type of problems: conventional procedures and optimization procedures (Mays and Tung 1991). Conventional procedures are typically based upon simulation models. Even though conventional methods are more flexible in representing the characteristics of an actual system, the solution process is generally iterative which requires rigorous trial and error. On the other hand, optimization procedures eliminate the trial and error process and provide the best solution based upon the objective function and the constraints (Mays and Tung 1991).

An optimization problem can be categorized as linear or non-linear, deterministic or probabilistic, static or dynamic, discrete or continuous, depending upon the type of the objective function and the constraint equations (Mays and Tung 1991). In this study, the dynamic programming optimization technique is adapted primarily because of two reasons: (1) identifying the most critical components of a water supply system is a multistage decision problem, which dynamic programming can handle effectively; and (2) hydraulics of pipe network consists of non-linear equations which could not be solved using readily available linear programming packages. Unlike linear programming and some non-linear programming, commercial software packages of dynamic programming are not generally available; so a dynamic programming code has developed using Microsoft Visual Basic 6.0. The hydraulic simulation software EPANet 2.0 (Rossman 2000) has coupled with Visual Basic using EPANet Programmer's Toolkit (Rossman 1999) to compute flow and pressure at different locations of the network.

3.2.1. Objective Function

The objective of the vulnerability assessment optimization model is to maximize the damage adjacent to a single fire hydrant node caused by destruction or disruption of system components such as pipes, pumps, tanks, etc., during occurrence of fire. Mathematically, the objective function can be expressed as:

$$\text{Maximize } Z = J\,(\text{pipe hydraulics};\ u_1, u_2, \ldots\ldots, u_N) \qquad (3.1)$$

where, Z = Total damage to the system;

J = Damage function calculated on the basis of pressure and flow at the fire node when one or more of the system components are destroyed or disrupted;

“pipe hydraulics” = Physical laws that govern flow and pressure in pipe networks;

u_i = Decision variable at any stage i, where $i = 1, 2, 3, \ldots.., N$; and

N = Total number of stages in the problem.

Because of the minimum requirements of both pressure and flow to suppress a fire (BCS 2005), the fire flow condition was analyzed twice and the damage function *J* was formulated in two alternative ways described below.

3.2.1.1. Pressure Based Damage Function

When fire occurs at a particular location, the demand at that node increases due to withdrawals by fire engines to suppress the fire. To determine the available pressure at fire node during a fire event, the demand at fire node is assumed to be equal to the base demand or average demand by the consumer plus the fire demand, which is assumed here to be 1,000 gpm for a single family residential area, or 2,500 gpm for a multifamily or commercial area (BCS 2005). With this added demand, a single period hydraulic simulation is performed using EPANet (Rossman 2000) and the resulting pressure at the fire node is noted and compared to the required minimum pressure for fire fighting which is 20 psi. The pressure based damage function *J* is then calculated as follows:

$$J = \begin{cases} \alpha \, [(P_{req} - P_{fire\text{-}node}) / P_{req}] + \beta \, [L_{operable} / R_{max}] & \text{for } P_{fire\text{-}node} < P_{req} \\ 0 & \text{for } P_{fire\text{-}node} = P_{req} \\ \gamma \, [(P_{req} - P_{fire\text{-}node}) / P_{req}] & \text{for } P_{fire\text{-}node} > P_{req} \end{cases} \qquad (3.2)$$

where, P_{req} = minimum required pressure for fire fighting (e.g., 20 psi);

$P_{fire\text{-}node}$= available pressure at fire node from hydraulic simulation (psi);

$L_{operable}$=distance to the nearest operable hydrant (i.e., hydrant at which the fire flow can be withdrawn at pressure greater than or equal to P_{req}) (ft);

R_{max} = allowable radius from the fire node to the nearby hydrants (ft); and

α, β, γ = weighting coefficients with $\alpha + \beta = \gamma = 1$.

At the fire node the demand is always positive but the available pressure ($P_{fire\text{-}node}$) can be positive, zero, or even negative. The negative pressure situation can be explained as follows: in water distribution systems, water flows from areas of higher energy to areas of lower energy. This “energy” consists of three terms: potential energy, pressure energy and kinetic energy, expressed in units of length representing vertical height of water column. While moving from higher energy to lower energy, some energy is used up by water which is called the head loss. When head loss between two points A and B, for example, becomes too high then water cannot actually flow from point A to point B. In such a situation, the hydraulic model EPANet (Rossman 2000) gives a negative pressure at point B. Because pressures below 0 psi incur high probabilities of cavitation, which would be damaging to fire engine pumps, during calculating pressure based damage function (equation 3.2) any values of $P_{fire\text{-}node}$ less than 0 would be unacceptable and thus in such a case and also in the case when $P_{fire\text{-}node}$ equals to 0, the pressure term $[(P_{req} - P_{fire\text{-}node}) / P_{req}]$ reduces to 1. When the available pressure at fire node is P_{req} or 20 psi then the pressure term $[(P_{req} - P_{fire\text{-}node}) / P_{req}]$ in equation 3.2 reduces to 0 and when the available pressure at fire node is more than P_{req} or 20 psi then the pressure term $[(P_{req} - P_{fire\text{-}node}) / P_{req}]$ becomes negative. The distance term $[L_{operable} / R_{max}]$ is added to the pressure based damage function (equation 3.2) only when the available pressure at the fire node is less than the required pressure, which is 20 psi. The fire hydrants are generally located 1000 ft apart along the distribution network. During a fire event, if the hydrant at fire location can not deliver water at required pressure then water is obtained from the nearest operable hydrant. A hydrant will be operable if the pressure at that hydrant is at least 20 psi in case of fire at that location. The length of the fire hose carried by a fire engine is generally about 1000 ft, and if at least two fire trucks are available during a fire condition then water can be obtained collectively from a radius of 2000 ft around the fire location. Thus R_{max} is here 2000 ft assuming at least two fire trucks are available during a fire event at any location. The value of $L_{operable}$ will vary from greater than zero to 2000 ft and thus the distance term will always be less than or equal to 1. When the available pressure at fire location is greater than or equal to P_{req} or 20 psi then there is no need to get water from the nearby hydrants and thus the distance term is not added to the pressure term in such conditions (equation 3.2). Both the pressure term $[(P_{req} - P_{fire\text{-}node}) / P_{req}]$ and the distance term $[L_{operable} / R_{max}]$ in the pressure based damage function equation are dimensionless, and the relative influence of these two terms is specified through the coefficients α, β and γ. The values of the coefficients α and β are assigned in such a way that α plus β will always equal to 1. When the available pressure at the fire node is sufficient to suppress the fire, there is no need to get additional supply from nearby hydrants; thus, the pressure based damage function (equation 3.2) is independent of the distance term [$L_{operable}$ / R_{max}] and the value of γ will always equal 1. Therefore, values of the pressure based damage function will vary from negative values (indicating more than sufficient pressure at needed fire flow) to 1 (indicating complete failure of the water distribution system to supply water for fire fighting).

3.2.1.2. Flow Based Damage Function

A formulation of the damage function that compares available flow rate to needed flow rate is also possible. In this formulation, pressure at the hydrant node is fixed at its minimum and available flow is determined using the hydraulic model; this contrasts with the above section where flow was fixed and available pressure was determined. In the hydraulic model, the flow through a fire hydrant can be modeled at fixed pressure by specifying the node to be an "emitter" (Rossman 2000). An emitter is a device that discharges water to the atmosphere through an open orifice. Flow through an emitter is proportional to the square root of pressure available at that node: $q = Cp^{0.5}$, where q = flow through the emitter in gpm; p = available pressure in psi; and C = discharge coefficient for emitter in gpm/psi$^{0.5}$ (Rossman 2000). To determine the maximum flow available at a fire hydrant, the available pressure is assumed to be 20 psi and a discharge coefficient for that emitter is determined according to the hydrant's physical characteristics. For a 10-inch diameter connection fire hydrant $C = 1850$ gpm/psi$^{0.5}$, and for a 3-inch diameter connection $C = 166.5$ gpm/psi$^{0.5}$. Then a single period hydraulic simulation is performed, and the free orifice flow at the hydrant (noted as the emitter's "actual demand" in the simulation result) is determined. The maximum available flow at the fire node would be the "actual demand" minus "base demand" (Rossman 2000); that is, if normal consumer demands were also associated with a node, they would be subtracted to find the flow available exclusively for fire fighting. The flow based damage function J is thus calculated as follows:

$$J = \begin{cases} \alpha\,[(Q_{req} - Q_{max\text{-}available}) / Q_{req}] + \beta\,[L_{operable} / R_{max}] & \text{for } Q_{max\text{-}available} < Q_{req} \\ 0 & \text{for } Q_{max\text{-}available} = Q_{req} \\ \gamma\,[(Q_{req} - Q_{max\text{-}available}) / Q_{req}] & \text{for } Q_{max\text{-}available} > Q_{req} \end{cases} \tag{3.3}$$

where, Q_{req} = required flow for fire fighting according to regional fire code (gpm);

$Q_{max\text{-}available}$ = maximum available flow at fire node from hydraulic simulation = ["Actual demand" – "Base demand"] (gpm);

$L_{operable}$=distance to the nearest operable hydrant (ft);

R_{max} = allowable radius from the fire node to the nearby hydrants (ft); and

α, β, γ = weighting coefficients with $\alpha + \beta = \gamma = 1$.

When the available flow at a fire node is less than the required flow (Q_{req}) for fire fighting the flow term [($Q_{req} - Q_{max\text{-}available}$) / Q_{req}] in equation (3.3) becomes less than 1. When the available flow is equal to Q_{req} then the flow term [($Q_{req} - Q_{max\text{-}available}$) / Q_{req}] becomes 0, and when the available flow at fire node is greater than Q_{req} then the flow term [($Q_{req} - Q_{max\text{-}available}$) / Q_{req}] becomes negative. The distance term [$L_{operable}$ / R_{max}] is added to the flow based damage function (equation 3.3) when the available flow at the fire node is less than the required flow. In such a case water is generally obtained from the nearest operable hydrants to suppress the fire. For the cases when the available flow at fire location is greater than or equal to the required flow for fire fighting there is no need to get water from nearby hydrants and thus the distance term [$L_{operable}$ / R_{max}] is not added with the flow term [($Q_{req} - Q_{max\text{-}available}$) / Q_{req}]. Like the pressure based damage function (equation 3.2), the flow based damage function (equation 3.3) is dimensionless, and the relative significance of flow term [($Q_{req} - Q_{max\text{-}available}$) / Q_{req}] versus the distance term [$L_{operable}$ / R_{max}] is determined by the coefficients α, β, and γ. The values of the coefficients α and β are assigned so that α plus β will equal to 1. The value of γ would always be equal to 1 since this coefficient is used in calculating the flow based damage function only when the available flow at a fire node is more that the required, which means there is no need to get additional water from nearby hydrants during fire condition. Because $L_{operable}$ varies between 0 and R_{max} , the distance term [$L_{operable}$ / R_{max}] will always be less than or equal to 1. Thus the value of the flow based damage function (equation 3.3) will vary from some negative values to some values less than or equal to 1.

3.2.2. Decision Variables

The dynamic program decision variables are the elements of the system which are to be destroyed or disrupted. It is obvious that destroying the pumping station or the elevated storage tank would not only cause the maximum damage to the system but would also be a matter of straightforward computation of damage using EPANet (Rossman 2000). On the other hand, destruction or disruption of multiple pipes to cause maximized damage is a matter of multistage decisions. In this study, only the water mains are considered to be destroyed or disrupted and thus the water mains are the model decision variables and are represented as the u's in equation 3.1. The subscripts with the decision variable u represent the indexes for stages.

In dynamic programming problems, stages are the points of the problem where decisions are to be made. In this study, decisions are to be made whether or not each water main/component is to be destroyed. Thus every water main of the system corresponds to a stage and the total number of water mains will correspond to the total number of stages in this problem. Again, only one decision has to be made at each stage: whether or not the particular water main is destroyed or disrupted. If a water main is destroyed at any current stage then the decision variable would be 1 for that stage, if not, then the decision variable would be 0. Thus,

$$u_k = \begin{cases} 1 & \text{if component is destroyed or disrupted} \\ 0 & \text{if component is not destroyed or disrupted} \end{cases} \qquad (3.4)$$

Where, u_k = decision variable at any current stage k.

3.2.3. System State and Constraints

In dynamic programming, the "state" or the current condition of the system is expressed by the system state variables X_k. These variables describe the current state of the system at any stage k. These state variables can link the successive stages of a dynamic programming problem in such a way that each stage is optimized separately and the resulting decision remains feasible for the entire problem (Mays 1996). The function that expresses the relationships between the input state, the output state and the decision at each stage is called the "state transition function".

The system constraints include the limits to the state variable X_k. In this model the maximum allowable failures, meaning, the maximum number of water main/component to be destroyed, will be set as X_{max}. Thus, at any stage the state variable will always be less than or equal to X_{max}. Furthermore, the decision at a current stage k would depend upon the decision that has made in the previous stage k-1. For example, if a certain pipe has destroyed at any stage, then it is impossible to destroy it again in a later stage. The model state transition function and the constraints can be expressed as:

$X_k = X_{k-1} + u_k$ State Transition Function (3.5)

$X_0 = 0$ Initialization constraint (3.6)

$X_N \leq X_{max}$ Terminal constraint (3.7) where, X_k = state variable at any current stage k;

X_{k-1} = state variable at any previous stage k-1;

u_k = decision variable at any current stage k;

X_0 = state variable at "zero-th" stage;

X_N = state variable at final stage;

X_{max} = maximum allowable failures (or, elements to be destroyed); and

N = total number of stages in the problem.

3.3. Model Development and Application

After September 11, 2001, because of security concerns, water utilities throughout the U.S. have restricted access to detailed information on most urban water supply systems. In response to this concern for security of real systems' data, Brumbelow et al. (2005) developed a virtual city water supply system named "Micropolis" to support further studies on urban water supply systems security. Micropolis is a detailed model of a virtual small town, with a population of 5,000. Its water infrastructure model consists of one surface reservoir, one aquifer, one elevated tank, 8 pumps, 1088 pipes, 1262 junction nodes, 52 fire hydrants and 196 valves. Among those 1088 pipes there are 574 water mains which will be considered to be the stages in the optimization model because the destruction or disruption of those water mains would be more critical than destruction of service lines.

Using the dynamic programming formulation described above, an optimization model was developed using Microsoft Visual Basic 6.0 and the Micropolis water supply system. In order to calculate the objective function (equation 3.1), EPANet (Rossman 2000) hydraulic simulation model is coupled with the optimization model using EPANet Programmer's Toolkit (Rossman 1999). The flow chart for the algorithm of the optimization model is presented in Fig. 3.1 and the program code for the model has presented in APPENDIX-C. The inputs and outputs of the optimization model are as follows:

Model Inputs: (1) the network file of the water supply system,

(2) the EPANet report file and the output file name,

(3) maximum allowable failures,

(4) location of fire,

(5) required pressure for fire fighting,

(6) required flow for fire fighting,

(7) allowable radius to be considered for nearby hydrants, and

(8) damage function type (pressure based or flow based) to be used for the particular computation.

Model Outputs: (1) optimal decisions (u^*), these are the components/water mains of the network which if destroyed or disrupted would cause the maximum damage to the system under a fire flow condition,

(2) optimum damage function value (J^*), and

(3) operable nodes for that particular fire location.

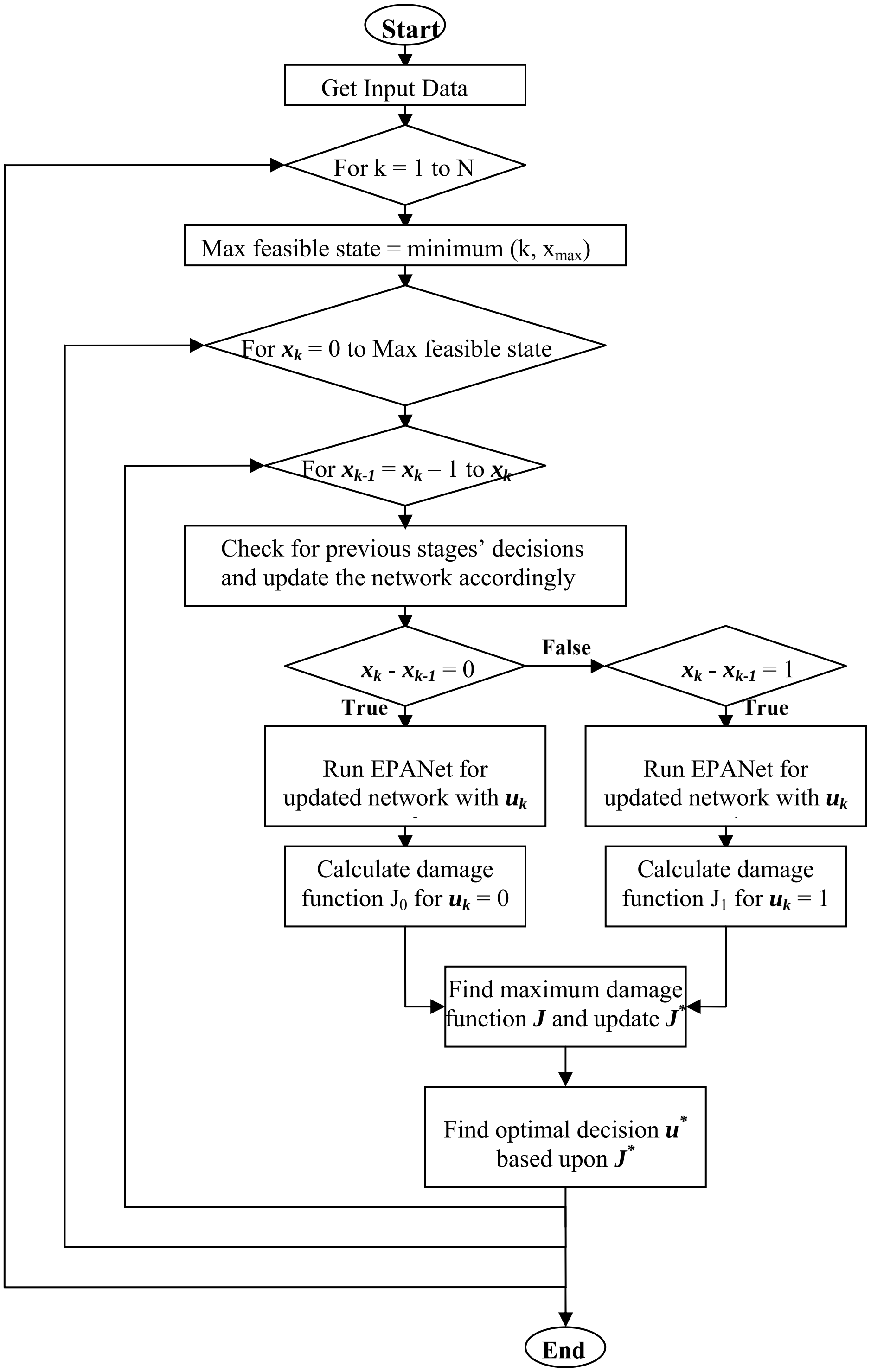

Fig. 3.1. Flow chart of the dynamic programming optimization procedure

The city of Micropolis has 52 fire hydrant locations and thus the fire flow analysis can be performed on each of those 52 hydrants. Because the hydrants are located at a distance of 500 ft to 1000 ft apart along the water mains, most of the hydrants in a close proximity along the same water main may respond to fire demands and system damage in a similar manner. In order to eliminate the repetition of results and also to reduce the time needed for analysis, six vulnerable fire locations throughout the city were selected for intensive analysis.

For each fire hydrant the input data of the network file, required pressure for fire fighting and allowable radius for nearby hydrants are set constant; the required flow for fire fighting is either 1000 gpm or 2500 gpm depending upon the location of the fire hydrant (BCS 2005). Using the maximum allowable failures X_{max} equal to 1, 2, 3, etc., the simulation was performed using both the pressure based and flow based damaged function (equation 3.2 and 3.3).

As stated previously, all the 574 water mains have been considered as the stages for the dynamic programming optimization model. Thus for each value of the allowable state the model steps through 574 stages and at each stage the model calculates the damage function (equation 3.2 and 3.3) using the EPANet hydraulic simulation model (Rossman 2000). During this process the optimization model has to call the EPANet Toolkit functions (Rossman 1999) residing in a dynamic link library (DLL) software file repeatedly, and a situation eventually arose where the DLL failed to execute because of insufficient memory in the machine used for simulations. Accommodating this issue of memory constraints to allow full inclusion of all 574 stages was deemed outside the scope of this study. Instead, the number of dynamic programming stages was reduced to overcome the problem. Because of the presence of intermediate nodes along the water mains, a single water main is often divided into different segments and enumerated as several mains in the hydraulic model. To reduce the number of stages in the optimization model, 55 representative water main segments were chosen from the 574 water mains to be the stages used in the dynamic programming solution. The 55 water mains selected were chosen as relatively large diameter pipes that collectively described the system topology and connectivity. That is, the 55 selected mains represent the most important ones in terms of probable flow and importance of connections to multiple system nodes. The 55 selected water mains used as dynamic programming stages are listed in Table 3.1.

The model is applied in an iterative fashion. For each of the six critical fire hydrant locations, the maximum allowable failures (X_{max}) is set to 1. Now using the dynamic programming optimization model's pressure based damage function, the single most critical water main of the system (i.e., the one whose removal from the system results in maximum damage) is identified. Then the maximum allowable failures (X_{max}) is set to 2 and using the model the 2 most critical system components are identified. This process continues to increasing numbers of attacks/failures of mains.

It is expected that, as the number of maximum allowable failures (X_{max}) will increase, the damage (equation 3.1) will also increase; however the damage will not increase indefinitely. By increasing the number of maximum allowable failures (X_{max}) a state will be reached when any incremental increase in number of component failure will not contribute to any incremental increase in damage; this condition is referred to as a "plateau." For each of the six selected fire locations, the maximum allowable failures (X_{max}) is increased from 1 to until the pressure based damage reaches a plateau.

Table 3.1. List of Water Mains Used as Stages in the Model

Main ID	Length (ft)	Diameter (in)	Main ID	Length (ft)	Diameter (in)
MA478	179.56	12	MA766	145.00	12
MA495	217.04	12	MA772	110.56	12
MA505	127.24	8	MA788	108.96	12
MA549	189.16	2	MA793	134.80	12
MA552	201.96	12	MA802	201.96	12
MA565	104.96	12	MA811	222.76	12
MA576	195.76	12	MA814	167.72	12
MA591	224.80	4	MA817	174.44	12
MA599	208.56	4	MA819	163.44	12
MA609	265.60	12	MA821	6.00	12
MA610	337.64	4	MA823	299.76	12
MA638	175.80	12	MA864	228.44	6
MA647	200.12	8	MA883	164.00	6
MA654	155.44	8	MA895	237.12	6
MA662	136.56	8	MA906	206.20	6
MA672	403.68	8	MA925	209.76	6
MA676	388.96	8	MA963	361.56	12
MA678	405.88	8	MA964	366.6	8
MA679	373.20	8	MA965	234.80	4
MA691	369.80	4	MA989	263.12	12
MA693	155.84	4	MA991	355.04	12
MA728	343.44	4	MA997	273.92	12
MA735	192.20	4	MA1006	160.76	12
MA737	398.36	4	MA1013	361.80	6
MA740	353.12	4	MA1019	390.36	6
MA745	99.16	12	MA1020	363.56	6
MA749	105.48	12	MA1024	370.96	6
MA758	153.20	12			

As mentioned earlier, when the available pressure at the fire node is less than the required then water is obtained from nearest operable hydrants. But if a situation arises where none of the nearby hydrants remains operable, then there is no other way to obtain water for suppressing the fire and the system will fail. The computation will be stopped in such a condition. The same procedure is repeated for all six fire locations using the flow based damage function.

The number of failures versus damages and corresponding optimal decisions with list of operable nodes for both the pressure based and flow based damage functions at all six critical fire locations have been tabulated in APPENDIX-A. During the simulation, the chosen values of the coefficients α and β are 0.99 and 0.01 respectively. The coefficient α corresponds to the weight of the pressure term (equation 3.2) and flow term (equation 3.3) in the damage function equations when the pressure and/or flow at the fire hydrant is less than the required according to the regional fire code. The coefficient β corresponds to the weight of the distance term in pressure based and flow based damage function when water to be obtained from a nearby hydrant in the event of less available pressure and flow at the fire hydrant. As the hydrant at a fire location will more significantly contribute water with required pressure and flow than that from a nearby hydrant, the value of the weighting coefficient α is kept significantly higher than the value of the coefficient β. The selection of the values of the coefficients α and β is a choice made by the analyst. To demonstrate the effect of the coefficients α and β in damage function equation, a sensitivity analysis has also performed using different values of the coefficients α and β, and the resulting failure versus damage curves for different values of α and β have been presented in APPENDIX-B.

4. RESULTS AND DISCUSSION

4.1 Introduction

This section applies the vulnerability assessment methodology described in Section 3 to the water system of Micropolis. First the methodology is applied to some selected locations of the water system to assess the system's vulnerability during fire flow conditions. The results from the optimization model are then interpreted in terms of the system's "robustness" and "resilience" and are summarized using the terms "Green Light," "Yellow Light," and "Red Light" conditions to describe the state of the system during a fire event.

Analyzing the results, three mitigation strategies are proposed to reduce the vulnerability caused by destroying or disrupting the critical pipes during occurrence of fire. Later in this section, the proposed mitigation strategies are applied in the same selected locations of the Micropolis water system and the results from both the unmitigated and the mitigated conditions are analyzed and compared to describe the effectiveness of the proposed methodology.

Finally, a benefit-cost analysis is performed at each selected location to evaluate the most economically optimum mitigation strategy for the system under fire flow condition. During the analysis, fixed values of the weighting coefficients α and β referring to the damage function equations (equations 3.2 and 3.3) are used. To demonstrate the model's sensitivity toward the weight of the pressure and flow terms (equations 3.2 and 3.3) compared to the distance term, different values of the coefficients α and β are used under unmitigated condition and the results from this analysis are described at the last part of this section.

4.2 Results of the Vulnerability Analysis

Using the methodology described in the previous section, vulnerability analysis was performed for six fire hydrant locations: HY17, HY29, HY40, HY53, HY61, and HY66. Among those six hydrants, HY17, HY29, and HY61 are located in single family residential areas; HY40 serves a commercial area; HY53 is located in a multifamily residential area; and HY66 serves both a single family residential area and a commercial/ industrial area of the city of Micropolis. Fig. 4.1 shows the building map of Micropolis along with the locations of the hydrants and the service areas covered by each of those six hydrants. The service areas are circles around each of the six hydrants of radius 1000 feet; it is assumed that a fire inside a service area might lead to the hydrant being tapped for fire suppression. During the simulation, a fire flow of 1000 gpm is used at hydrant locations HY17, HY29, and HY61 (located in single family residential areas); a fire flow of 2500 gpm is used at locations HY40, HY53, and HY66 (located in multifamily residential and industrial/commercial areas); and a required pressure of 20 psi is used for all hydrants for analyzing the fire flow. In addition, a lesser fire flow of 1000 gpm is used at locations HY40, HY53 and HY66 to study the effects of fire flow magnitudes.

For all six fire locations, both the pressure based (equation 3.2) and flow based (equation 3.3) damage functions have been used to evaluate the maximized damage.

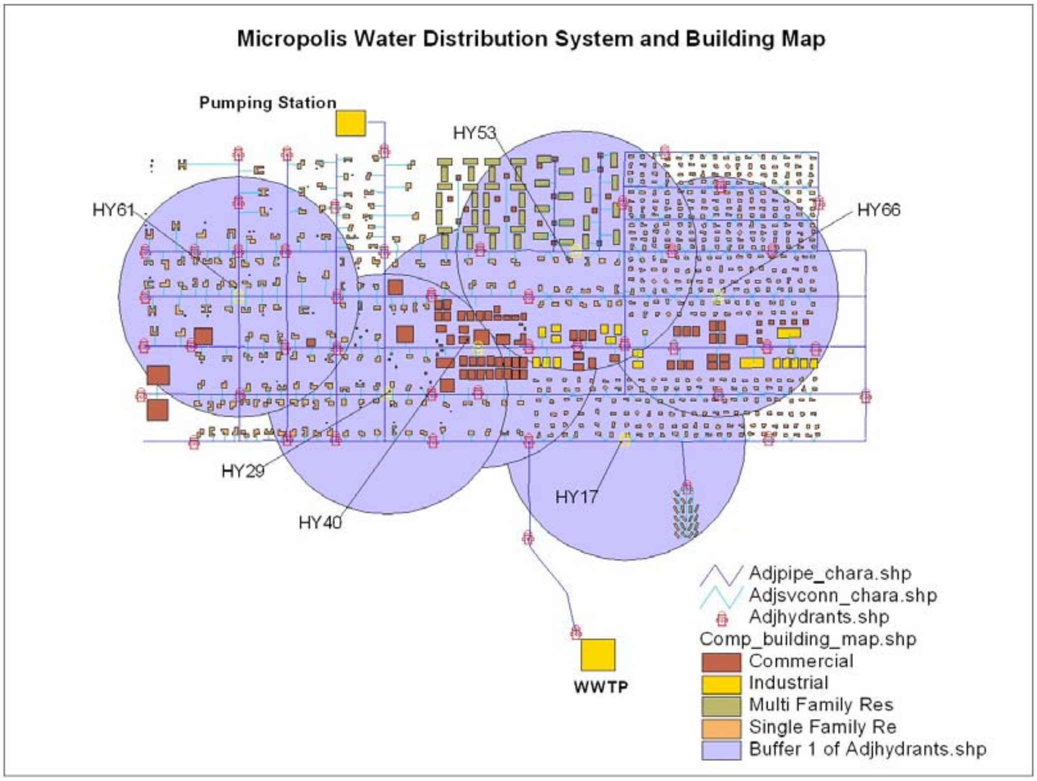

Fig. 4.1. Building map of Micropolis with water distribution network shown with blue lines and hydrants included in the vulnerability analysis indicated with yellow markers

As discussed in Section 3 both the pressure based and flow based damage functions will vary from some negative value to 1. When using the pressure based damage function, a constant fire flow of 1000 gpm (single family residential area) or

2500 gpm (multi-family/commercial area) is used as an input in addition to the base demand and the available pressure is evaluated and compared to the required pressure at the respective fire location. Similarly, when the flow based damage function is used, the available pressure of 20 psi is used as an input and the resulting available flow is computed and compared with the required fire flow according to the regional code. Thus in the ideal situation it is expected that both the pressure based and the flow based damage function will contribute to similar type of response to the system. But if a situation arises when multiple number of mains break causes substantial reduction of pressure or flow in the system, then the pressure based and flow based damage functions might not represent the similar level of damages.

4.2.1. Robustness, Resilience, and “Green-Yellow-Red Light” Conditions

A system’s functionality and behavior under failures and attacks are often expressed by the terms “robustness” and “resilience”. “Robustness” is a system’s capacity to sustain some amount of damage and still provide its intended level of service. Thus, robustness in case of a water distribution system providing fire fighting flows would be its capacity for damage that does not prohibit it from providing fire flows at adequate flow and pressure. A system operating in this mode is here referred to as being in a “Green Light” condition.

“Resilience”, on the other hand, is the system’s ability to sustain the impact of damage and recover and resume its operations to continue to provide some minimum of services. In case of a water distribution system providing fire flows, resilience would be its ability to operate at diminished capacity providing lesser flow and pressure than desired. A system operating in this mode is here referred to as being in a “Yellow Light” condition. In such a case, the resulting economic losses generally remain within manageable limits (Haimes 1998).

If a situation arises when damage becomes so great that the damage overcomes the both the system’s robustness and resilience and the system becomes unable to provide any flow and pressure, then this situation will correspond to a complete failure of the system. A system in this mode is referred to as being in a “Red Light” condition. A “Red Light” situation is indicated in the hydraulic model when it can not be solved or when none of the nearby hydrants remains operational.

In this methodology, the damage functions (equation 3.2 and 3.3) were formulated in such a way that the values for both the pressure based and flow based damage will vary from some negative value up to 1. When the damage function is less than or equal to 0, it indicates that the system is performing adequately and this situation will be referred to as a “Green Light” condition. For any values of damage functions greater than 0 but less than 1, the system will be in a state of “Yellow Light” condition. When the damage function reaches the maximum value 1, then the system is in failure mode and such a situation will be referred to as a “Red Light” condition.

For each fire condition, the maximum allowable number of failures (X_{max}) of the system is varied from 1 to until the damage reaches a plateau and/or damage becomes so great that the hydraulic model can not be solved and the results from the model are summarized below using the “Green Light”/ “Yellow Light”/ “Red Light” concept.

4.2.2. Hydrant HY17

Fig. 4.2 represents number of failures versus damages at hydrant HY17 using the pressure based and flow based damage functions. Since both damage function formulations are dimensionless with a maximum value of 1, they can be plotted on the same scale to compare the similarity or dissimilarity between them.

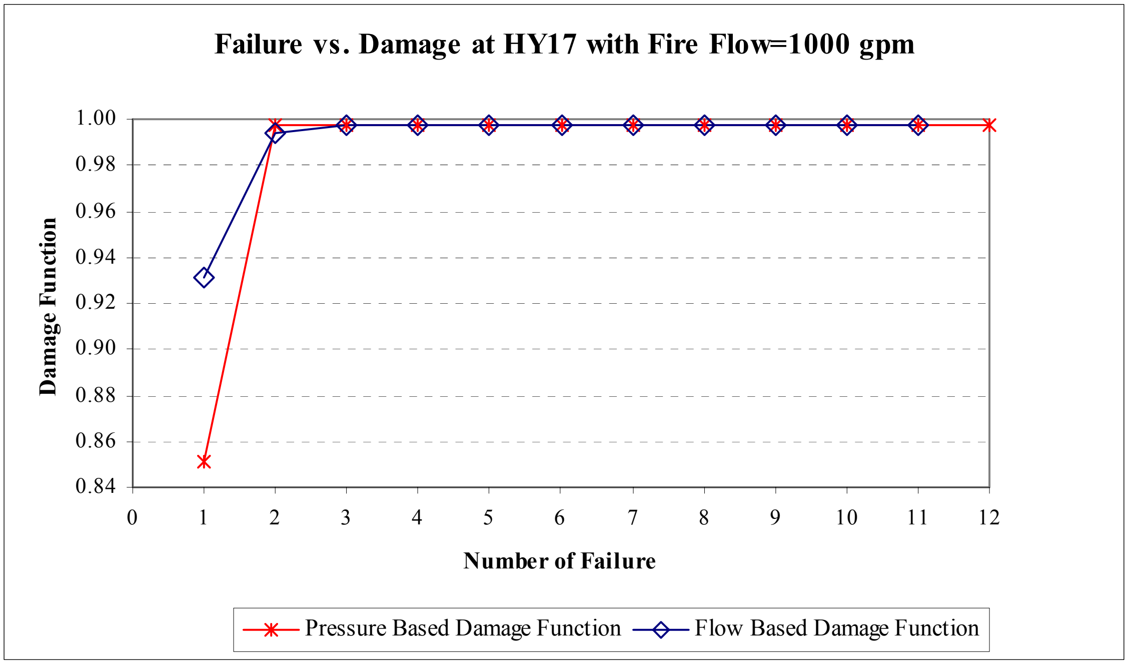

Fig. 4.2. Number of failures versus damage function at hydrant HY17 with fire flow=1000 gpm

The figure indicates that with a maximum allowable failures (X_{max}) equals 1, both the pressure based and flow based damage functions become greater than 0, thus, the system is not robust for fire at hydrant HY17. The figure also indicates that the pressure based and flow based damage functions reach plateaus after removal of 2 mains and 3 mains, respectively. However, at the plateaus, both the damage function values are less than 1. Thus the system demonstrates its “Resilience” / “Yellow Light” condition when fire occurs at hydrant HY17. The presence of resilience for more than 3 failures is solely due to the system’s ability to draw water from other nearby hydrants.

4.2.3. Hydrant HY29

Fig. 4.3 represents number of failures versus damages when fire occurs at hydrant HY29. In this case, the pressure based damage function shows different result than that of flow based damage function. The constant values of pressure based damage function indicate that for any number of maximum allowable failures (X_{max}), the pressure at this hydrant is either 0 or negative and water is obtained from a nearest operable hydrant to suppress the fire. Because pressure at this hydrant is less than or equal to 0, so the pressure term $[(P_{req} - P_{fire\text{-}node}) / P_{req}]$ in equation 3.2 is always 1. This pressure term along with the constant distance term $[L_{operable} / R_{max}]$ contribute to the constant damage function equal to 0.997 for any number of component failures. However, the hydraulic model can not be solved using pressure based damage function (equation 3.2) when the maximum allowable failures (X_{max}) is greater than 16. Although the damage function is less than 1, the system corresponding to pressure based damage function demonstrates a "Red Light" condition because the hydraulic model could not be solved further.

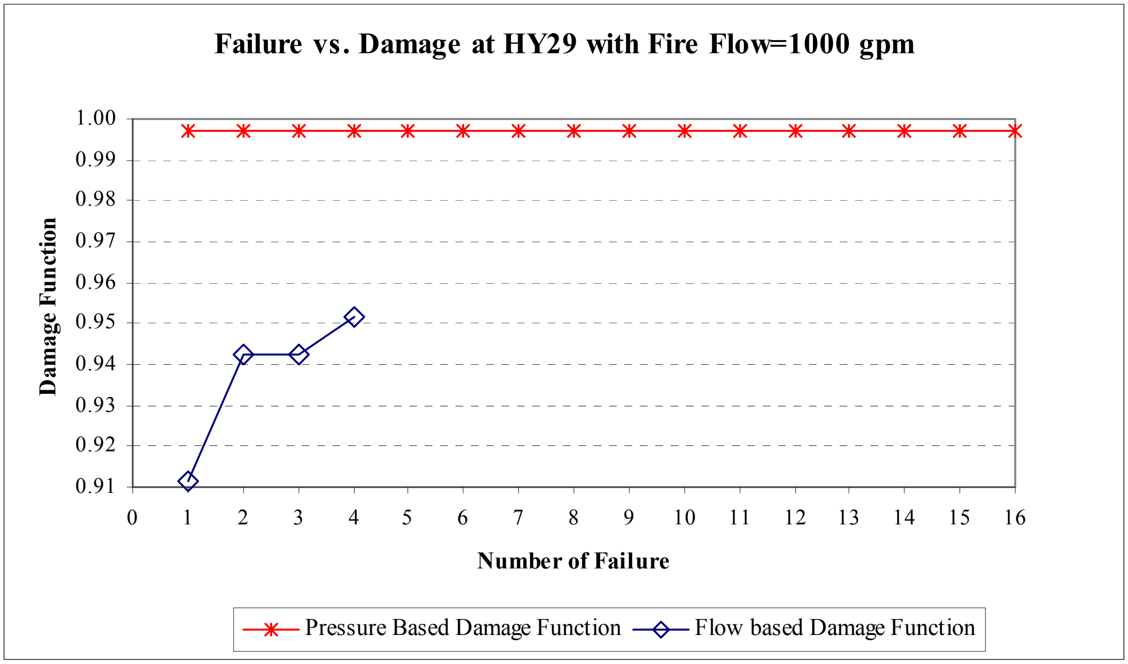

Fig. 4.3. Number of failures versus damage function at hydrant HY29 with fire flow=1000 gpm

When the flow based damage function is used at hydrant HY29, none of the nearby hydrants remains operable for maximum allowable failures (X_{max}) more than 4. Thus, the system is non operational and this situation indicates a "Red Light" condition with fire at hydrant HY29 when maximum allowable failures (X_{max}) is greater than 4.

4.2.4. Hydrant HY40

The fire flow analysis at hydrant HY40 was performed using both 1000 gpm and 2500 gpm fire flows. The number of failures versus damages at hydrant HY40 with fire flow equal to 1000 gpm is presented in Fig. 4.4a. The figure indicates that the pressure based damage function remains constant for any number of maximum allowable failures (X_{max}). This constant damage situation at HY40 with 1000 gpm fire flow is because of the fact that the available pressure at this location during fire is always less than or equal to 0. Thus, the pressure term in damage function equation (equation 3.2) remains 1 and

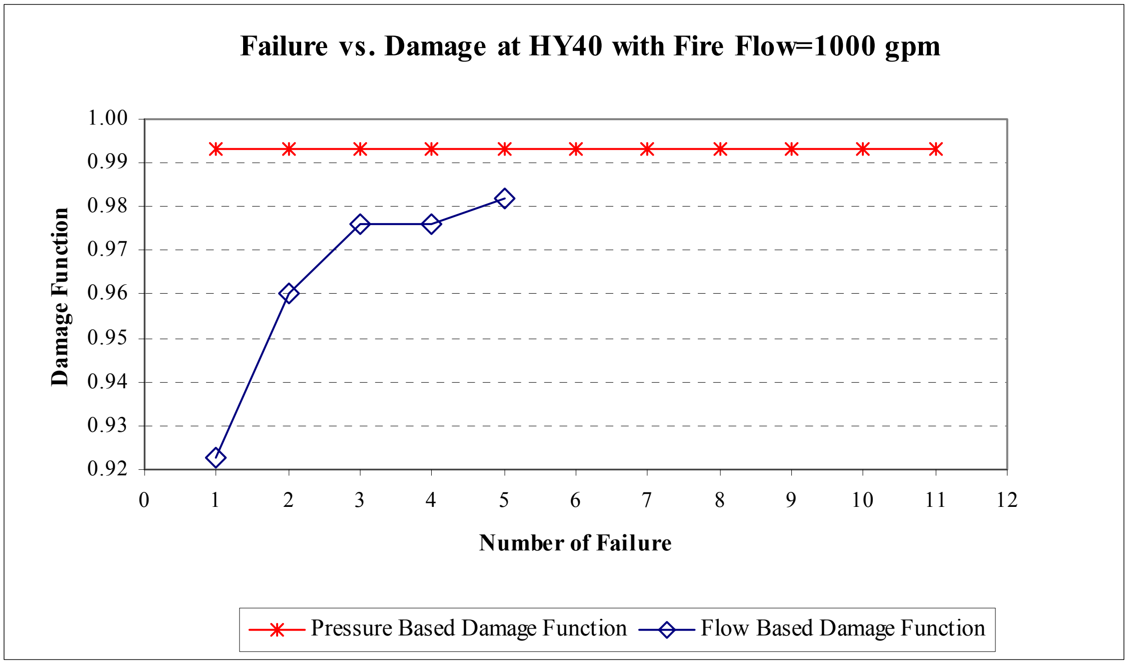

Fig. 4.4a. Number of failures versus damage function at hydrant HY40 with fire flow=1000 gpm

with the contribution from the distance term due to a nearest operable hydrant HY64, the resulting maximized pressure based damage at this location remains constant. However, the hydraulic model can not be solved when maximum allowable failures (X_{max}) become greater than 11. The flow based damage function, on the other hand, increases with increase in number of maximum allowable failures (X_{max}) up to X_{max} equals 5. After that none of the nearby hydrants remains operable and the system fails. Thus, both the pressure based and flow based damage functions with fire flow equal to 1000 gpm demonstrate a "Red Light" condition when fire occurs at hydrant HY40.

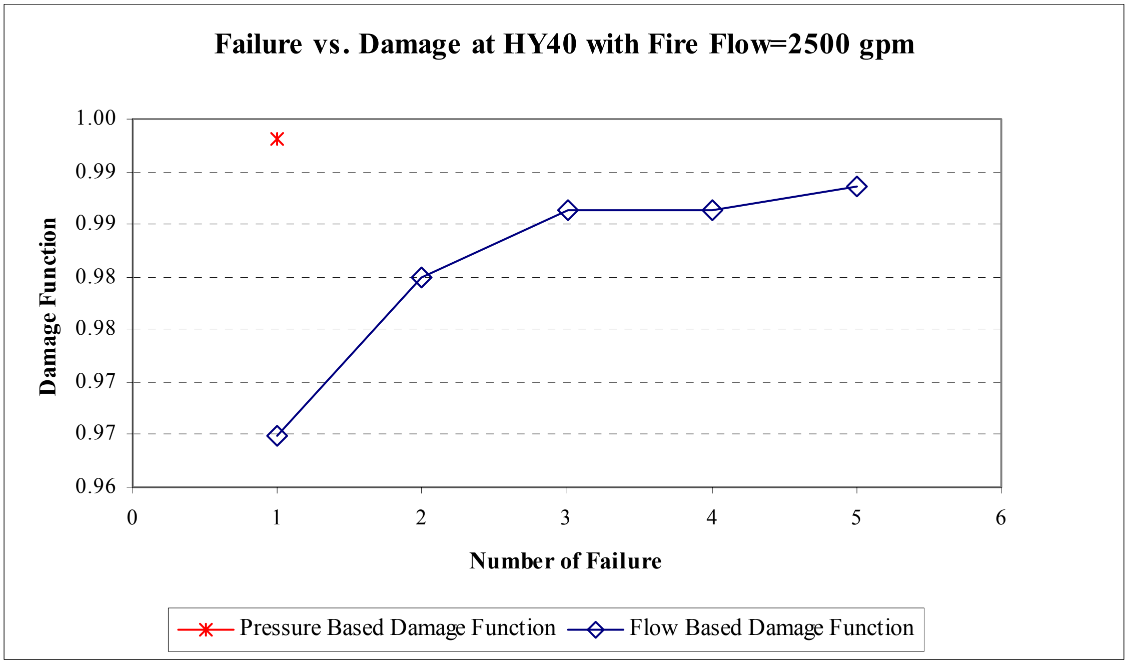

Fig. 4.4b. Number of failures versus damage function at hydrant HY40 with fire flow=2500 gpm

Fig. 4.4b shows the number of failures versus damages at hydrant HY40 with 2500 gpm fire flow. In this case, for a maximum allowable failures (X_{max}) of 1, the pressure based damage function reaches a value close to 1; after that the optimization model can not remove any more pipes irrespective to any number of maximum allowable failures (X_{max}). This non responding behavior of the optimization model is because of the fact that, with failure of the single most critical pipe MA478, the pressure based damage function (equation 3.2) reaches the maximum value and the removal of any more pipes is not making the damage function larger. The flow based damage function, however, never reaches the plateau because after maximum allowable failures (X_{max}) equal to 5, none of the nearby hydrants remains operational and the hydraulic simulation is stopped. Thus, results from both the pressure based and flow based damage functions demonstrate a "Red Light" condition at hydrant HY40 with 2500 gpm fire flow.

4.2.5. Hydrant HY53

The fire flow analyses at hydrant HY53 were performed using both 1000 gpm and 2500 gpm flows, and the results are shown in Figs. 4.5a and 4.5b, respectively. Fig. 4.5a indicates that the pressure based damage function remains constant at a value 0.993 until maximum allowable failures (X_{max}) equals 3. Then the damage function increases slightly from 0.993 to 0.998 with an additional failure of one more pipe. The damage function remains constant at that value until maximum allowable failures (X_{max}) equals 8.

With X_{max} greater than 8 the pressure based damage function reduces to a value 0.993 and remains constant afterwards. This phenomenon can be explained as follows: the available pressure at HY53 during fire is always less than or equal to 0, and thus the pressure term $[(P_{req} - P_{fire\text{-}node}) / P_{req}]$ in damage function equation (equation 3.2) remains 1 for any number of component failures or X_{max}. For X_{max} less than or equal to 3, the nearest operable hydrant to HY53 is HY64, which is 600 ft away (nearest operable hydrants are listed in Appendix A in Table A.1.5). For all the values of X_{max} between 4 and 8 HY64 remains no longer operable and the nearest operable hydrant to HY53 is

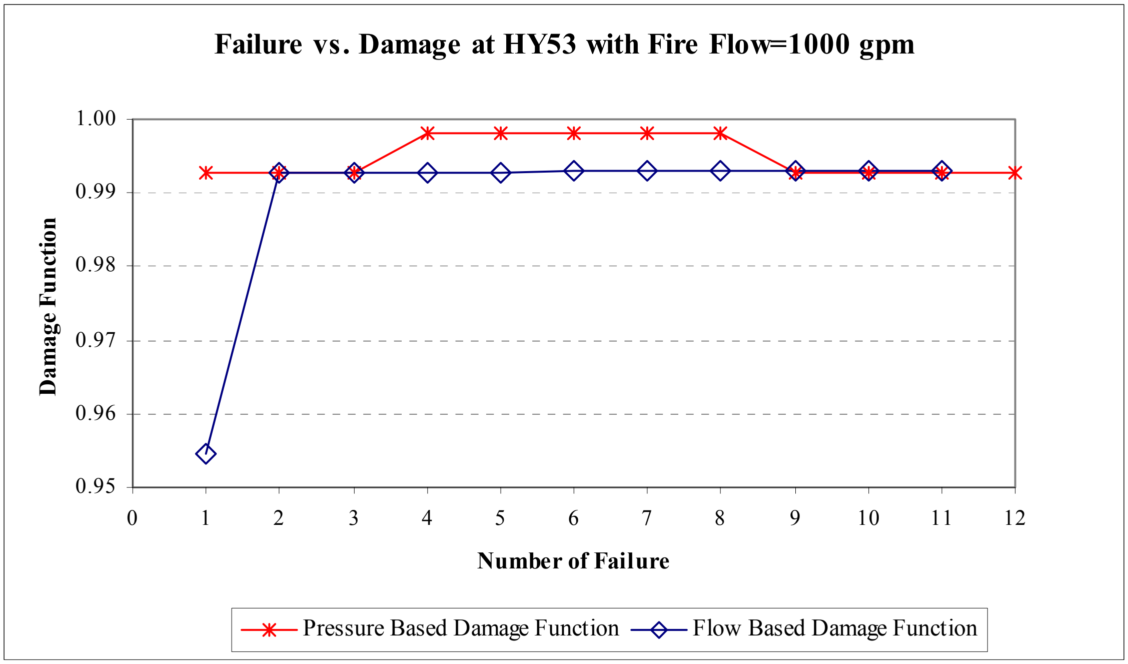

Fig. 4.5a. Number of failures versus damage function at hydrant HY53 with fire flow=1000 gpm

now HY51 which is more than 600 ft away. Thus the distance term in pressure based damage function (equation 3.2) increases for X_{max} between 4 and 8 and the corresponding damage function also increases. For X_{max} greater than 8, HY64 becomes operable again as different set of optimal decisions appear in such condition and the damage function value reduces to 0.993 again and remains constant afterwards. Because of this unusual nature of the pressure based damage function at HY53, the result can not be interpreted as “Green/Yellow/Red Light” condition. The flow based damage function with 1000 gpm fire flow reaches the plateau when maximum allowable failures (X_{max})

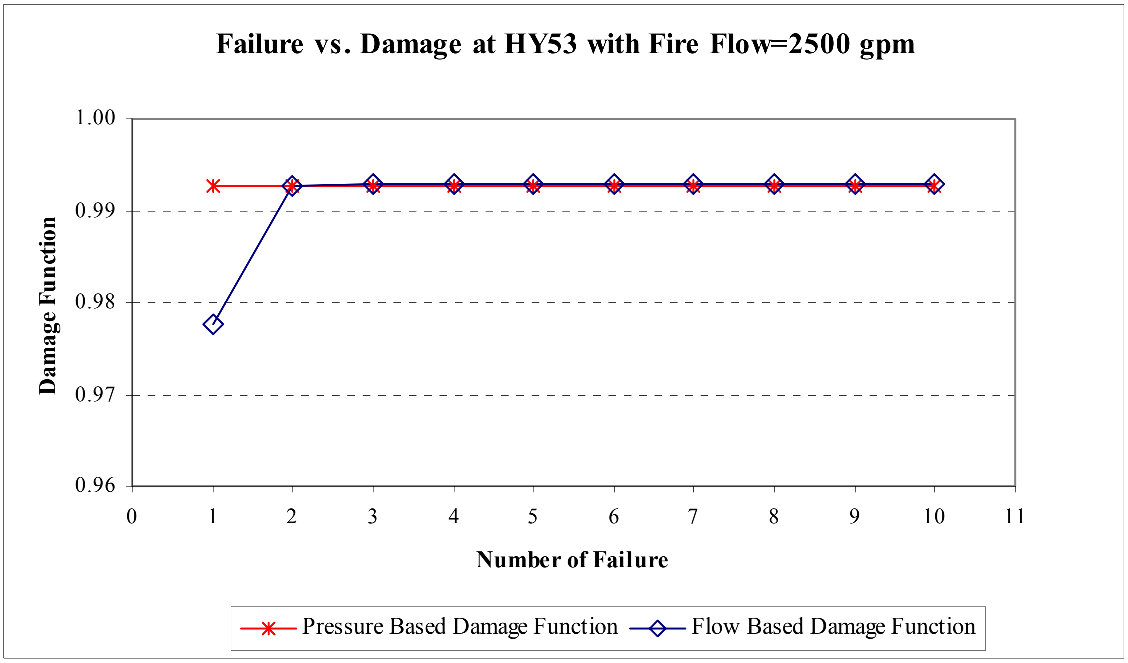

Fig. 4.5b. Number of failures versus damage function at hydrant HY53 with fire flow=2500 gpm

equals to 2. As the flow based damage function value is less than 1 at the plateau, the system demonstrates its “Resilience” / “Yellow Light” condition. The presence of resilience after X_{max} equals to 2 proves the system’s ability to draw water from nearby operable hydrants.

Fig. 4.5b shows that with 2500 gpm fire flow, the pressure based damage function at hydrant HY53 remains constant at 0.993 for any number of maximum allowable failures (X_{max}). This constant damage function value is due to occurrence of negative or zero pressure at the fire hydrant. The flow based damage function, on the other hand, increases with increase in maximum allowable failures (X_{max}) and reaches a plateau at X_{max} equals to 2. Because both the damage functions reach a value less than 1 at the plateau, the system demonstrates its “Resilience” / “Yellow Light” condition.

4.2.6. Hydrant HY66

Fig. 4.6a and Fig. 4.6b represent number of failures versus damages at hydrant HY66 with 1000 gpm and 2500 gpm fire flows respectively. With 1000 gpm fire flow (Fig. 4.6a), both the pressure based and flow based damage functions reach the plateaus at X_{max} equals to 5 and X_{max} equals to 4 respectively. At the plateaus, both the damage functions achieve a value 0.998, thus, the system demonstrates its “Yellow Light” condition.

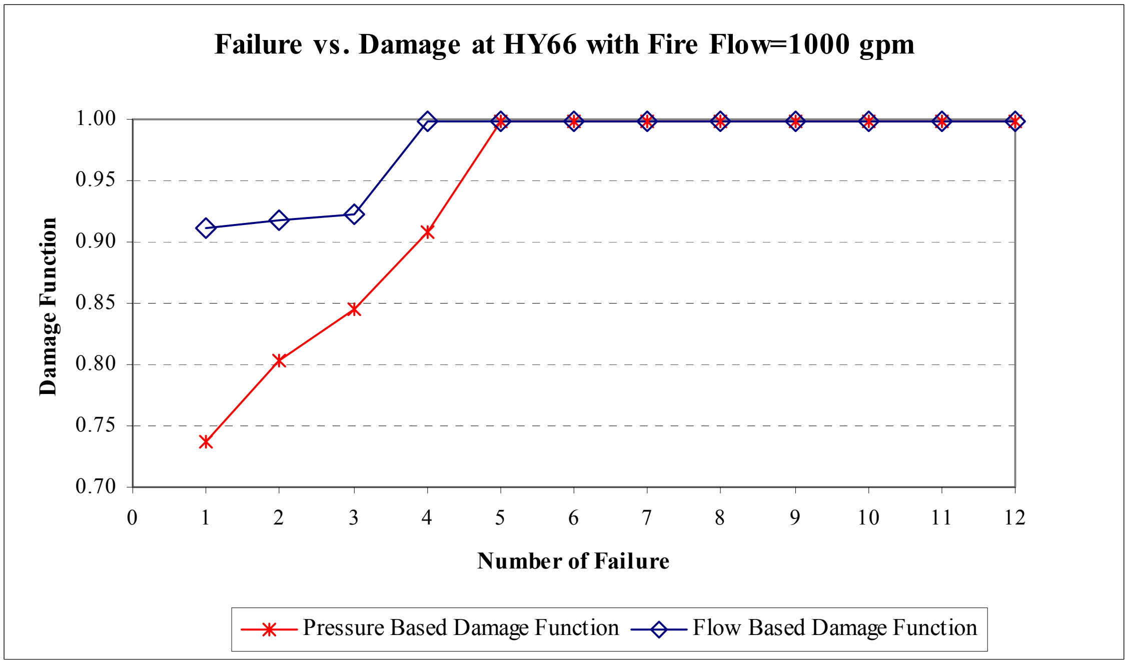

Fig. 4.6a. Number of failures versus damage function at hydrant HY66 with fire flow=1000 gpm

Fig. 4.6b shows that with a higher fire flow (e.g., 2500 gpm) the pressure based damage function becomes constant for any number of allowable failures (X_{max}). However, the flow based damage function increases with increase in number of failure and the damage reaches a plateau at X_{max} equals to 4. Because at the plateaus, both the damage functions reach a value less than 1, the system demonstrates its “Resilience” / “Yellow Light” condition. In this case, the system draws water from its nearby operable hydrants.

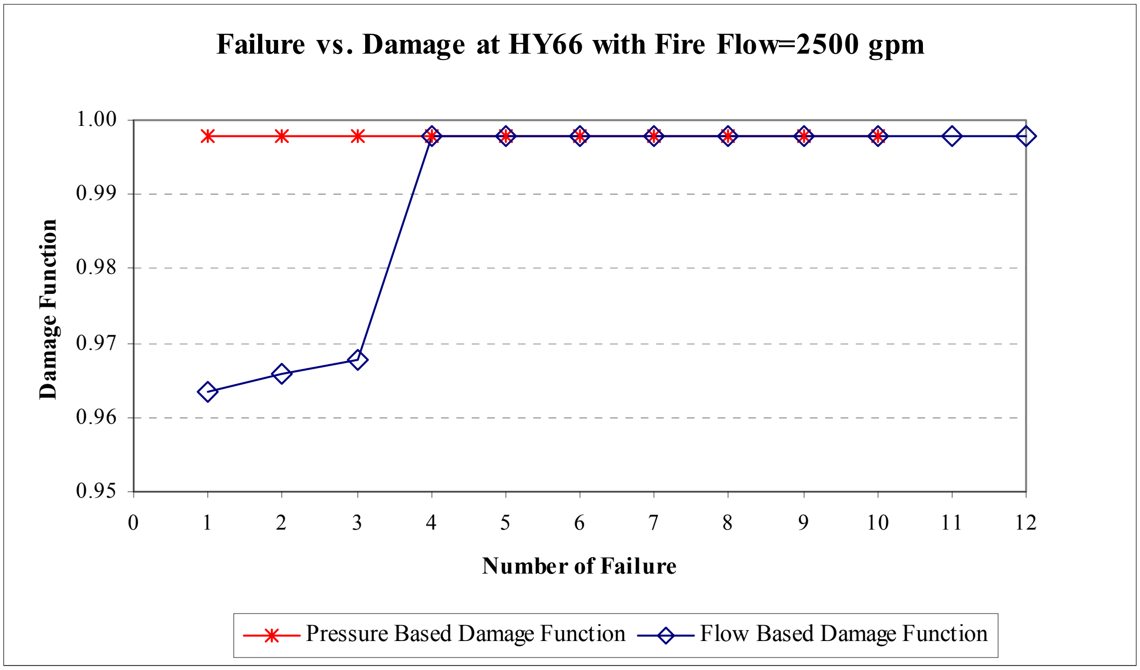

Fig. 4.6b. Number of failures versus damage function at hydrant HY66 with fire flow=2500 gpm

4.2.7. Hydrant HY61

When the methodology discussed in this section is applied at hydrant HY61 with maximum allowable failures (X_{max}) equals to 1, none of the nearby hydrants remains operable and both the pressure and flow based damage functions became infinitely large. This situation obviously demonstrates a “Red Light” condition. Because of the infinite damage, the number of failures versus damages can not be plotted and shown for hydrant HY61.

4.3. Analysis and Recommendation of Mitigation Strategies

Mitigation is the process by which vulnerabilities of a system are reduced. In the present research, the vulnerability of a water supply system was analyzed with respect to the system's ability to provide adequate flow and pressure for fire responses during failure or attack on the system. Thus mitigation, in this case, will be the process by which the threat toward the water system will be reduced and the system's performance will be improved. These objectives can be achieved by hardening the water supply system's critical components. In the previous sections, the critical water mains of the system for fire at six selected locations are identified. By knowing those critical components, couple of strategy will be developed in this section to secure those critical components and thereby, to increase the system's ability of providing adequate water with required flow and pressure for fire fighting.

In the vulnerability analysis presented above, it was found that some elements of the Micropolis water distribution system were repeatedly among the most critical components for fire flows at different hydrants. (The decision elements for all scenarios are given in Appendix A). On the basis of the results, three mitigation strategies were considered that included hardening a specific set of pipes, and further simulations were performed on the hardened water supply system to assess its changed vulnerability under each mitigation strategy. The general idea of hardening a water supply system is to make the system less vulnerable to physical threats than it is at present. There are different approaches to hardening of the system including: shielding the pipes, burying the pipes deeper into the ground, replacing the existing pipes with better materials, installing surveillance cameras near the critical water mains, and providing redundancy in the distribution network, among others. Because most of the pipes/water mains in the city of Micropolis are decades old and are made of less durable pipe materials like cast iron and asbestos cement, hardening of the critical water mains could be accomplished by replacing those pipes with more durable ductile iron pipes. Ductile iron pipes are generally stronger and less brittle than the cast iron pipes. The tensile strength and ductility of ductile iron is increased by adding small quantities of magnesium in the molten iron (Twort et. al., 1994). Because of the increased durability and flexibility of ductile iron pipes, they are gradually replacing most cast iron pipes in distribution networks (Mays, 1996). In the mitigation scenario simulations, "hardened" pipes were assumed to be incapable of failure and removed from the possible set of damaged pipes for system optimization.

During simulation of the model for different mitigation strategies only the flow based damage function (equation 3.3) was used to evaluate damage at the previously stated locations. The pressure based damage function (equation 3.2) was not used during further evaluation of damage because of the common occurrence of negative pressure at fire locations, which caused the pressure term of the pressure based damage function to become unity. Because the contribution from the pressure term is more significant than that from the distance term, the damage function value becomes constant for any number of component failures during occurrence of negative pressure. Thus the attempt to use pressure based damage function was not very useful and only the flow based damage function is used for further calculations. This rationale can be observed in Figs. 4.2 to 4.6b where plateaus for the pressure based function began at low numbers of failures. The flow based functions, in contrast, convey more refined information across a larger possible number of failures.

As was done in the vulnerability analysis, the mitigation strategies were analyzed with fire flow requirements based on the urban areas where the selected hydrants are located, in accordance with typical local codes. For instance, hydrants HY17, HY29, and HY61 were analyzed with 1000 gpm fire flow because those hydrants are located in single family residential areas, and hydrants HY40, HY53, and HY66 were analyzed with both 1000 gpm and 2500 gpm fire flows as they are located in multi-family and commercial areas. The location of the above mentioned six hydrants along with the base demand at all the junction nodes have shown in Fig. 4.7.

The assessed mitigation strategies include:

- Mitigation Strategy-I: This strategy includes hardening of pipe MA1006. The pipe MA1006 is a 12 inch diameter main that connects the main pumping station with the distribution network. This pipe showed up as the single most critical component of the network for all six fire locations. Thus, hardening this particular pipe was considered as the first mitigation strategy.

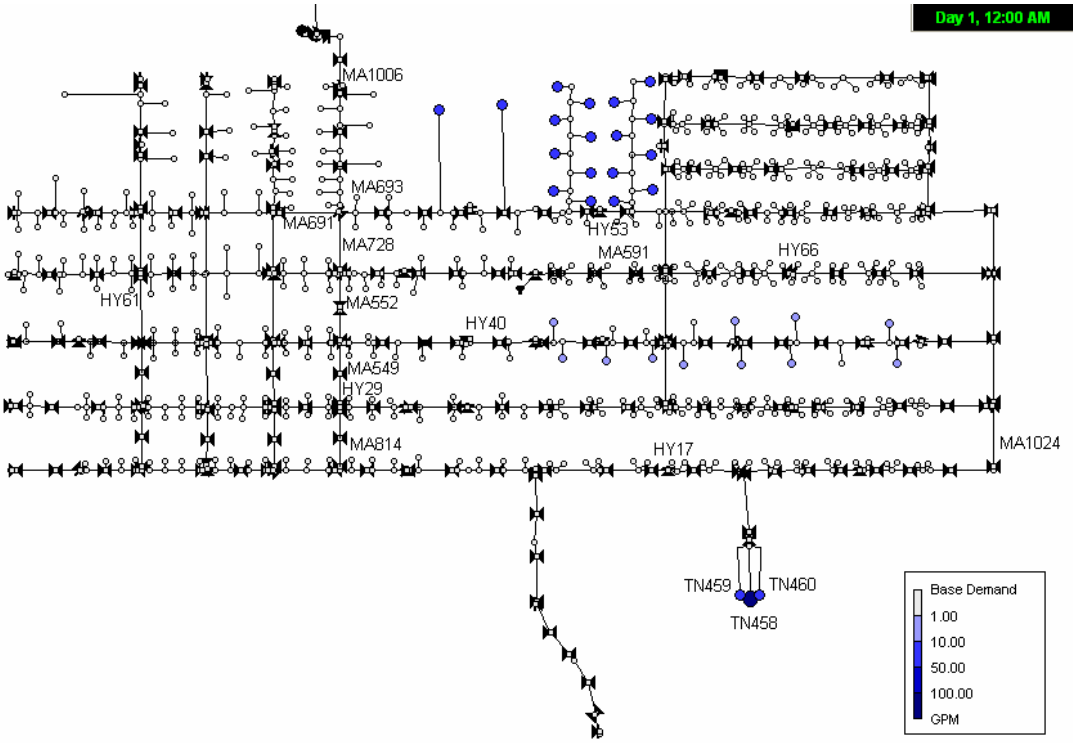

Fig. 4.7. Network map of Micropolis with nodal base demands, hydrants used for vulnerability and mitigation analysis, and mains hardened in various mitigation scenarios

- <u>Mitigation Strategy-II:</u> This strategy recommends hardening of pipes MA549, MA552, MA591, and MA1006. Pipe MA591 is another significant pipe of the network that conveys water from the city's water tower to the eastern part of the network. This pipe along with pipes MA549 and MA552 showed up as critical components for most of the previously mentioned hydrants when simulation was performed with

Mitigation Strategy-I. Thus hardening of pipe MA549, MA552 and MA591 along with the pipe MA1006 can be considered as a better mitigation option for this system.

- Mitigation Strategy-III: This strategy recommends hardening of pipes MA549, MA552, MA591, MA691, MA693, MA728, and MA1006. The pipes MA691, MA693, and MA728 provide connectivity between MA1006 and the rest of the network. Thus, even after hardening the main MA1006 if the three pipes mentioned above being removed, the pump station will be isolated from the rest of the network. Moreover, the pipes MA691, MA693, and MA728 showed up as critical components during simulations with Mitigation Strategy-II. On the basis of the results from Strategy-II, Strategy-III was defined to be hardening of MA691, MA693, and MA728 along with the pipes recommended in Strategy-II.

The list of optimal decisions for $X_{max} = 3$ (i.e., a maximum of 3 non-hardened components could be removed from the system) from simulation of both the unmitigated and all three mitigation strategies at all six hydrant locations are tabulated in Table 4.1, and the results of failure versus damage with three alternative mitigation strategies for all six hydrants are presented in the following sections from Fig. 4.8 to Fig. 4.13.

Table 4.1. Optimal Decisions on Critical Network Components for $X_{max} = 3$

Fire Hydrant	Optimal Decisions for $X_{max} = 3$			
	Unmitigated	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
HY17	MA802, MA989, MA1006	MA591, MA691, MA693	MA802, MA989, MA1024	MA802, MA989, MA1024
HY29	MA1006, MA1020, MA1024	MA549, MA638, MA814	MA691, MA693, MA728	MA478, MA638, MA814
HY40	MA478, MA1006, MA1024	MA478, MA549, MA552	MA478, MA691, MA693	MA478, MA672, MA678
HY53	MA693, MA883, MA1006	MA591, MA691, MA693	MA693, MA883, MA965	MA883, MA991, MA997
HY61	MA1006 (system failed after X_{max}=1)	MA591, MA691, MA693	MA691, MA693, MA728	MA737, MA740, MA1024
HY66	MA1006, 1019, MA1024	MA576, MA591, MA691	MA576, MA691, MA693	MA576, MA802, MA883

4.3.1. Analysis of Mitigation Strategies at Hydrant HY17

Fig. 4.8 represents the flow based damage function at hydrant HY17 for both unmitigated and all three mitigated conditions. From the figure it can be concluded that all three mitigation strategies have the same effect on this hydrant and the damage function value caused by the removal of one pipe in the unmitigated situation can be reduced by more than 50% with applying either one of the mitigation strategies. None of the mitigation strategies has any significant effect in reducing the damage at HY17 when the number of component failures (X_{max}) is more than one.

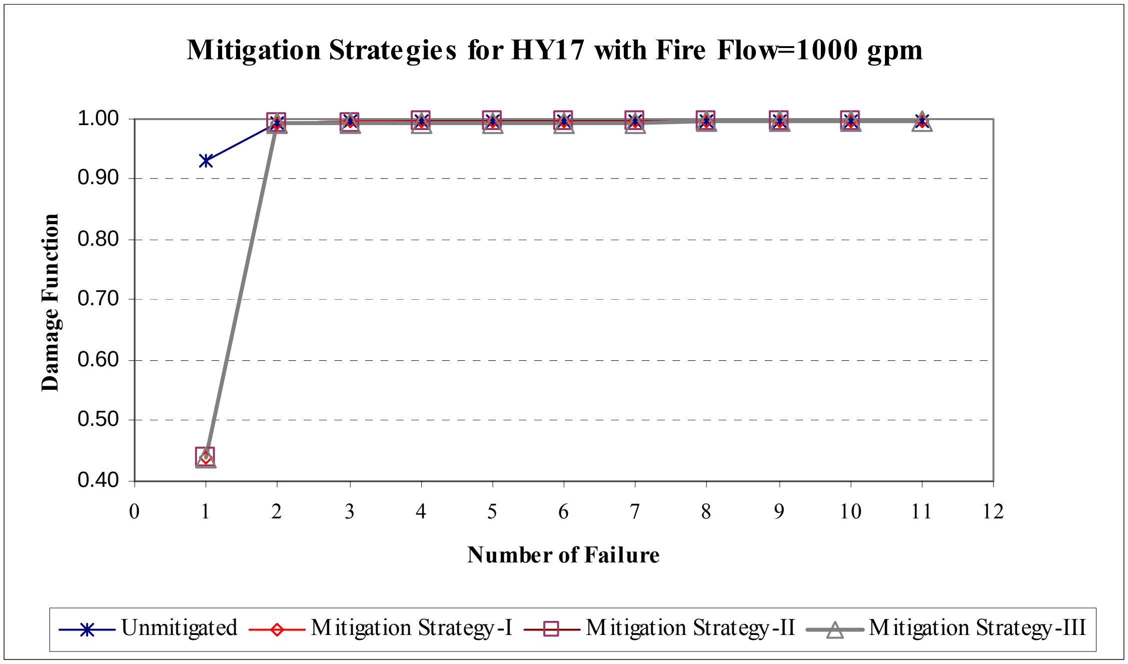

Fig. 4.8. Mitigation strategies for hydrant HY17 with fire flow=1000 gpm

4.3.2. Analysis of Mitigation Strategies at Hydrant HY29

Fig. 4.9 shows number of failures versus damages for the different mitigation strategies, and Table 4.2 shows the list of optimal decisions for a maximum number of failures (X_{max}) of 4 during fire at hydrant HY29. With unmitigated condition the system demonstrated its “Red Light” condition when maximum allowable failures (X_{max}) was greater than 4. Strategy-I reduces the damages, and the system retains significant resiliency until the maximum number of failures (X_{max}) reaches 10.

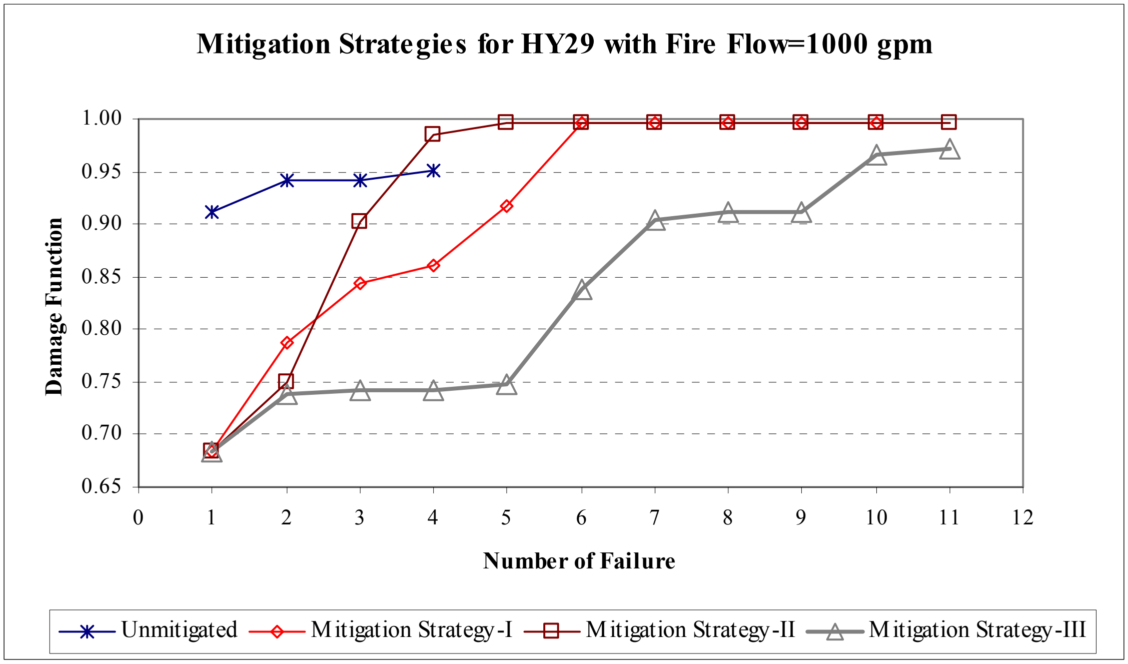

Fig. 4.9. Mitigation strategies for hydrant HY29 with fire flow=1000 gpm

With strategy-II, the system retains greater resiliency up to maximum allowable failures (X_{max}) equal to 11. But in this case, the damage is higher than that during unmitigated condition. Referring to equation 3.3, the damage function is a combination of both the flow term [($Q_{req} - Q_{max\text{-}available}$) / Q_{req}] and the distance term [$L_{operable}$ / R_{max}] when available flow is less than the required. Because most of the fire flow will be obtained from the target fire hydrant rather than from nearby hydrants, the flow term is weighted significantly higher than the distance term. Thus, higher damage with Mitigation Strategy-II for X_{max} equals to 4 indicates that the available flow at HY29 is lower with Strategy-II than that with unmitigated condition when four pipes are removed.

Table 4.2. List of Optimal Decisions for $X_{max} = 4$ with Fire at Hydrant HY29

Optimal Decisions for $X_{max} = 4$			
Unmitigated	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
MA549, MA814, MA1006, MA1024	MA549, MA638, MA691, MA814	MA691, MA693, MA728, MA1024	MA478, MA638, MA814, MA883

This situation can be explained with reference to Fig. 4.7 and Table 4.2. The base demands (i.e., without fire flows) at all nodes in Micropolis are shown in Fig. 4.7. When fire occurs at HY29, the demand increases instantly at that location and the system tries to meet that increased demand along with the base demands at all other nodes. In the unmitigated condition with X_{max} equals to 4, pipes MA549, MA814, MA1006, and MA1024 caused the maximized damage when flow based damage function was used. Referring to Fig. 4.7, there are significant amounts of base demand in the terminal nodes TN458, TN459 and TN460 under normal condition. When pipes MA814 and MA1024 were removed, the area with higher demand was isolated and the system provided adequate flow towards HY29 to meet the emergency loading condition during fire. With Mitigation Strategy-II, pipes MA591 and MA1006 are hardened with two other water mains and the four most critical components are now pipes MA691, MA693, MA728 and MA1024. Although MA1006 was hardened, the removal of pipes MA691, MA693 and MA728 made the pump station isolated and the only source for supplying water is the elevated storage tank. Because the pipe MA814 remained in the network, the system had to provide some flow toward the high demand area and thus the available flow at HY29 becomes less than that of unmitigated condition which in turn resulted in higher damage with Strategy-II. Thus, Strategy-II appears to increase damage because it ensures greater flows for normal needs will reach other areas of the distribution system.

With Strategy-I and III, both the pump station and the storage tank provided adequate water to the system and the system could deliver more flow to HY29 after meeting the demands at nodes TN458, TN459 and TN460. With Mitigation Strategy-III, the system retains significant resiliency up to maximum allowable failures (X_{max}) equal to 11. After that the hydraulic model can not be solved, thus, the system demonstrates its “Red Light” condition when maximum number of failures is greater than 11.

4.3.3. Analysis of Mitigation Strategies at Hydrant HY40

Figs. 4.10a and 4.10b show number of failures versus damages for different mitigation strategies during fire at hydrant HY40 with fire flows of 1000 gpm and 2500 gpm respectively. From both the results it can be noticed that the damage function with

Mitigation Strategy-II for X_{max} equals to 5 is higher than that with the unmitigated condition. This situation can be explained with referring to Fig. 4.7 and Table 4.3.

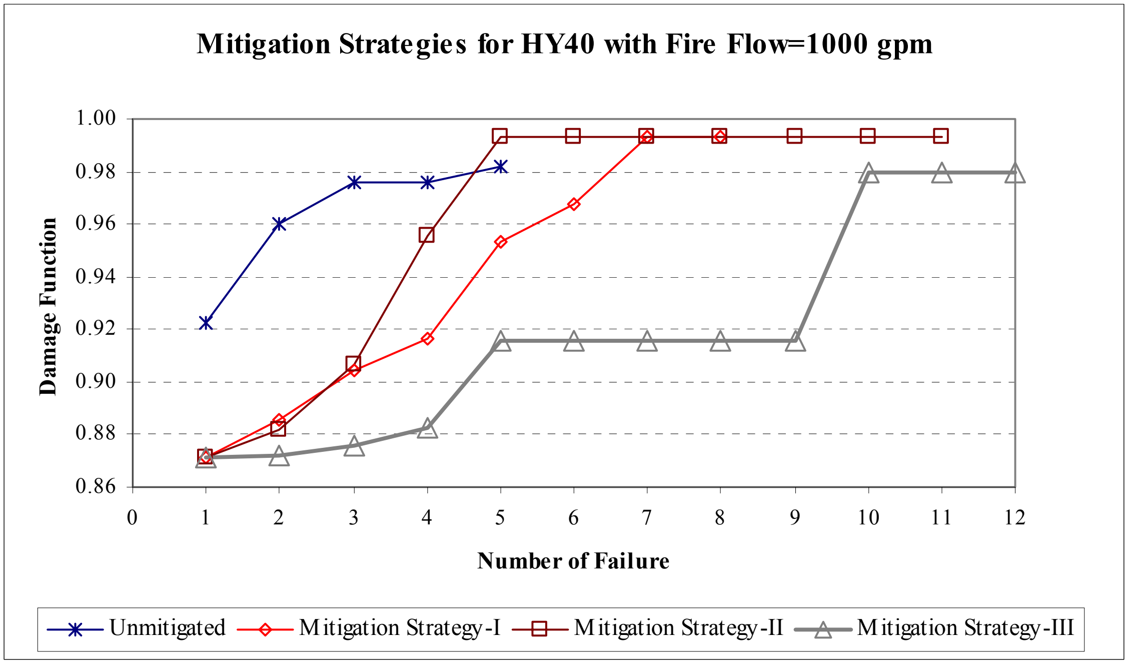

Fig. 4.10a. Mitigation strategies for hydrant HY40 with fire flow=1000 gpm

During unmitigated condition, removal of pipe MA1006 isolated the pump station and also pipes MA549 and MA1024 being critical separated the high demand area of the network (Fig. 4.7). Thus the only source in such condition was the elevated storage tank which could not provide adequate water to those high demand areas because of the longer flow path. But with Mitigation Strategy-II, pipes MA1006, MA549, MA552 and MA591 were hardened and in such a condition water from the storage tank provided some flow to the terminal nodes TN458, TN459 and TN460 through

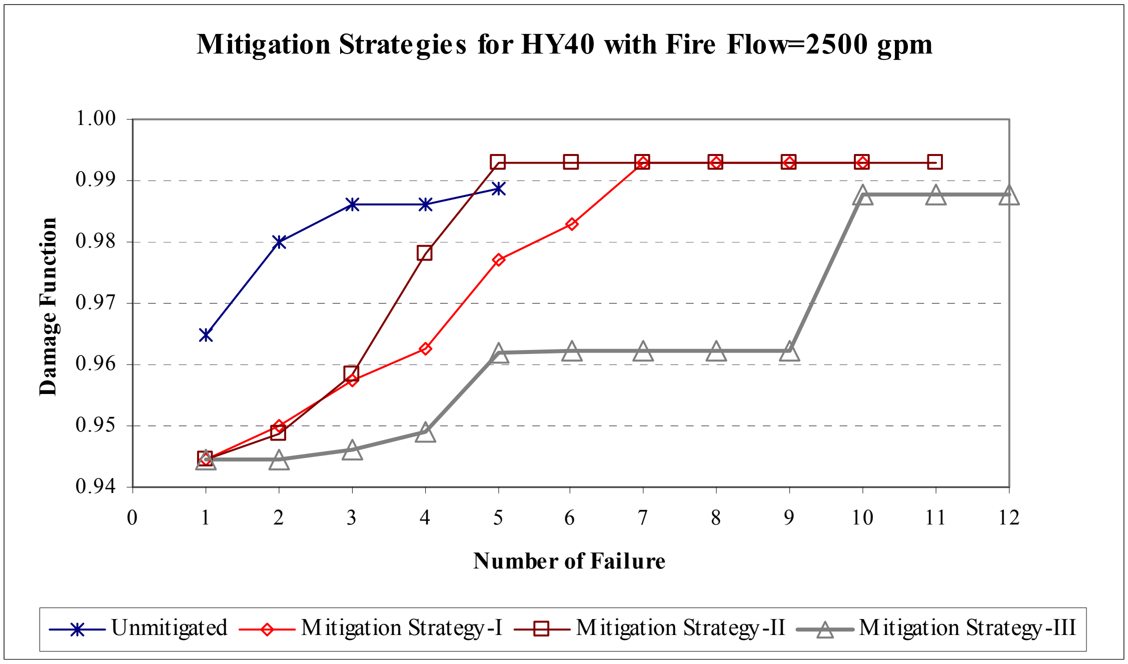

Fig. 4.10b. Mitigation strategies for hydrant HY40 with fire flow=2500 gpm

Table 4.3. List of Optimal Decisions for X_{max} = 5 with Fire at Hydrant HY40

Optimal Decisions for X_{max} = 5			
Unmitigated	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
MA478, MA549, MA552, MA1006, MA1024	MA478, MA549, MA552, MA691, MA1024	MA478, MA691, MA693, MA728, MA989	MA478, MA672, MA678, MA737, MA1024

comparatively shorter flow path and thus the available flow at hydrant HY40 became less than that of unmitigated condition. As a result, the damage is more at HY40 with Strategy-II for X_{max} equals to 5 than that at unmitigated situation.

With Mitigation Strategy-I, the damage reaches the plateau at X_{max} equals to 7 for both 1000 gpm and 2500 gpm. However, with 1000 gpm fire flow, the model could not remove more than 8 pipes even though the allowable decision of removing pipes was set to 9 (Table A.2.3). This is because of the fact that with maximum allowable failures (X_{max}) equals to 8, the damage function reaches its maximum value and removing any more pipes does not make the damage any bigger. Thus the marginal value of the ninth pipe is 0 and the model can not remove more than 8 pipes.

With 2500 gpm fire flow during unmitigated condition the system demonstrated its “Red Light” condition for maximum allowable failures (X_{max}) more than 5. With Mitigation Strategy-I, the system retains significant resiliency up to X_{max} equals to 10. With Mitigation Strategy-II, the system retains its resiliency up to X_{max} equals to 11. With Mitigation Strategy-III the system retains greater resiliency up to X_{max} equals to 12. When more than 12 pipes were removed, the hydraulic model was unsolvable, and it is assumed the system reached “Red Light” status.

4.3.4. Analysis of Mitigation Strategies at Hydrant HY53

Fig. 4.11a and Fig. 4.11b show the number of failures versus damages for different mitigation strategies with 1000 gpm and 2500 gpm fire flows respectively at

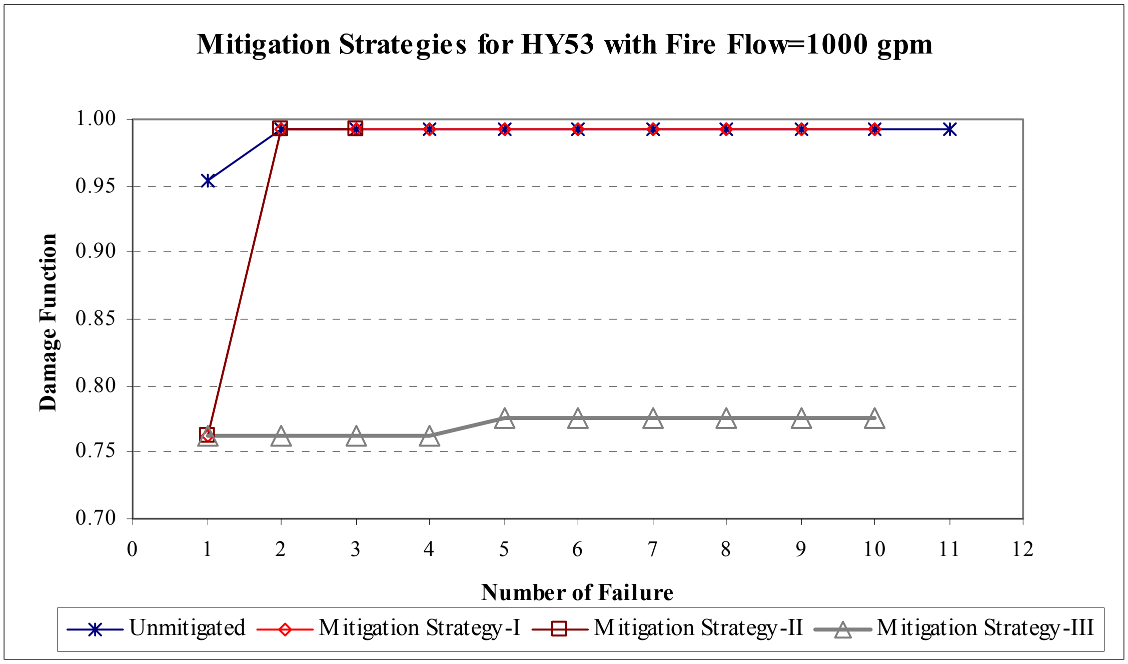

Fig. 4.11a. Mitigation strategies for hydrant HY53 with Fire Flow=1000 gpm

hydrant HY53. From the results with lower fire flow it can be concluded that with all three mitigation strategies, the damage can be reduced by 20% when X_{max} equals to 1. For any values of X_{max} greater than 1, the Strategy-I and II is not significant compared to the unmitigated condition. Strategy-III, on the other hand, significantly reduces the overall damages in this case and the system retains great resiliency up to X_{max} equals to 10.

The analyses with higher fire flows show similar results with a relatively higher magnitude in damages. The reason is obvious; referring to equation 3.3, for the same magnitude of available flow, the flow term $[(Q_{req} - Q_{max\text{-}available}) / Q_{req}]$ will be more for higher required flow than that with a lower required flow. Thus the magnitude of damage with 2500 gpm fire flow is higher than that with 1000 gpm fire flow.

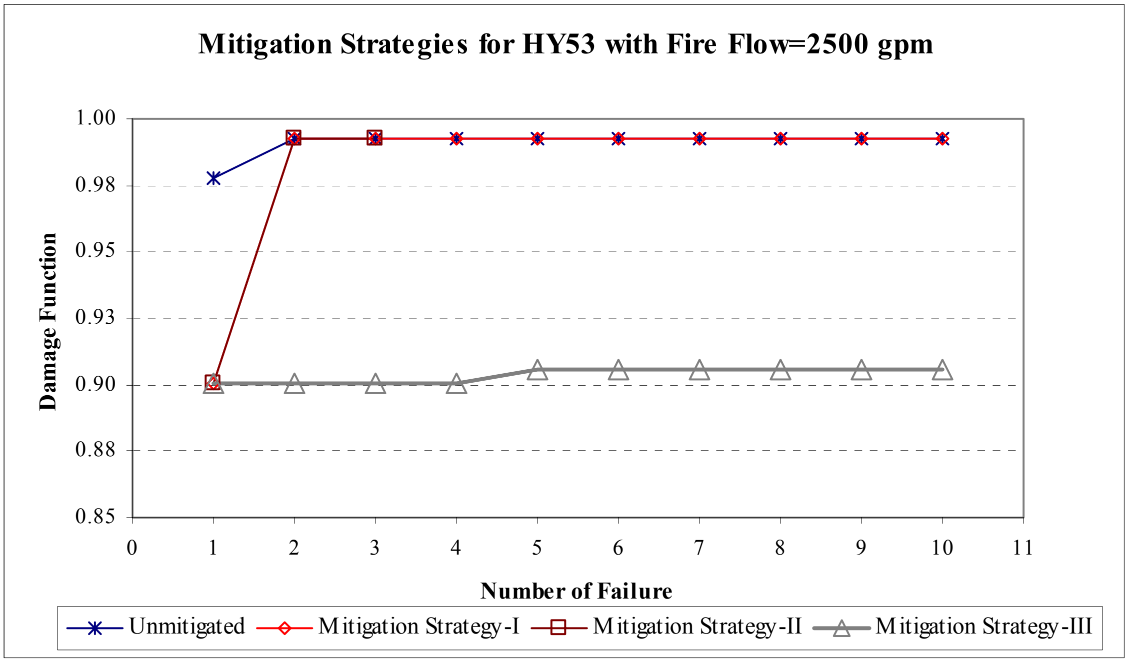

Fig. 4.11b. Mitigation strategies for hydrant HY53 with Fire Flow=2500 gpm

4.3.5. Analysis of Mitigation Strategies at Hydrant HY66

The simulation results from different mitigation strategies for hydrant HY66 are shown in Figs. 4.12a and 4.12b. Fig. 4.12a shows the different mitigation strategies with 1000 gpm fire flow. From the figure it can be seen that all three strategies reduce damage significantly. With Strategy-I, the system retains its resiliency up to X_{max} equals to 10. However with both Strategy-II and III, the system retains significant resiliency up to X_{max} equals to15.

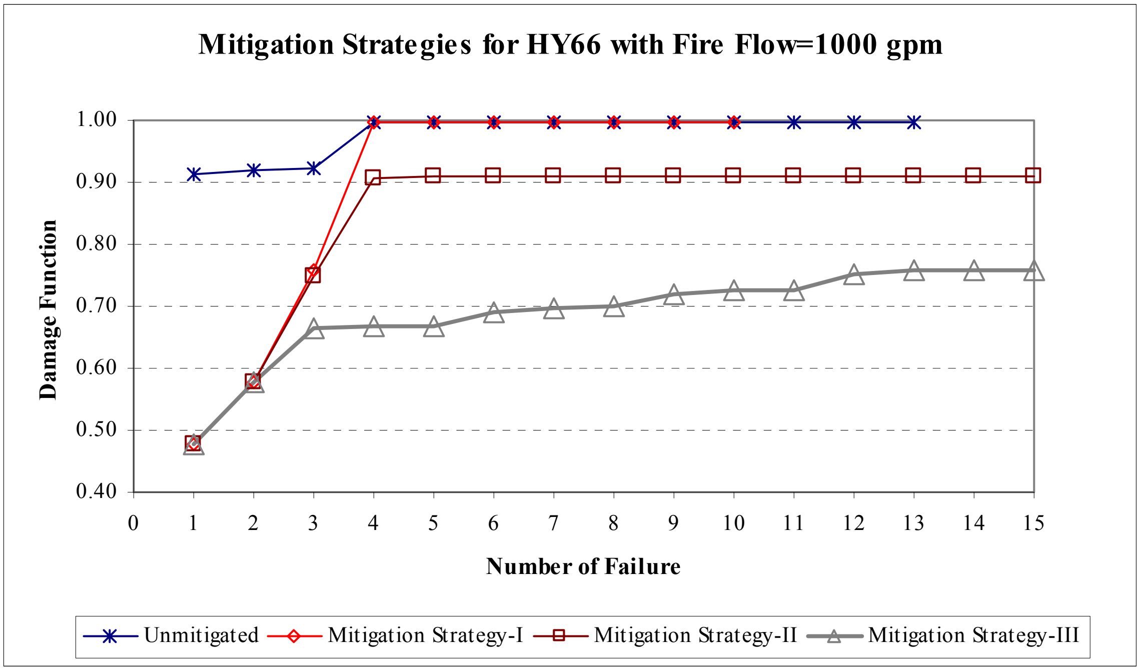

Fig. 4.12a. Mitigation strategies for hydrant HY66 with fire flow=1000 gpm

Fig. 4.12b shows the simulation results for different mitigation strategies when 2500 gpm fire flow is used. The results are somewhat similar to the results from 1000 gpm fire flows with higher magnitude in damages. The damages are higher with higher fire flow requirements than that with lower fire flow requirements because of the fact that, higher the required flow magnitude, greater is the flow term in equation 3.3 and thus, the damage is also higher.

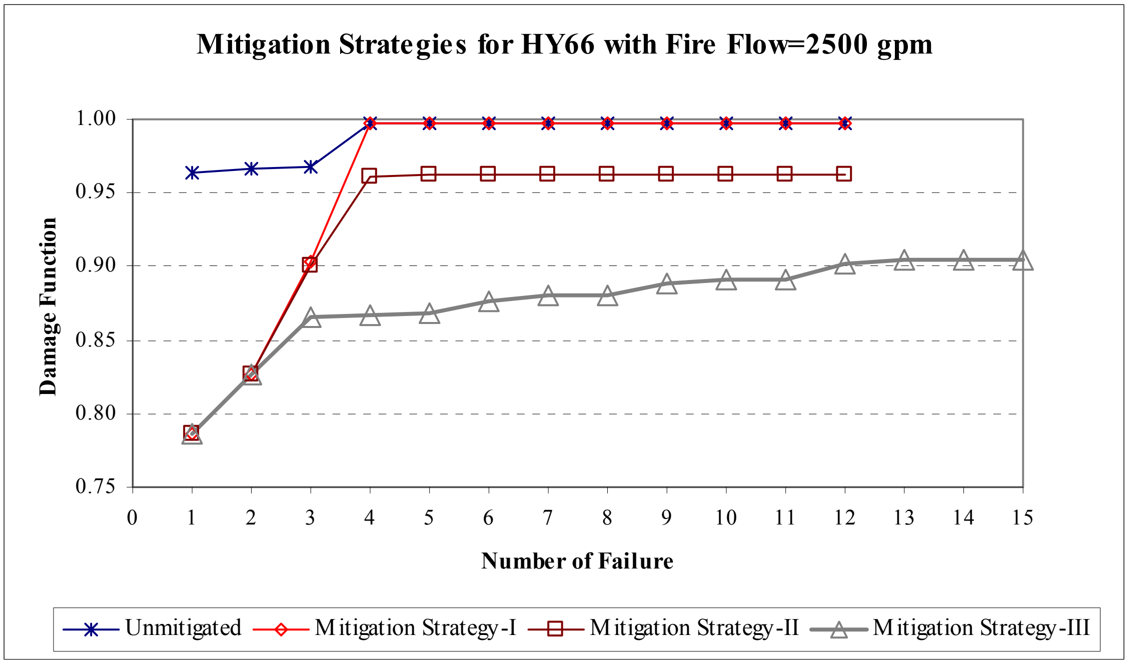

Fig. 4.12b. Mitigation strategies for hydrant HY66 with fire flow=2500 gpm

4.3.6. Analysis of Mitigation Strategies at Hydrant HY61

The damage at hydrant HY61 was infinitely large for any value of X_{max} greater than or equals to 1 during unmitigated condition. When mitigation strategies are applied with fire at this location the damages reduce significantly, especially with Mitigation Strategy-III. Fig. 4.13 shows the simulation results from different mitigation strategies. The figure indicates that the system responds in a similar manner with Strategy-I and II when fire occurs at HY61. With Strategy-I and II the damage functions reach plateaus after removal of 3 mains and 4 mains respectively with a value 0.996. Thus, in both the cases, the system demonstrates its “Resilience” / “Yellow Light” condition. However, Strategy-III reduces the damage even more significantly and the system retains its resiliency up to X_{max} equals to 13.

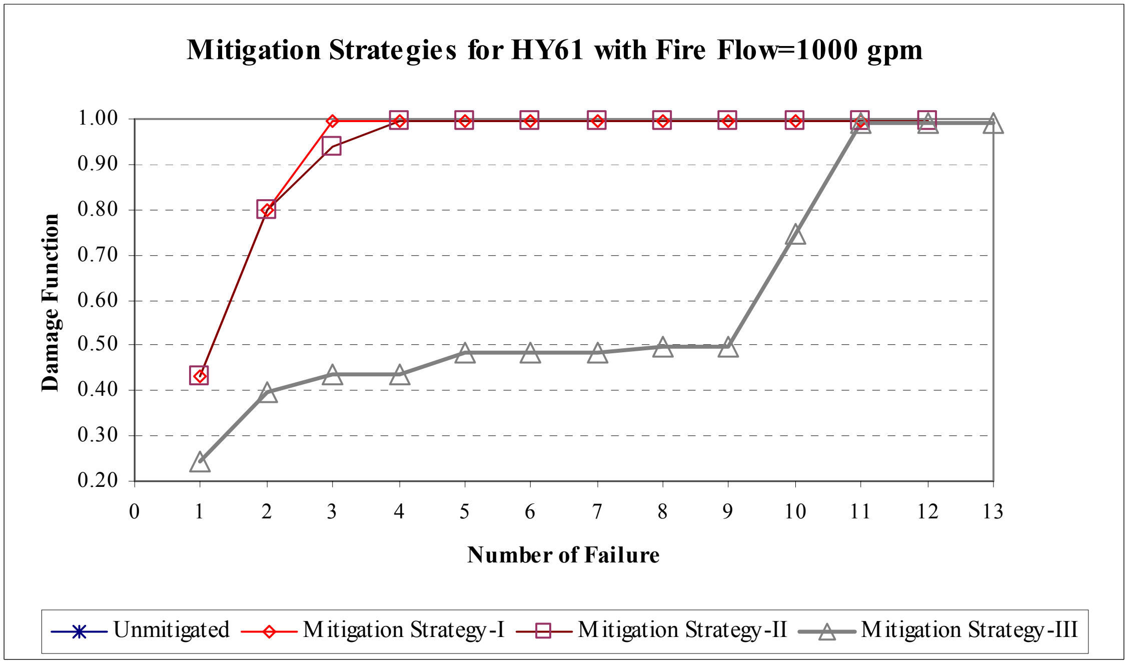

Fig. 4.13. Mitigation strategies for hydrant HY61 with fire flow=1000 gpm

4.3.7. Benefit Cost Analysis for Proposed Mitigation Strategies

The proposed mitigation strategies for reducing the damage are based upon the optimal decision of destroying/disrupting the water mains with fire at selected locations. From the simulation results of the mitigation strategies, it can be noted that all three mitigation strategies can reduce the damage moderate to substantially during fire condition. But, in any decision making process the selection of alternative strategies also depends upon economic feasibility (Wurbs and James 2002). To demonstrate the economic feasibility of the mitigation strategies, a benefit cost analysis was performed with fire at hydrants HY17, HY29, HY40, HY53, and HY66. Since all three strategies recommend hardening of certain number of pipes, the economic cost of the alternative strategies will correspond to the cost of hardening. As mentioned earlier, hardening of the critical water mains can be achieved by replacing those pipes with same diameter ductile iron pipes. Assuming an excavation and backfill cost of $1.05/ft and the cost of ductile iron, cement lined, class 50 water pipe with 12 inch, 8 inch, and 4 inch diameter as $29.61/ft, $11.39/ft and $18.56/ft, respectively (Mossman 1997) the estimated cost of hardening for all three mitigation strategies are listed in Table 4.4.

Table 4.4. Estimated Costs of Hardening for Proposed Mitigation Strategies

Mitigation Strategy	Estimated Cost ($)
I	5,000
II	17,700
III	28,500

The benefits are calculated on the basis of reduction in damages by applying different mitigation strategies with fire at the above five locations. Because the property values are different at different locations, the costs of rebuilding the assets in the areas covered by the hydrants HY17, HY29, HY40, HY53, and HY66 (Fig. 4.1) were

Table 4.5. Net Benefit Comparison for Different Mitigation Strategies at $X_{max} = 3$

Fire Location with Required Fire Flow (FF)	Mitigation Strategy	Estimated Cost $	Estimated Benefit $	Benefit-Cost Ratio	Net Benefit $
HY17	I	5,000	840	0.17	-4,160
FF=1000gpm	II	17,700	53,370	3.02	35,670
	III	28,500	53,369	1.87	24,869
HY29	I	5,000	2,465,053	493.01	2,460,053
FF=1000gpm	II	17,700	1,020,353	57.65	1,002,653
	III	28,500	5,068,082	177.83	5,039,582
HY40	I	5,000	1,173,981	234.80	1,168,981
FF=2500gpm	II	17,700	1,135,624	64.16	1,117,924
	III	28,500	1,637,330	57.45	1,608,830
HY53	I	5,000	574	0.11	-4,426
FF=2500gpm	II	17,700	0	0.00	-17,700
	III	28,500	5,906,156	207.23	5,877,656
HY66	I	5,000	1,949,620	389.92	1,944,620
FF=2500gpm	II	17,700	2,031,771	114.79	2,014,071
	III	28,500	3,089,384	108.40	3,060,884

estimated based on the cost of rebuilding facilities on a per square foot basis (Chiang 1997). The estimated cost was then multiplied by the damage function for both unmitigated and all three mitigated conditions to get the estimated cost of damage at the respective fire locations. The benefit from adapting a certain mitigation strategy is equivalent to how much building replacement cost is saved from fire damage in implementing the strategy. From the estimated benefit and cost, a benefit-cost ratio and net benefits are calculated and presented in Table 4.5. From the table, it can be concluded that for a maximum allowable failure (X_{max}) of 3, Mitigation Strategy-III yields more net benefit than the other two strategies at all hydrant locations except HY17. Thus Strategy-III is economically optimum.

4.4. Sensitivity Analysis of Weighting Coefficients α and β

A sensitivity analysis on the values of the weighting coefficients α and β was performed with fire at hydrants HY17, HY29, HY40, HY53 and HY66. During this analysis only flow based damage function was used because the pressure based damage function was not very effective in previous simulations. The resulting number of failures versus damages for all hydrant location with unmitigated condition are presented in Fig. B.1 through B.5 in APPENDIX-B. During this analysis three different sets of values for α and β were chosen, these are: (i) $\alpha=0.99$ and $\beta=0.01$, (ii) $\alpha=0.92$ and $\beta=0.08$, and (iii) $\alpha=0.85$ and $\beta=0.15$. It should be noted that all three sets of values of α were chosen to be significantly higher than the values of β. The reason for choosing higher values of α is that, this coefficient represents the weight of the flow term in damage function equation when the available flow at fire location is less than the required flow for suppressing the fire. In this situation, water will be obtained primarily from the hydrant at fire location and the additional flow will be obtained from any nearby operable hydrants. The coefficient β, on the other hand, represents the weight of the distance term in equation 3.3. As the target fire hydrant will contribute most of the flow for fire fighting, the values of α will always be higher than that of the coefficient β. And, for any values of α and β, the sum of the coefficient α and β will be equal to 1. From the figures it can be concluded that for any sets of values of α and β, the shape of the 'Failure versus Damage' curves remains unchanged at all hydrant locations. However, the magnitude of damage changes with the values of α and β. This represents that the model is very sensitive to the selection of values for the coefficients α and β.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The study of vulnerability of water supply systems has drawn great attention around the world recently. The proposed methodology in this study demonstrates how to identify the most critical pipes of any water supply system for a fire event. Obviously the pumping stations and elevated storage tanks are the most critical components of the system, however, this methodology is focused toward the pipes/links of the system because of two reasons: (1) pipes make up the largest capital investment in any water utility (Mays, 1996) and (2) the supply mains are relatively unprotected and easily accessible. The results from the optimization model illustrate that even though the critical components/pipes of a water supply system vary depending upon the location of fire, some of the same water mains appeared as the most vulnerable components for fire at all six locations under consideration. Based on those critical components/water mains of the system, three mitigation strategies were proposed to harden specific sets of water mains. In addition to hardening of the specific system components as recommended in this study, the following additional mitigation measures could also be applied:

- Installation of surveillance cameras, electrifying fences, guards, etc. around the pumping stations, elevated storage tanks, and near critical water mains,
- Providing standby pumps if one or more pumps in the pumping station get out of service,

- Installing alternative sources of power supply for pumping operation in case of emergency,
- Providing trained field operators for emergency response, and
- Maintaining an inventory of locations of the fire department and available fire trucks at those locations.

Simulations of the mitigation strategies show that the damage can be reduced significantly by adapting the mitigation measures, and the system's robustness and resilience can be improved as well. Because cost is associated with hardening and adding security of the system, a benefit cost analysis was also performed for all three mitigation strategies assuming a maximum allowable failure equals to 3. Although the model shows that all of the three proposed strategies can reduce the damages substantially during fire, Strategy-III gives more net benefit and stands out to be economically optimum among all three mitigation strategies.

In this study the optimization model has been developed in a generalized way so that the same model can be used for any water supply system provided that the model inputs have been added correctly. Most of the vulnerability assessment tools developed so far for the water systems have emphasized on chemical/biological threats. This model could provide a new direction for researchers. Occurrence of fire during a terrorist attack is obviously a physical threat to water system which in turn might cause a substantial damage to the society because of the interdependency of water infrastructure with other critical infrastructures. Thus this optimization model could be used as a potential vulnerability assessment tool for urban water supply system in future.

5.2. Recommendations for Future Research

In assessing the vulnerability of the water supply system during this study, only pipes were considered as potential critical components of the system. In reality, the junction nodes are also critical elements of the system and are needed to be considered. Lewis (2006) developed Model Based Vulnerability Analysis (MBVA) methodology to assess the vulnerability of any critical infrastructure using network theory. In his proposed methodology, Lewis (2006) focused on the critical nodes, identified with respect to the degree distribution of the nodes, and analyzed the system's vulnerability and risk at those critical components. Because "degree" of a node represented the number of links connected to that node, removal of nodes from a network resulted in loss of connectivity between the nodes and this made higher degree nodes more vulnerable to deliberate attack/removal. The idea of critical node analysis based upon the degree of a node can be adapted for future study of water supply systems. Conceptually, the hydrants and the terminal nodes are single-degree nodes, where as, the junction nodes are multiple-degree nodes. Thus optimization models can be developed for the water system to find out the most critical nodes of the system which may cause substantial damage to the system. Because of the restrictions in certain format of the model input file, the proposed model cannot be used to identify the critical nodes/junctions and the corresponding degree for those nodes of the system; however, the proposed model can be modified to perform the above mentioned analysis. To achieve this, more understanding of the network structures, man hour and effort is required. If this can be done in near future, hopefully it will give us better and efficient security strategies to protect the water system.

ABBREVIATIONS

AMSA	Association of Metropolitan Sewerage Agencies
ASDWA	Association of State Drinking Water Administrators
AWWA	American Water Works Association
BCS	Cities of Bryan and College Station, Texas
EWDS	Early Warning Detection System
FF	Fire Flow
GA	Genetic Algorithm
GIS	Geographic Information System
GPM	Gallons per minute
HHM	Hierarchical Holographic Modeling
IRAM	Infrastructure Risk Analysis Model
MBVA	Model Based Vulnerability Analysis
MLE	Markov Latent Effect
NRWA	National Rural Water Association
PCCIP	President's Commission on Critical Infrastructure Protection
PMRM	Partitioned Multi-objective Risk Method
PSI	Pounds per square inch
RAM-W	Risk Assessment Methodology for Water utilities
RPM	Randomized Pollution Matrix
SCADA	Supervisory Control And Data Acquisition

TCEQ	Texas Commission on Environmental Quality
US	United States
USACE	United States Army Corps of Engineers
USBR	United States Bureau of Reclamation
USEPA	United States Environmental Protection Agency

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APPENDIX A

RESULTS FROM THE OPTIMIZATION MODEL

Table A.1.1. Results at HY17 with 1000 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	HY64	MA1006	HY64
2	MA1006, MA1020	HY64	MA802, MA989	HY14, HY24, HY28, HY40-HY45, HY53-HY55, HY64, HY66, HY68, HY69
3	MA802,MA989, MA1006	HY64	MA802, MA989, MA1006	HY64
4	MA691, MA693, MA728, MA963	HY64	MA802, MA989, MA1006, MA1024	HY64
5	MA691, MA693, MA728, MA802, MA963	HY64	MA802, MA989, MA1006, MA1019, MA1024	HY64
6	MA552, MA691, MA693, MA728, MA802, MA963	HY64	MA802, MA989, MA1006, MA1019, MA1020, MA1024	HY64
7	MA552, MA672, MA678, MA691, MA693, MA728, MA737	HY64	MA802, MA989, MA1006, MA1013, MA1019, MA1020, MA1024	HY64
8	MA552, MA647, MA672, MA678, MA691, MA693, MA728, MA737	HY64	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737	HY64

Table A.1.1. (Continued)

X_{max}	Pressure Based Damage		Flow Based Damage	
	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
9	MA552, MA647, MA672, MA678, MA679, MA691, MA693, MA728, MA737	HY64	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA1006	HY64
10	MA552, MA647, MA672, MA678, MA679, MA691, MA693, MA728, MA735, MA737	HY64	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA989	HY64
11	MA552, MA647, MA672, MA676, MA678, MA679, MA691, MA693, MA728, MA735, MA737	HY64	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA989, MA1024	HY64
12	MA552, MA647, MA672, MA676, MA678, MA679, MA691, MA693, MA728, MA735, MA737, MA740	HY64	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA989, MA997, MA1006	None

Table A.1.2. Results at HY29 with 1000 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	HY64	MA1006	HY64
2	MA814, MA1006	HY64	MA1006, MA1024	HY64
3	MA691,MA693, MA1006	HY64	MA1006, MA1020, MA1024	HY64
4	MA691, MA693, MA728, MA1006	HY64	MA549, MA814, MA1006, MA1024	HY64
5	MA549, MA691, MA693, MA728, MA1006	HY64	MA549, MA638, MA814, MA1006, MA1013	None
6	MA549, MA638, MA691, MA693, MA728, MA1006	HY64		
7	MA549, MA552, MA638, MA691, MA693, MA728, MA1006	HY64		
8	MA549, MA552, MA638, MA672, MA691, MA693, MA728, MA1006	HY64		
9	MA549, MA552, MA638, MA672, MA678, MA691, MA693, MA728, MA1006	HY64		
10	MA549, MA552, MA638, MA647, MA672, MA678, MA691, MA693, MA728, MA1006	HY64		

Table A.1.2. (Continued)

X_{max}	Pressure Based Damage		Flow Based Damage	
	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
11	MA549, MA552, MA638, MA647, MA672, MA678, MA679, MA691, MA693, MA728, MA1006	HY64		
12	MA549, MA552, MA638, MA647, MA672, MA676, MA678, MA679, MA691, MA693, MA728, MA1006	HY64		

Table A.1.3. Results at HY40 with 1000 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	HY64	MA1006	HY64
2	MA478, MA505	HY1, HY4, HY6, HY11, HY12, HY14, HY17, HY29, HY37, HY38, HY42-HY44, HY50-HY54, HY62, HY64, HY65, HY68	MA478, MA1006	HY64
3	MA478, MA505, MA549	Same as above	MA478, MA1006, MA1024	HY64
4	MA478, MA505, MA549, MA552	Same as above	MA478, MA1006, MA1020, MA1024	HY64
5	MA478, MA505, MA549, MA552, MA565	Same as above	MA478, MA549, MA552, MA1006, MA1024	HY64
6	MA478, MA505, MA549, MA552, MA565, MA576	Same as above	MA478, MA549, MA552, MA691, MA1006, MA1013	None
7	MA478, MA505, MA549, MA552, MA565, MA576, MA599	Same as above		

Table A.1.3. (Continued)

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
8	MA478, MA505, MA549, MA552, MA565, MA576, MA599, MA609	Same as above		
9	MA478, MA505, MA549, MA552, MA565, MA576, MA599, MA609, MA610	Same as above		
10	MA478, MA505, MA549, MA552, MA565, MA576, MA599, MA609, MA610, MA638	Same as above		
11	MA478, MA505, MA549, MA552, MA565, MA576, MA599, MA609, MA610, MA638, MA647	Same as above		

Table A.1.4. Results at HY40 with 2500 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA478	HY64	MA1006	HY64
2			MA478, MA1006	HY64
3			MA478, MA1006, MA1024	HY64
4			MA478, MA1006, MA1020, MA1024	HY64
5			MA478, MA549, MA552, MA1006, MA1024	HY64
6			MA478, MA549, MA552, MA691, MA1006, MA1013	None

Table A.1.5. Results at HY53 with 1000 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	HY64	MA1006	HY64
2	MA883, MA1006	HY64	MA883, MA1006	HY64
3	MA691, MA693, MA728	HY51, HY52, HY64	MA693, MA883, MA1006	HY64
4	MA691, MA693, MA728, MA883	HY14, HY45, HY51, HY52, HY55	MA693, MA883, MA1006, MA1024	HY64
5	MA691, MA693, MA728, MA883, MA906	HY14, HY45, HY51, HY52, HY55	MA591, MA691, MA693, MA883, MA1006	HY64
6	MA691, MA693, MA728, MA883, MA906, MA925	HY14, HY45, HY51, HY52, HY55	MA591, MA691, MA693, MA728, MA883, MA1006	HY64
7	MA691, MA693, MA728, MA883, MA906, MA925, MA991	HY14, HY45, HY51, HY52, HY55	MA552, MA591, MA691, MA693, MA728, MA883, MA1006	HY64
8	MA691, MA693, MA728, MA883, MA906, MA925, MA991, MA997	HY14, HY45, HY51, HY52, HY55	MA552, MA591, MA691, MA693, MA728, MA802, MA883, MA1006	HY64
9	MA552, MA610, MA691, MA693, MA728, MA735, MA737, MA740, MA745	HY51, HY52, HY64	MA552, MA591, MA691, MA693, MA728, MA802, MA883, MA1006, MA1013	HY64

Table A.1.5. (Continued)

X_{max}	Pressure Based Damage		Flow Based Damage	
	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
10	MA552, MA610, MA691, MA693, MA728, MA735, MA737, MA740, MA745, MA749	HY51, HY52, HY64	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883, MA1006, MA1013	HY64
11	MA552, MA610, MA691, MA693, MA728, MA735, MA737, MA740, MA745, MA749, MA758	HY51, HY52, HY64	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883, MA895, MA1006, MA1013	HY64
12	MA552, MA610, MA691, MA693, MA728, MA735, MA737, MA740, MA745, MA749, MA758, MA766	HY51, HY52, HY64		

Table A.1.6. Results at HY53 with 2500 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	HY64	MA1006	HY64
2	MA883, MA1006	HY64	MA883, MA1006	HY64
3	MA691, MA693, MA728	HY51, HY52, HY64	MA693, MA883, MA1006	HY64
4	MA691, MA693, MA728, MA883	HY14, HY45, HY51, HY52, HY55	MA693, MA802, MA883, MA1006	HY64
5	MA691, MA693, MA728, MA883, MA906	HY14, HY45, HY51, HY52, HY55	MA591, MA691, MA693, MA883, MA1006	HY64
6	MA691, MA693, MA728, MA883, MA906, MA925	HY14, HY45, HY51, HY52, HY55	MA591, MA691, MA693, MA728, MA883, MA1006	HY64
7	MA691, MA693, MA728, MA883, MA906, MA925, MA991	HY14, HY45, HY51, HY52, HY55	MA552, MA591, MA691, MA693, MA728, MA883, MA1006	HY64
8	MA691, MA693, MA728, MA883, MA906, MA925, MA991, MA997	HY14, HY45, HY51, HY52, HY55	MA552, MA591, MA691, MA693, MA728, MA802, MA883, MA1006	HY64
9	MA552, MA610, MA691, MA693, MA728, MA735, MA737, MA740, MA745	HY51, HY52, HY64	MA552, MA591, MA691, MA693, MA728, MA802, MA883, MA1006, MA1013	HY64

Table A.1.6. (Continued)

X_{max}	Pressure Based Damage		Flow Based Damage	
	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
10	MA552, MA610, MA691, MA693, MA728, MA735, MA737, MA740, MA745, MA749	HY51, HY52, HY64	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883, MA1006, MA1013	HY64

Table A.1.7. Results at HY66 with 1000 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	HY64	MA1006	HY64
2	MA1006, MA1019	HY64	MA1006, MA1019	HY64
3	MA1006, MA1019, MA1024	HY64	MA1006, MA1019, MA1024	HY64
4	MA691, MA693, MA728, MA963	HY64	MA576, MA591, MA691, MA1006	HY64
5	MA691, MA693, MA728, MA963, MA1006	HY64	MA576, MA591, MA691, MA693, MA1006	HY64
6	MA691, MA693, MA728, MA963, MA1006, MA1013	HY64	MA576, MA591, MA691, MA693, MA1006, MA1024	HY64
7	MA552, MA576, MA691, MA693, MA728, MA802, MA1006	HY64	MA552, MA576, MA591, MA691, MA693, MA728, MA1006	HY64
8	MA552, MA576, MA691, MA693, MA728, MA793, MA802, MA1006	HY64	MA552, MA576, MA591, MA691, MA693, MA728, MA811, MA1006	HY64
9	MA552, MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737	HY64	MA552, MA576, MA591, MA691, MA693, MA728, MA793, MA802, MA1006	HY64
10	MA552, MA576, MA610, MA647, MA672, MA678, MA691, MA693, MA728, MA737	HY64	MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737	HY64

Table A.1.7. (Continued)

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
11	MA552, MA576, MA610, MA647, MA672, MA678, MA679, MA691, MA693, MA728, MA737	HY64	MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA1006	HY64
12	MA552, MA576, MA610, MA647, MA672, MA678, MA679, MA691, MA693, MA728, MA735, MA737	HY64	MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA1006	HY64

Table A.1.8. Results at HY66 with 2500 gpm Fire Flow: Unmitigated Condition

	Pressure Based Damage		Flow Based Damage	
X_{max}	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	HY64	MA1006	HY64
2	MA1006, MA1019	HY64	MA1006, MA1019	HY64
3	MA1006, MA1019, MA1024	HY64	MA1006, MA1019, MA1024	HY64
4	MA691, MA693, MA728, MA963	HY64	MA576, MA591, MA691, MA1006	HY64
5	MA691, MA693, MA728, MA963, MA1006	HY64	MA576, MA591, MA691, MA693, MA1006	HY64
6	MA691, MA693, MA728, MA963, MA1006, MA1013	HY64	MA576, MA591, MA691, MA693, MA1006, MA1024	HY64
7	MA552, MA576, MA691, MA693, MA728, MA802, MA1006	HY64	MA552, MA576, MA591, MA691, MA693, MA728, MA802	HY64
8	MA552, MA576, MA691, MA693, MA728, MA793, MA802, MA1006	HY64	MA552, MA576, MA591, MA691, MA693, MA728, MA802, MA1006	HY64
9	MA552, MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737	HY64	MA552, MA576, MA591, MA691, MA693, MA728, MA793, MA802, MA1006	HY64
10	MA552, MA576, MA610, MA647, MA672, MA678, MA691, MA693, MA728, MA737	HY64	MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737	HY64

Table A.1.8. (Continued)

X_{max}	Pressure Based Damage		Flow Based Damage	
	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
11			MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA1006	HY64
12			MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA1006	HY64

Table A.1.9. Results at HY61 with 1000 gpm Fire Flow: Unmitigated Condition

X_{max}	Pressure Based Damage		Flow Based Damage	
	Optimal Decisions	Operable Nodes	Optimal Decisions	Operable Nodes
1	MA1006	None	MA1006	None

Table A.2.1. Results at HY17 with 1000 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA802	MA802	MA802
2	MA802, MA1024	MA802, MA1024	MA802, MA1024
3	MA591, MA691, MA693	MA802, MA989, MA1024	MA802, MA989, MA1024
4	MA591, MA691, MA693, MA728	MA691, MA693, MA728, MA989	MA802, MA989, MA991, MA1024
5	MA552, MA591, MA691, MA693, MA728	MA691, MA693, MA728, MA963, MA989	MA802, MA989, MA991, MA997, MA1024
6	MA552, MA591, MA691, MA693, MA728, MA802	MA691, MA693, MA728, MA963, MA989, MA1019	MA495, MA793, MA802, MA883, MA989, MA1024
7	MA552, MA591, MA691, MA693, MA728, MA802, MA1024	MA495, MA691, MA693, MA728, MA802, MA963, MA989	MA495, MA793, MA802, MA883, MA965, MA989, MA1024
8	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737	MA495, MA691, MA693, MA728, MA802, MA963, MA989, MA1024	MA495, MA505, MA565, MA576, MA609, MA793, MA802, MA963
9	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA802	MA495, MA691, MA693, MA728, MA802, MA963, MA989, MA1019, MA1024	MA495, MA505, MA565, MA576, MA609, MA793, MA802, MA963, MA1024
10	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA1024	MA495, MA691, MA693, MA728, MA802, MA963, MA989, MA991, MA1019, MA1024	MA495, MA505, MA565, MA576, MA609, MA793, MA802, MA963, MA989, MA1024

Table A.2.1. (Continued)

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
11	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA989, MA1024		MA495, MA505, MA565, MA576, MA609, MA793, MA802, MA963, MA965, MA989, MA1024
12	MA552, MA591, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA989, MA997, MA1024		MA495, MA505, MA565, MA576, MA609, MA793, MA802, MA963, MA965, MA989, MA1020, MA1024

Table A.2.2. Results at HY29 with 1000 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA814	MA814	MA814
2	MA549, MA814	MA691, MA693	MA638, MA814
3	MA549, MA638, MA814	MA691, MA693, MA728	MA478, MA638, MA814
4	MA549, MA638, MA691, MA814	MA691, MA693, MA728, MA1024	MA478, MA638, MA814, MA883
5	MA549, MA638, MA691, MA693, MA728	MA691, MA693, MA728, MA963, MA989	MA478, MA638, MA672, MA678, MA814
6	MA549, MA638, MA691, MA693, MA728, MA1024	MA691, MA693, MA728, MA963, MA989, MA1019	MA478, MA638, MA672, MA678, MA737, MA811
7	MA549, MA638, MA691, MA693, MA728, MA989, MA991	MA691, MA693, MA728, MA963, MA989, MA1019, MA1020	MA478, MA638, MA672, MA678, MA737, MA811, MA1024
8	MA549, MA638, MA691, MA693, MA728, MA814, MA989, MA991	MA691, MA693, MA728, MA963, MA989, MA997, MA1013, MA1019	MA478, MA638, MA672, MA678, MA737, MA811, MA989, MA1024
9	MA549, MA638, MA691, MA693, MA728, MA814, MA963, MA989, MA991	MA691, MA693, MA728, MA963, MA989, MA997, MA1013, MA1019, MA1020	MA478, MA638, MA672, MA678, MA737, MA811, MA814, MA989, MA1024
10	MA549, MA552, MA591, MA609, MA610, MA638, MA647, MA672, MA691, MA693	MA691, MA693, MA728, MA963, MA989, MA997, MA1013, MA1019, MA1020, MA1024	MA478, MA638, MA672, MA678, MA737, MA811, MA814, MA963, MA989, MA1019

Table A.2.2. (Continued)

	Optimal Decisions using Flow Based Damage Function		
*X*_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
11		MA478, MA638, MA691, MA693, MA728, MA802, MA963, MA989, MA1019, MA1020, MA1024	MA478, MA638, MA672, MA678, MA737, MA811, MA814, MA963, MA989, MA1019, MA1024

Table A.2.3. Results at HY40 with 1000 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA478	MA478	MA478
2	MA478, MA552	MA478, MA691	MA478, MA814
3	MA478, MA549, MA552	MA478, MA691, MA693	MA478, MA672, MA678
4	MA478, MA549, MA552, MA691	MA478, MA691, MA693, MA728	MA478, MA672, MA678, MA737
5	MA478, MA549, MA552, MA691, MA1024	MA478, MA691, MA693, MA728, MA989	MA478, MA672, MA678, MA737, MA1024
6	MA478, MA549, MA552, MA691, MA693, MA728	MA478, MA691, MA693, MA728, MA989, MA991	MA478, MA672, MA678, MA737, MA989, MA1024
7	MA478, MA549, MA552, MA691, MA693, MA728, MA989	MA478, MA691, MA693, MA728, MA989, MA991, MA1019	MA478, MA672, MA678, MA737, MA989, MA1019, MA1024
8	MA478, MA549, MA552, MA691, MA693, MA728, MA989, MA991	MA478, MA691, MA693, MA728, MA963, MA964, MA965, MA989	MA478, MA672, MA678, MA737, MA989, MA1019, MA1020, MA1024
9	MA478, MA549, MA552, MA691, MA693, MA728, MA989, MA991 (Could not take out more than 8 pipes)	MA478, MA691, MA693, MA728, MA963, MA964, MA965, MA989, MA1019	MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013
10		MA478, MA691, MA693, MA728, MA963, MA964, MA965, MA989, MA991, MA1019	MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013, MA1019

Table A.2.3. (Continued)

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
11		MA478, MA691, MA693, MA728, MA963, MA964, MA965, MA989, MA991, MA1019, MA1024	MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013, MA1019, MA1020
12			MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013, MA1019, MA1020, MA1024

Table A.2.4. Results at HY40 with 2500 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA478	MA478	MA478
2	MA478, MA552	MA478, MA691	MA478, MA814
3	MA478, MA549, MA552	MA478, MA691, MA693	MA478, MA672, MA678
4	MA478, MA549, MA552, MA691	MA478, MA691, MA693, MA728	MA478, MA672, MA678, MA737
5	MA478, MA549, MA552, MA691, MA1024	MA478, MA691, MA693, MA728, MA989	MA478, MA672, MA678, MA737, MA1024
6	MA478, MA549, MA552, MA691, MA693, MA728	MA478, MA691, MA693, MA728, MA963, MA989	MA478, MA672, MA678, MA737, MA989, MA1024
7	MA478, MA549, MA552, MA691, MA693, MA728, MA989	MA478, MA691, MA693, MA728, MA963, MA989, MA1019	MA478, MA672, MA678, MA737, MA989, MA1019, MA1024
8	MA478, MA549, MA552, MA691, MA693, MA728, MA989, MA991	MA478, MA691, MA693, MA728, MA963, MA989, MA997, MA1019	MA478, MA672, MA678, MA737, MA989, MA1019, MA1020, MA1024
9	MA478, MA549, MA552, MA691, MA693, MA728, MA963, MA964, MA989	MA478, MA691, MA693, MA728, MA963, MA964, MA965, MA989, MA1019	MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013
10	MA478, MA549, MA552, MA691, MA693, MA728, MA963, MA964, MA989, MA1019	MA478, MA691, MA693, MA728, MA963, MA964, MA965, MA989, MA991, MA1019	MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013, MA1019

Table A.2.4. (Continued)

X_{max}	Optimal Decisions using Flow Based Damage Function		
	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
11		MA478, MA691, MA693, MA728, MA963, MA964, MA965, MA989, MA991, MA997, MA1019	MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013, MA1019, MA1020
12			MA478, MA672, MA678, MA737, MA883, MA895, MA963, MA989, MA1013, MA1019, MA1020, MA1024

Table A.2.5. Results at HY53 with 1000 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA883	MA883	MA883
2	MA693, MA883	MA693, MA883	MA883, MA991
3	MA591, MA691, MA693	MA693, MA883, MA965	MA883, MA991, MA997
4	MA591, MA691, MA693, MA883	MA691, MA693, MA728, MA883 (System Unbalanced)	MA565, MA609, MA610, MA883
5	MA591, MA691, MA693, MA728, MA883		MA565, MA609, MA610, MA883, MA1013
6	MA552, MA591, MA691, MA693, MA728, MA883		MA565, MA609, MA610, MA883, MA895, MA1013
7	MA552, MA591, MA691, MA693, MA728, MA802, MA883		MA565, MA609, MA610, MA758, MA883, MA895, MA1013
8	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883		MA565, MA599, MA609, MA610, MA758, MA883, MA895, MA1013
9	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883, MA1013		MA565, MA599, MA609, MA610, MA758, MA883, MA895, MA925, MA1013
10	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883, MA895, MA1013		MA565, MA599, MA609, MA610, MA758, MA883, MA895, MA925, MA991, MA1013

Table A.2.6. Results at HY53 with 2500 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA883	MA883	MA883
2	MA693, MA883	MA693, MA883	MA883, MA991
3	MA693, MA802, MA883	MA693, MA802, MA883	MA883, MA991, MA997
4	MA591, MA691, MA693, MA883	MA691, MA693, MA728, MA883 (System Unbalanced)	MA565, MA609, MA610, MA883
5	MA591, MA691, MA693, MA728, MA883		MA565, MA609, MA610, MA883, MA1013
6	MA552, MA591, MA691, MA693, MA728, MA883		MA565, MA609, MA610, MA883, MA895, MA1013
7	MA552, MA591, MA691, MA693, MA728, MA802, MA883		MA565, MA609, MA610, MA758, MA883, MA895, MA1013
8	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883		MA565, MA599, MA609, MA610, MA758, MA883, MA895, MA1013
9	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883, MA1013		MA565, MA599, MA609, MA610, MA758, MA883, MA895, MA925, MA1013
10	MA552, MA565, MA591, MA609, MA610, MA691, MA693, MA883, MA895, MA1013		MA565, MA599, MA609, MA610, MA758, MA883, MA895, MA925, MA991, MA1013

Table A.2.7. Results at HY66 with 1000 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA576	MA576	MA576
2	MA576, MA802	MA576, MA802	MA576, MA802
3	MA576, MA591, MA691	MA576, MA691, MA693	MA576, MA802, MA883
4	MA576, MA591, MA691, MA693	MA576, MA691, MA693, MA728	MA576, MA793, MA802, MA883
5	MA576, MA591, MA691, MA693, MA728	MA576, MA691, MA693, MA728, MA802	MA576, MA793, MA802, MA883, MA964
6	MA552, MA576, MA591, MA691, MA693, MA728	MA576, MA691, MA693, MA728, MA802, MA1019	MA576, MA793, MA802, MA883, MA964, MA965
7	MA552, MA576, MA591, MA691, MA693, MA728, MA811	MA576, MA691, MA693, MA728, MA802, MA1013, MA1019	MA576, MA610, MA672, MA678, MA737, MA802, MA883
8	MA552, MA576, MA591, MA691, MA693, MA728, MA793, MA802	MA576, MA691, MA693, MA728, MA793, MA802, MA1013, MA1019	MA576, MA610, MA672, MA678, MA737, MA802, MA883, MA1019
9	MA552, MA576, MA591, MA610, MA691, MA693, MA728, MA793, MA802	MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA802	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802
10	MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737	MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA965	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802, MA883

Table A.2.7. (Continued)

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
11		MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA793, MA802, MA814	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802, MA883, MA1019
12		MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA793, MA802, MA814, MA819	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802, MA883, MA964, MA965

Table A.2.8. Results at HY66 with 2500 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA576	MA576	MA576
2	MA576, MA802	MA576, MA802	MA576, MA802
3	MA576, MA591, MA691	MA576, MA691, MA693	MA576, MA802, MA883
4	MA576, MA591, MA691, MA693	MA576, MA691, MA693, MA728	MA576, MA793, MA802, MA883
5	MA576, MA591, MA691, MA693, MA728	MA576, MA691, MA693, MA728, MA802	MA576, MA793, MA802, MA883, MA964
6	MA552, MA576, MA591, MA691, MA693, MA728	MA576, MA691, MA693, MA728, MA802, MA1019	MA576, MA793, MA802, MA883, MA964, MA965
7	MA552, MA576, MA591, MA691, MA693, MA728, MA802	MA576, MA691, MA693, MA728, MA802, MA1013, MA1019	MA576, MA610, MA672, MA678, MA737, MA802, MA883
8	MA552, MA576, MA591, MA691, MA693, MA728, MA793, MA802	MA576, MA691, MA693, MA728, MA793, MA802, MA1013, MA1019	MA576, MA610, MA672, MA678, MA737, MA802, MA883, MA1019
9	MA552, MA576, MA591, MA610, MA691, MA693, MA728, MA793, MA802	MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA802	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802
10	MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737	MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA802, MA965	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802, MA883

Table A.2.8. (Continued)

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
11	MA552, MA576, MA591, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA802	MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA793, MA802, MA814	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802, MA883, MA1019
12	MA552, MA576, MA591, MA610, MA672, MA678, MA679, MA691, MA693, MA728, MA737, MA802	MA576, MA610, MA672, MA678, MA691, MA693, MA728, MA737, MA793, MA802, MA814, MA819	MA478, MA565, MA576, MA609, MA610, MA672, MA678, MA737, MA802, MA883, MA964, MA965

Table A.2.9. Results at HY61 with 1000 gpm Fire Flow: Mitigated Conditions

	Optimal Decisions using Flow Based Damage Function		
X_{max}	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
1	MA691	MA691	MA1024
2	MA691, MA1024	MA691, MA1024	MA737, MA740
3	MA591, MA691, MA693	MA691, MA693, MA728	MA737, MA740, MA1024
4	MA591, MA691, MA693, MA728	MA691, MA693, MA728, MA989	MA737, MA740, MA963, MA989
5	MA552, MA591, MA691, MA693, MA728	MA691, MA693, MA728, MA963, MA989	MA737, MA740, MA963, MA989, MA1019
6	MA552, MA591, MA647, MA691, MA693, MA728	MA691, MA693, MA728, MA963, MA989, MA1019	MA737, MA740, MA963, MA989, MA1013, MA1019
7	MA552, MA591, MA647, MA672, MA691, MA693, MA728	MA691, MA693, MA728, MA963, MA989, MA1019, MA1020	MA737, MA740, MA963, MA989, MA997, MA1013, MA1019
8	MA552, MA591, MA647, MA672, MA679, MA691, MA693, MA728	MA495, MA576, MA609, MA610, MA691, MA693, MA728, MA963	MA495, MA576, MA609, MA610, MA737, MA740, MA883, MA963
9	MA552, MA591, MA647, MA672, MA679, MA691, MA693, MA728, MA740	MA495, MA505, MA576, MA609, MA610, MA691, MA693, MA728, MA963	MA495, MA576, MA609, MA610, MA737, MA740, MA883, MA906, MA963
10	MA552, MA591, MA647, MA672, MA679, MA691, MA693, MA728, MA735, MA740	MA495, MA505, MA576, MA609, MA610, MA691, MA693, MA728, MA963, MA1019	MA495, MA505, MA565, MA576, MA609, MA638, MA647, MA672, MA679, MA740

Table A.2.9. (Continued)

X_{max}	Optimal Decisions using Flow Based Damage Function		
	Mitigation Strategy-I	Mitigation Strategy-II	Mitigation Strategy-III
11		MA495, MA505, MA576, MA609, MA610, MA691, MA693, MA728, MA963, MA1013, MA1019	MA495, MA505, MA565, MA576, MA609, MA638, MA647, MA672, MA679, MA740, MA963
12		MA495, MA505, MA576, MA609, MA610, MA691, MA693, MA728, MA963, MA1013, MA1019, MA1020	MA495, MA505, MA565, MA576, MA609, MA638, MA647, MA672, MA679, MA740, MA793, MA963

APPENDIX B

SENSITIVITY ANALYSIS OF THE WEIGHTING COEFFICIENTS

α AND β

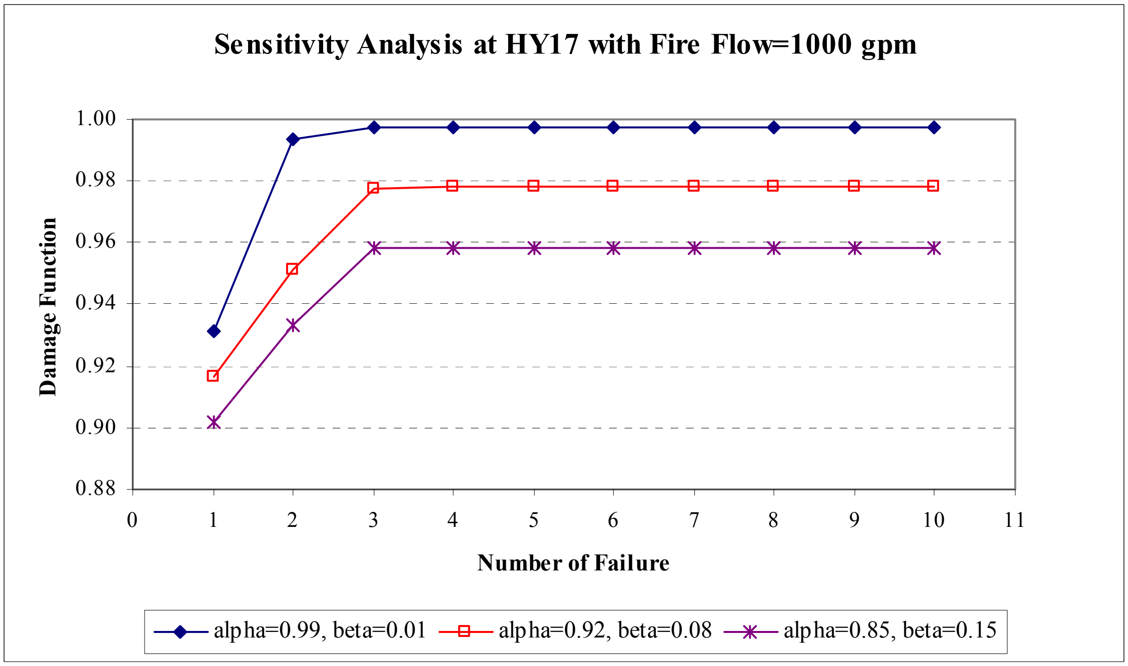

Fig. B.1. Sensitivity analysis of the coefficients α and β at hydrant HY17

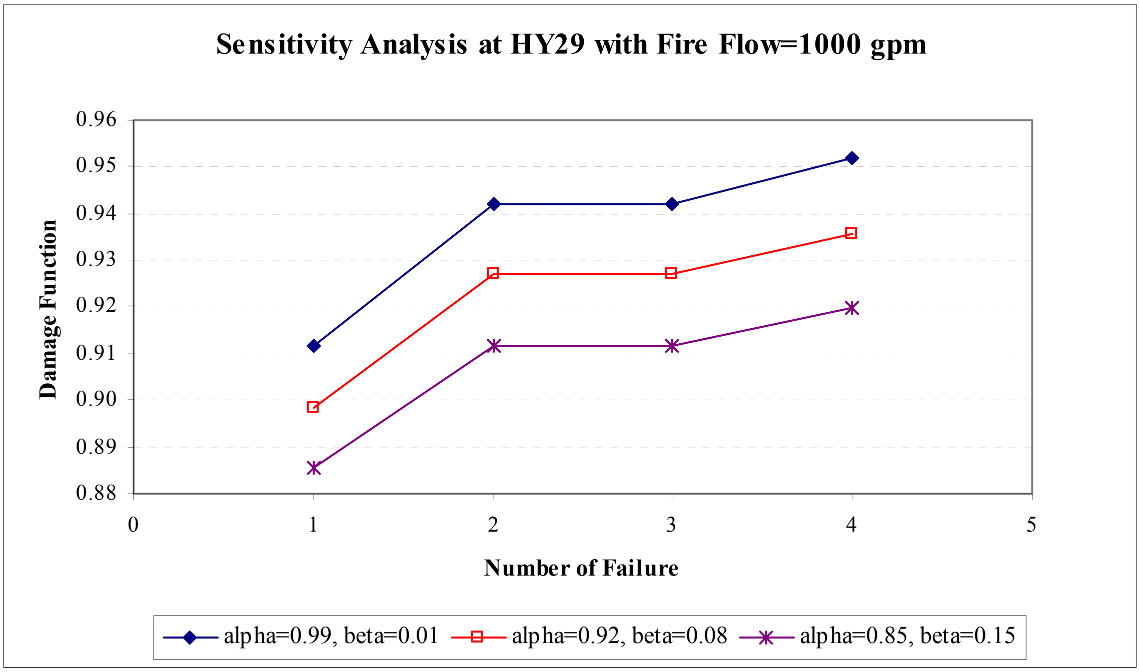

Fig. B.2. Sensitivity analysis of the coefficients α and β at hydrant HY29

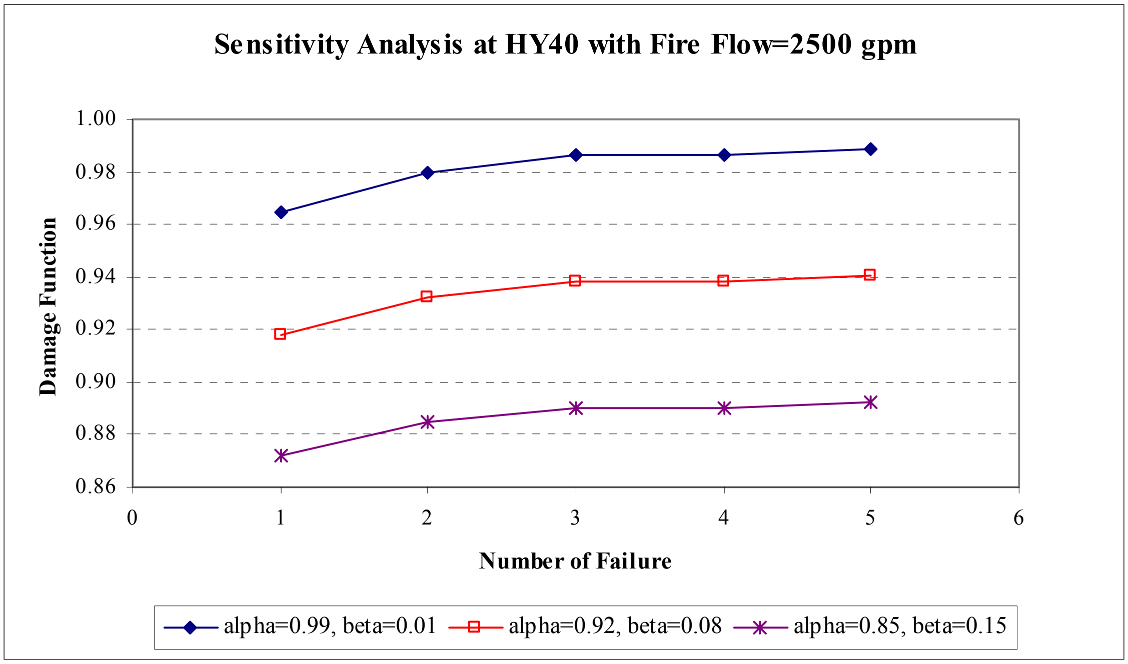

Fig. B.3. Sensitivity analysis of the coefficients α and β at hydrant HY40

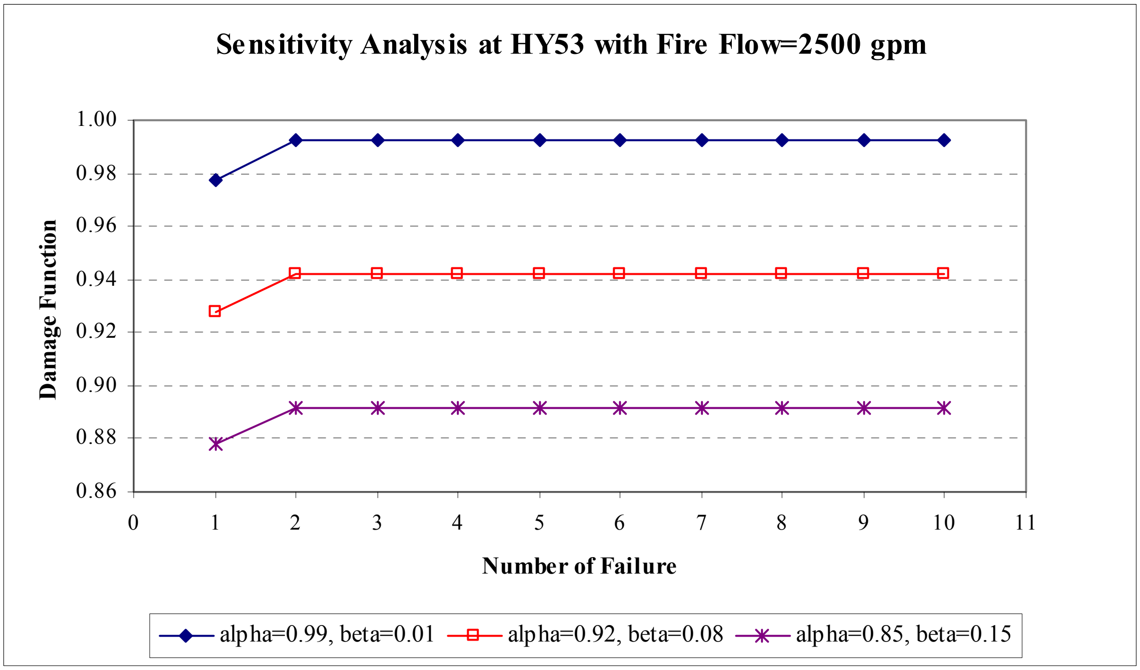

Fig. B.4. Sensitivity analysis of the coefficients α and β at hydrant HY53

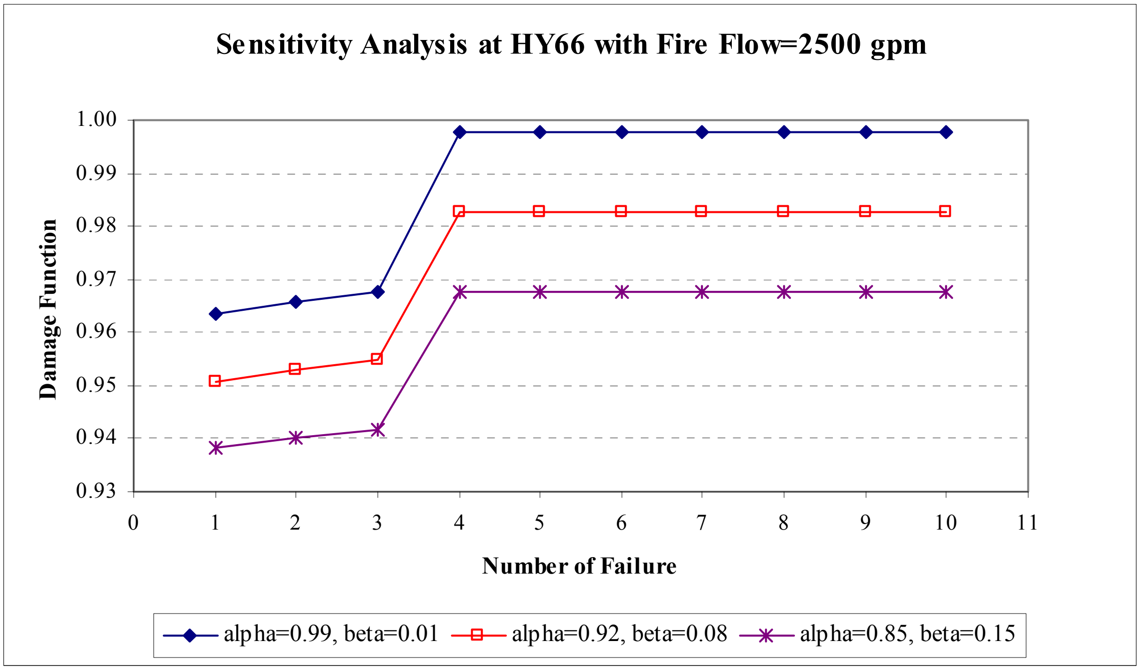

Fig. B.5. Sensitivity analysis of the coefficients α and β at hydrant HY66

APPENDIX C

PROGRAM CODE

```
Option Explicit                    'General Declaration

Private Sub cmdClear_Click()
   'Clear text boxes
   txtInput.Text = ""
   txtReport.Text = ""
   txtOutput.Text = ""
   txtLnkRmvd.Text = ""
   txtFireNode.Text = ""
   txtFireFlow.Text = ""
   txtPressure.Text = ""
   txtHYradius.Text = ""
   lstDisplay.Clear                          'Clear list box
   chkPressure.Value = vbUnchecked           'Uncheck Pressure
   chkFlow.Value = vbUnchecked               'Uncheck Flow
End Sub

Private Sub cmdExit_Click()
   End
End Sub

Private Sub cmdRun_Click()
   Dim InputFile As String, InputFile2 As String, ReportFile As String, OutputFile As String
   Dim FireNode As String
   Dim ThisPipe As String
   Dim links As Integer, pipes As Integer, x_max As Integer, hydrants As Integer, f_flow As Single,
P_required As Integer, R_max As Integer
```

```
    Dim dummy1, dummy2, dummy3, dummy4, dummy5, dummy6, dummy7, dummy8, dummy9, dummy10, dummy11, dummynode, Header
    Dim i, m, h, FN As Integer
    Dim Nnodes As Long
    Dim Ntanks As Long
    Dim Njunctions As Long
    Dim ErrorCode As Long
    Dim Main() As String * 6
    Dim Junction_Node() As String * 6
    Dim Hydrant() As String * 4
    Dim all_node() As String * 6
    Dim x_node() As Single
    Dim y_node() As Single
    Dim x_coordinate() As Single
    Dim y_coordinate() As Single
    Dim Distance() As Single

    'Get input from text boxes
    InputFile = txtInput.Text
    ReportFile = txtReport.Text
    OutputFile = txtOutput.Text
    x_max = txtLnkRmvd.Text
    FireNode = txtFireNode.Text
    f_flow = txtFireFlow.Text
    P_required = txtPressure.Text
    R_max = txtHYradius.Text
```

```
cmdRun.Enabled = False                 'Disable run button

cmdClear.Enabled = False               'Disable clear button

Screen.MousePointer = vbHourglass      'Change the mouse pointer to an hourglass shape


'Retrieving the number of  junction nodes in the network

ErrorCode = modEPANet.ENopen(InputFile, ReportFile, "")

ErrorCode = modEPANet.ENgetcount(0, Nnodes)

ErrorCode = modEPANet.ENgetcount(1, Ntanks)

ErrorCode = modEPANet.ENclose()

Njunctions = Nnodes - Ntanks


ReDim Junction_Node(Njunctions) As String * 6

ReDim all_node(Nnodes) As String * 6

ReDim x_node(Nnodes)

ReDim y_node(Nnodes)

ReDim Main(55) As String * 6


'Setting up an array for the mains to be removed

Main(1) = "MA478"

Main(2) = "MA495"

Main(3) = "MA505"

Main(4) = "MA549"

Main(5) = "MA552"

Main(6) = "MA565"

Main(7) = "MA576"

Main(8) = "MA591"

Main(9) = "MA599"
```

```
Main(10) = "MA609"
Main(11) = "MA610"
Main(12) = "MA638"
Main(13) = "MA647"
Main(14) = "MA654"
Main(15) = "MA662"
Main(16) = "MA672"
Main(17) = "MA676"
Main(18) = "MA678"
Main(19) = "MA679"
Main(20) = "MA691"
Main(21) = "MA693"
Main(22) = "MA728"
Main(23) = "MA735"
Main(24) = "MA737"
Main(25) = "MA740"
Main(26) = "MA745"
Main(27) = "MA749"
Main(28) = "MA758"
Main(29) = "MA766"
Main(30) = "MA772"
Main(31) = "MA788"
Main(32) = "MA793"
Main(33) = "MA802"
Main(34) = "MA811"
Main(35) = "MA814"
Main(36) = "MA817"
```

```
Main(37) = "MA819"

Main(38) = "MA821"

Main(39) = "MA823"

Main(40) = "MA864"

Main(41) = "MA883"

Main(42) = "MA895"

Main(43) = "MA906"

Main(44) = "MA925"

Main(45) = "MA963"

Main(46) = "MA964"

Main(47) = "MA965"

Main(48) = "MA989"

Main(49) = "MA991"

Main(50) = "MA997"

Main(51) = "MA1006"

Main(52) = "MA1013"

Main(53) = "MA1019"

Main(54) = "MA1020"

Main(55) = "MA1024"


links = UBound(Main)


'Setting up a lookup table/array for the Fire Hydrants

InputFile2 = "c:\lufthansa\research data\Micropolis Final2a.inp"

Open InputFile2 For Input As #2

Do

  Line Input #2, dummy1
```

```
Loop Until dummy1 = "[JUNCTIONS]"

Line Input #2, Header

h = 1

For i = 1 To Njunctions

   Input #2, dummy2, dummy3, dummy4, dummy5, dummy6

   Junction_Node(i) = dummy2

   If Left(Junction_Node(i), 2) = "HY" Then

      ReDim Preserve Hydrant(h) As String * 4

      Hydrant(h) = Junction_Node(i)

      h = h + 1

   End If

Next i

hydrants = h - 1                    'hydrants corresponds to the total no. of fire hydrants in the network

Close #2


'Releasing the memory allocated by the array Junction_Node()

Erase Junction_Node


'Getting node index for the Fire Node

For h = 1 To hydrants

   If Hydrant(h) = FireNode Then

      FN = h

   End If

Next h


ReDim Distance(hydrants)
```

```
'Getting the coordinates of each hydrant node from the input file
Open InputFile2 For Input As #3
Do
   Line Input #3, dummy1
Loop Until dummy1 = "[COORDINATES]"
Line Input #3, Header
h = 1
For i = 1 To Nnodes
   Input #3, dummynode, dummy2, dummy3
   all_node(i) = dummynode
   x_node(i) = dummy2
   y_node(i) = dummy3
   If Left(all_node(i), 2) = "HY" Then
      ReDim Preserve x_coordinate(h)
      ReDim Preserve y_coordinate(h)
      x_coordinate(h) = x_node(i)
      y_coordinate(h) = y_node(i)
      h = h + 1
   End If
Next i
Close #3

'Releasing the memory allocated by the arrays all_node(), x_node() & y_node()
Erase all_node
Erase x_node
Erase y_node
```

```
    'Calculating the distance to the hydrant nodes from the fire node
    For i = 1 To hydrants
        Distance(i) = ((x_coordinate(FN) - x_coordinate(i)) ^ 2 + (y_coordinate(FN) - y_coordinate(i)) ^ 2) ^
0.5
    Next i

    'Calling dynamic programming sub procedure
    Call DP_PipeNetwork((FireNode), (ThisPipe), links, x_max, hydrants, f_flow, P_required, FN, R_max,
InputFile, ReportFile, OutputFile, Main(), Hydrant(), Distance())

    Screen.MousePointer = vbDefault
    cmdRun.Enabled = True                  'Enable run button
    cmdClear.Enabled = True                'Enable clear button
End Sub

Private Sub DP_PipeNetwork(ByVal FireNode As String, ByVal ThisPipe As String, links As Integer,
x_max As Integer, hydrants As Integer, f_flow As Single, P_required As Integer, FN As Integer, R_max
As Integer, InputFile As String, ReportFile As String, OutputFile As String, Main() As String * 6,
Hydrant() As String * 4, Distance() As Single)
    Dim k As Integer                      'index of stages
    Dim x_k As Integer                     'state variable at current stage
    Dim x_k_1 As Integer                   'state variable at previous stage
    Dim u() As Integer                    'decision variable, i,e, the removal of each pipe
    Dim u_star() As Boolean                'optimal decision
    Dim J As Double                       'damage function if no pipe is removed at all
    Dim J0 As Double                       'damage function if pipe removed from previous stage
    Dim J1 As Double                       'damage function if pipe removed from current stage
```

```
Dim J_star() As Double                 'maximum damage function

Dim IncludeThisPipe() As Boolean

Dim DamageFunction1 As Double          'damage function calculated while checking pressure

Dim DamageFunction2 As Double          'damage function calculated while checking flow

Dim L_minimum As Single                'distance to the node next to Fire Node

Dim L_operable As Single               'distance to the next operable node

Dim MaxFeasibleState As Integer

Dim i As Integer, m As Integer, N As Integer, h As Integer

Dim Infeasible As Single

Dim temp As String

ReDim u(links)

ReDim u_star(0 To x_max, 0 To links, 0 To links)

ReDim J_star(0 To x_max, 0 To links)

ReDim IncludeThisPipe(links)


'Initializing u_star()

For i = 0 To x_max

   For k = 0 To links

      For h = 0 To links

         u_star(i, k, h) = True

      Next h

   Next k

Next i


'Initializing J_star()

Infeasible = -999999.999999

For i = 0 To x_max
```

```
        J_star(i, 0) = Infeasible
        For k = 1 To links
            If i > k Then
                J_star(i, k) = Infeasible
            End If
        Next k
    Next i

    'Initializing IncludeThisPipe()
    For k = 1 To links
        IncludeThisPipe(k) = True
    Next k

    'Calculating Damage Function without removing any pipe
    If chkPressure.Value = vbChecked Then
        Call RunEPANet1((FireNode), (ThisPipe), IncludeThisPipe(), links, hydrants, f_flow, P_required, FN, R_max, InputFile, ReportFile, L_minimum, L_operable, DamageFunction1, Main(), Hydrant(), Distance())
        J = DamageFunction1                   'Damage Function with no pipe removed at all
        J0 = J                         'Initializing J0
        J1 = J                         'Initializing J1
    ElseIf chkFlow.Value = vbChecked Then
        Call RunEPANet2((FireNode), (ThisPipe), IncludeThisPipe(), links, hydrants, f_flow, P_required, FN, R_max, InputFile, ReportFile, L_minimum, L_operable, DamageFunction2, Main(), Hydrant(), Distance())
        J = DamageFunction2                   'Damage Function with no pipe removed at all
        J0 = J                         'Initializing J0
```

```
    J1 = J                          'Initializing J1
End If
'Pursuing Dynamic Programming
For k = 1 To links
    MaxFeasibleState = Minimum(k, x_max)
    For x_k = 0 To MaxFeasibleState
        For x_k_1 = x_k - 1 To x_k

            'Checking what decisions have been made previously
            If x_k_1 <> k Then
                If x_k_1 >= 0 Then
                    m = 1
                    For i = 1 To links
                        If u_star(x_k_1, k - 1, i) = False Then
                            u(m) = i
                            m = m + 1
                        End If
                    Next i

                    'Calculating Damage Function
                    If x_k_1 = x_k Then
                        J0 = J_star(x_k, k - 1)
                    Else
                        u(m) = k            'pipe is removed from the current stage k
                        For N = 1 To m
                            For i = 1 To links
                                If u(N) = i Then
```

```
                              IncludeThisPipe(i) = False
                           End If
                        Next i
                     Next N

                     If chkPressure.Value = vbChecked Then
                        Call RunEPANet1((FireNode), (ThisPipe), IncludeThisPipe(), links, hydrants, f_flow,
P_required, FN, R_max, InputFile, ReportFile, L_minimum, L_operable, DamageFunction1, Main(),
Hydrant(), Distance())
                        J1 = DamageFunction1
                     ElseIf chkFlow.Value = vbChecked Then
                        Call RunEPANet2((FireNode), (ThisPipe), IncludeThisPipe(), links, hydrants, f_flow,
P_required, FN, R_max, InputFile, ReportFile, L_minimum, L_operable, DamageFunction2, Main(),
Hydrant(), Distance())
                        J1 = DamageFunction2
                     End If
                  End If

                  'Resetting IncludeThisPipe() as true
                  For i = 1 To links
                     IncludeThisPipe(i) = True
                  Next i

                  'Updating J_star and u_star
                  If J0 >= J1 Then
                     If x_k = 0 Then
                        J_star(x_k, k) = J
```

```
            Else
                J_star(x_k, k) = J0
            End If

            For i = 1 To links
                u_star(x_k, k, i) = u_star(x_k, k - 1, i)
            Next i
        Else
            If x_k = 0 Then
                J_star(x_k, k) = J
            Else
                J_star(x_k, k) = J1
            End If

            For i = 1 To links
                If i <> k And x_k > 0 Then
                    u_star(x_k, k, i) = u_star(x_k - 1, k - 1, i)
                ElseIf x_k = 0 Then
                Else
                    If x_k <> 0 Then
                    u_star(x_k, k, i) = False
                    End If
                End If
            Next i
        End If
    End If
End If
```

```
        Next x_k_1
    Next x_k
Next k

'Displaying result in the list box
lstDisplay.AddItem "Main ID Optimal Decision"
For k = 1 To links
    If u_star(x_max, links, k) = False Then
        lstDisplay.AddItem Main(k) & vbTab & CStr(u_star(x_max, links, k))
    End If
Next k
lstDisplay.AddItem "Damage Function for x-max = " & x_max & " is " & J_star(x_max, links)

'Displaying list of operable nodes
Dim ErrorCode As Long
Dim nodeindex As Long
Dim linkindex As Long
Dim node_flow As Single
Dim P_node() As Single
Dim MyNode As String
Dim OperableNode() As Boolean
Dim Distance_operable As Single
Dim EC As Long

ReDim P_node(hydrants)
ReDim OperableNode(hydrants)
```

```
For i = 1 To hydrants
  If i <> FN Then
    If Distance(i) <= R_max Then
      ErrorCode = modEPANet.ENopen(InputFile, ReportFile, "")
      ErrorCode = modEPANet.ENopenH
      MyNode = RTrim(Hydrant(i))
      ErrorCode = modEPANet.ENgetnodeindex(MyNode, nodeindex)
      ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 1, node_flow)
      ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 1, (node_flow + f_flow))
      For k = 1 To links
        If u_star(x_max, links, k) = False Then
          IncludeThisPipe(k) = False
          ThisPipe = RTrim(Main(k))
          ErrorCode = modEPANet.ENgetlinkindex(ThisPipe, linkindex)
          ErrorCode = modEPANet.ENsetlinkvalue(linkindex, 0, 0.5)
        End If
      Next k
      ErrorCode = modEPANet.ENsolveH()
      If ErrorCode = 1 Then
        OperableNode(i) = False
        ErrorCode = modEPANet.ENclose()
      Else
        ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 11, P_node(i))
        ErrorCode = modEPANet.ENclose()
        If P_node(i) > P_required Then
          OperableNode(i) = True
          lstDisplay.AddItem i & vbTab & "Operable Node = " & MyNode
```

```
                End If
            End If
        End If
    End If
Next

'Resetting IncludeThisPipe() as true
For i = 1 To links
    IncludeThisPipe(i) = True
Next i

'Printing results in output file
Open OutputFile For Output As #4
If chkPressure.Value = vbChecked Then
    Print #4, "Checking Pressure"
ElseIf chkFlow.Value = vbChecked Then
    Print #4, "Checking Flow"
End If

Print #4, "Fire Occurs at Node = " & FireNode
Print #4, "No. of Pipes Removed = " & x_max
Print #4, "Required Pressure for Fire Fighting = 20 psi"
Print #4, "Required Flow for Fire Fighting = " & f_flow
Print #4, "Main ID" & vbTab & "Optimal Decision"
For k = 1 To links
    If u_star(x_max, links, k) = False Then
        Print #4, Main(k) & vbTab & CStr(u_star(x_max, links, k))
```

```
        End If
    Next k
    Print #4, "Damage Function = " & CStr(J_star(x_max, links))
    Print #4, "Operable Nodes"
    For i = 1 To hydrants
        If P_node(i) > P_required Then
            Print #4, Hydrant(i)
        End If
    Next i

    'Checking whether the system is hydraulically balanced or not
    For k = 1 To links
        If u_star(x_max, links, k) = False Then
            IncludeThisPipe(k) = False
        End If
    Next k
    Call RunEPANet3(FireNode, ThisPipe, IncludeThisPipe, links, f_flow, P_required, InputFile,
ReportFile, Main(), EC)
    If EC = 1 Then
        lstDisplay.AddItem "System is Hydraulically Unbalanced"
        Print #4, "System is Hydraulically Unbalanced"
    End If
    Close #4
End Sub

Private Sub RunEPANet1(ByVal FireNode As String, ThisPipe As String, IncludeThisPipe() As Boolean,
links As Integer, hydrants As Integer, f_flow As Single, P_required As Integer, FN As Integer, R_max As
```

```
Integer, InputFile As String, ReportFile As String, L_minimum As Single, L_operable As Single,
DamageFunction1 As Double, Main() As String * 6, Hydrant() As String * 4, Distance() As Single)
    Dim ErrorCode As Long
    Dim nodeindex As Long
    Dim linkindex As Long
    Dim P_fnode As Single                    'Pressure at fire node
    Dim node_flow As Single                  'Nodal base demand
    Dim d As Single                          'd represents a negligible pipe diameter
    Dim k As Integer
    Dim alpha, beta, gamma As Single

    d = 0.5
    gamma = 1
    beta = 0.01
    alpha = 1 - beta

    'Opening Toolkit System and Performing Hydraulic Simulation
    ErrorCode = modEPANet.ENopen(InputFile, ReportFile, "")
    ErrorCode = modEPANet.ENopenH
    ErrorCode = modEPANet.ENgetnodeindex(FireNode, nodeindex)
    ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 1, node_flow)
    ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 1, (node_flow + f_flow))
    For k = 1 To links
        If IncludeThisPipe(k) = False Then
            ThisPipe = RTrim(Main(k))
            ErrorCode = modEPANet.ENgetlinkindex(ThisPipe, linkindex)
            ErrorCode = modEPANet.ENsetlinkvalue(linkindex, 0, d)
```

```
        End If
    Next k
    ErrorCode = modEPANet.ENsolveH()
    ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 11, P_fnode)
    ErrorCode = modEPANet.ENclose()

    'Calculating the Damage Function
    If P_fnode < P_required Then
        Call OperableNodes((FireNode), f_flow, P_required, links, hydrants, FN, R_max, k, d, L_operable,
InputFile, ReportFile, ThisPipe, IncludeThisPipe(), Main(), Hydrant(), Distance())

        If P_fnode <= 0 Then
            DamageFunction1 = alpha + beta * (L_operable / R_max)
        Else
            DamageFunction1 = alpha * (P_required - P_fnode) / P_required + beta * (L_operable / R_max)
        End If

    ElseIf P_fnode > P_required Then
        DamageFunction1 = gamma * (P_required - P_fnode) / P_required

    Else
        DamageFunction1 = 0
    End If
End Sub

Private Function Minimum(k As Integer, x_max As Integer) As Integer
```

```
   If k <= x_max Then
      Minimum = k
   Else
      Minimum = x_max
   End If
End Function

Private Sub RunEPANet2(ByVal FireNode As String, ThisPipe As String, IncludeThisPipe() As Boolean,
links As Integer, hydrants As Integer, f_flow As Single, P_required As Integer, FN As Integer, R_max As
Integer, InputFile As String, ReportFile As String, L_minimum As Single, L_operable As Single,
DamageFunction2 As Double, Main() As String * 6, Hydrant() As String * 4, Distance() As Single)
   Dim ErrorCode As Long
   Dim nodeindex As Long
   Dim linkindex As Long
   Dim P_fnode As Single                   'Pressure at fire node
   Dim Q_available As Single               'Maximum available flow at fire location
   Dim node_flow As Single                 'Nodal base demand
   Dim node_elevation As Single            'Nodal Elevation
   Dim node_emitter As Single              'Emitter coefficient for fire node
   Dim node_actflow As Single              'Nodal actual demand
   Dim d As Single                          'd represents a negligible pipe diameter
   Dim k As Integer
   Dim alpha, beta, gamma As Single

   d = 0.5
   gamma = 1
   beta = 0.01
```

```
alpha = 1 - beta



'Opening Toolkit System and Performing Hydraulic Simulation
ErrorCode = modEPANet.ENopen(InputFile, ReportFile, "")
ErrorCode = modEPANet.ENopenH
ErrorCode = modEPANet.ENgetnodeindex(FireNode, nodeindex)
ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 0, node_elevation)
ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 0, (node_elevation + 2.3 * P_required))
ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 3, node_emitter)
ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 3, (node_emitter + 1850))
For k = 1 To links
  If IncludeThisPipe(k) = False Then
    ThisPipe = RTrim(Main(k))
    ErrorCode = modEPANet.ENgetlinkindex(ThisPipe, linkindex)
    ErrorCode = modEPANet.ENsetlinkvalue(linkindex, 0, d)
  End If
Next k
ErrorCode = modEPANet.ENsolveH()
ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 1, node_flow)
ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 9, node_actflow)
ErrorCode = modEPANet.ENclose()

'Calculating the Damage Function
Q_available = node_actflow - node_flow

If Q_available < f_flow Then
```

```
        Call OperableNodes((FireNode), f_flow, P_required, links, hydrants, FN, R_max, k, d, L_operable,
InputFile, ReportFile, ThisPipe, IncludeThisPipe(), Main(), Hydrant(), Distance())
        DamageFunction2 = alpha * (f_flow - Q_available) / f_flow + beta * (L_operable / R_max)


    ElseIf Q_available > f_flow Then
        DamageFunction2 = gamma * (f_flow - Q_available) / f_flow


    Else
        DamageFunction2 = 0
    End If
End Sub


Private Sub OperableNodes(ByVal FireNode As String, f_flow As Single, P_required As Integer, links As
Integer, hydrants As Integer, FN As Integer, R_max As Integer, k As Integer, d As Single, L_operable As
Single, InputFile As String, ReportFile As String, ThisPipe As String, IncludeThisPipe() As Boolean,
Main() As String * 6, Hydrant() As String * 4, Distance() As Single)
    Dim i As Integer
    Dim ErrorCode As Long
    Dim nodeindex As Long
    Dim linkindex As Long
    Dim node_flow As Single
    Dim P_node() As Single                      'pressure at node of interest
    Dim MyNode As String
    Dim OperableNode() As Boolean
    Dim Distance_operable As Single


    ReDim P_node(hydrants)
```

```
ReDim OperableNode(hydrants)

'Calculating the distance to the next operable node from the fire node
L_operable = 9999999
For i = 1 To hydrants
    If i <> FN Then
        If Distance(i) <= R_max Then
            ErrorCode = modEPANet.ENopen(InputFile, ReportFile, "")
            ErrorCode = modEPANet.ENopenH
            MyNode = RTrim(Hydrant(i))
            ErrorCode = modEPANet.ENgetnodeindex(MyNode, nodeindex)
            ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 1, node_flow)
            ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 1, (node_flow + f_flow))
            For k = 1 To links
                If IncludeThisPipe(k) = False Then
                    ThisPipe = RTrim(Main(k))
                    ErrorCode = modEPANet.ENgetlinkindex(ThisPipe, linkindex)
                    ErrorCode = modEPANet.ENsetlinkvalue(linkindex, 0, d)
                End If
            Next k
            ErrorCode = modEPANet.ENsolveH()
            If ErrorCode = 1 Then
                OperableNode(i) = False
                ErrorCode = modEPANet.ENclose()
            Else
                ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 11, P_node(i))
                ErrorCode = modEPANet.ENclose()
```

```
          If P_node(i) > P_required Then
            OperableNode(i) = True
            Distance_operable = Distance(i)

            If Distance_operable < L_operable Then
              L_operable = Distance_operable
            End If

          Else
            OperableNode(i) = False
          End If
        End If
      End If
    End If
  Next i
End Sub

Private Sub RunEPANet3(ByVal FireNode As String, ThisPipe As String, IncludeThisPipe() As Boolean,
links As Integer, f_flow As Single, P_required As Integer, InputFile As String, ReportFile As String,
Main() As String * 6, EC As Long)
  Dim ErrorCode As Long
  Dim nodeindex As Long
  Dim linkindex As Long
  Dim node_flow As Single               'Nodal base demand
  Dim node_elevation As Single          'Nodal Elevation
  Dim node_emitter As Single            'Emitter coefficient for fire node
```

```
Dim d As Single                         'd represents a negligible pipe diameter
Dim k As Integer
Dim alpha, beta, gamma As Single

d = 0.5
'Opening Toolkit System and Performing Hydraulic Simulation
ErrorCode = modEPANet.ENopen(InputFile, ReportFile, "")
ErrorCode = modEPANet.ENopenH
ErrorCode = modEPANet.ENgetnodeindex(FireNode, nodeindex)

If chkPressure.Value = vbChecked Then
  ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 1, node_flow)
  ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 1, (node_flow + f_flow))
  For k = 1 To links
    If IncludeThisPipe(k) = False Then
      ThisPipe = RTrim(Main(k))
      ErrorCode = modEPANet.ENgetlinkindex(ThisPipe, linkindex)
      ErrorCode = modEPANet.ENsetlinkvalue(linkindex, 0, d)
    End If
  Next k
  ErrorCode = modEPANet.ENsolveH()

  If ErrorCode = 1 Then
    EC = ErrorCode
  End If
  ErrorCode = modEPANet.ENclose()
```

```
    ElseIf chkFlow.Value = vbChecked Then

        ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 0, node_elevation)

        ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 0, (node_elevation + 2.3 * P_required))

        ErrorCode = modEPANet.ENgetnodevalue(nodeindex, 3, node_emitter)

        ErrorCode = modEPANet.ENsetnodevalue(nodeindex, 3, (node_emitter + 1850))

        For k = 1 To links

            If IncludeThisPipe(k) = False Then

                ThisPipe = RTrim(Main(k))

                ErrorCode = modEPANet.ENgetlinkindex(ThisPipe, linkindex)

                ErrorCode = modEPANet.ENsetlinkvalue(linkindex, 0, d)

            End If

        Next k

        ErrorCode = modEPANet.ENsolveH()


        If ErrorCode = 1 Then

            EC = ErrorCode

        End If


        ErrorCode = modEPANet.ENclose()

    End If

End Sub
```

VITA

Lufthansa Rahman Kanta was born to Mohammad Lutfor Rahman and Mrs. Mahmuda Rahman of House #3, Road #7, Uttara, Dhaka-1230, Bangladesh. Among the three siblings, she is the first.

She attended B.A.F. Shaheen School, Dhaka, for her school education up to junior high and Holly Cross College, Dhaka, for high school education. She earned a Bachelor of Science degree in Civil Engineering from Bangladesh University of Engineering and Technology, Dhaka, in 1995. She worked as a Hydraulic Engineer at Surface Water Modeling Center, Dhaka, for five years after completion of her undergraduate education. She enrolled as a graduate student in the Department of Civil Engineering at Texas A&M University in September 2003. In July 31, 2004, a terrible accident occurred in her apartment because of gas leak leading to fire and she lost her four-year-old beloved daughter Lamiya Zahin. She also got severely injured and stayed out of school for one year. She resumed her graduate studies at Texas A&M University from September 2005 and received a Master of Science degree in Civil Engineering in December 2006. This thesis is the result of her research work and a tribute to her beloved daughter.

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