DEVELOPMENT OF CONSEQUENCE MANAGEMENT STRATEGIES FOR

WATER DISTRIBUTION SYSTEMS

By

Terranna Baranowski

Dissertation

Submitted to the Faculty of the

Graduate School of Vanderbilt University

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

in

Environmental Engineering

May, 2007

Nashville, Tennessee

Approved:

Professor Eugene J. LeBoeuf

Professor Mark D. Abkowitz

Professor James H. Clarke

Professor Sankaran Mahadevan

To my wonderful mom, Gena Buchanan, who has always been my strongest supporter,

and

To my future husband, Tim Haxton, who has loved me unconditionally,

and

To my late grandmother, Marge Baranowski, who was always a good listener

ACKNOWLEDGEMENTS

I would like to express my gratitude to a number of people who have supported, encouraged, and helped me over the course of my Ph.D. study.

First, I would like to express gratitude to my advisor, Dr. Eugene J. LeBoeuf, who has offered numerous words of advice throughout my study. He has spent endless hours helping to edit my manuscripts. His technical and editorial advice was essential to the completion of this dissertation.

I would also like to express thanks to my dissertation committee, Drs. James Clarke, Mark Abkowitz, and Sankaran Mahadevan, who offered endless guidance on the course of my research. I appreciate the time they spent listening to my research presentations.

Many friends have helped me along the way. To my many officemates, Kati Bell, Christine Switzer, Sarynna Lopez, Leeann Williams, Ravi Palakodeti, and Lu Zhang, thanks for the endless words of wisdom, long talks about everything under the sun, and the encouragement to keep going. To my research group members, Kati Bell, Yusong Li, Lu Zhang, Ravi Palakodeti, Wei Wang, and Janey Smith, thanks for listening to numerous research presentations and offering advice on research paths.

To the IGERT fellows, thanks for listening to my research presentations even though they were not necessarily in your area of expertise. I want to express my gratitude specifically to Robert Guratzsch, Ned Mitchell, John McFarland, Angel Urbina, Kevin Brown, and Ramesh Rebba, who helped me whenever I was stuck with my research. Finally, I want to thank my life-long friends that I've made at Vanderbilt, Audrey Copeland, Sarynna Lopez, and Megan Keen, who were always around to keep

my spirits high, to lend a listening ear, and to give me a social life outside of school. Your friendship means to world to me and I will always be grateful for your friendship.

I would not be where I am today without the loving support of my family. My mom, Gena Buchanan, was always around to support and encourage my endeavors. I truly appreciate all the long talks and encouraging pep talks. I would not be able to achieve my dreams without your guidance and wisdom. I want to express thanks to my brother, Derick Baranowski, for all the laughs and conversations over the years. My life would be at a loss without you in it. To the rest of my family, thanks for always being interested in what I was doing and the endless questions of when I would be finished.

Finally, I want to express my gratitude to my fiancé, Tim Haxton. Thanks for always being there when I needed you, for listening to endless complaints, moans and groans over the last four years, and for enduring late nights whenever a paper was due. I cannot wait to become your wife and live out the rest of our dreams together.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

1.1 Perspective

On September 11, 2001, the concept of what constitutes a credible threat to the security of our nation's critical infrastructure changed. Threats that previously had been considered low risk are now being examined and incorporated into emergency plans and procedures. Ongoing efforts to upgrade infrastructure security have taken on a far greater importance and urgency (U.S. Congress 2001). One environmental system at great risk of contamination by chemical and biological agents is the nation's water supply and distribution networks. Water utilities are responsible for the distribution of high quality water, while providing sufficient flowrates and pressures to meet consumer demand and fire-fighting capabilities.

In response to this increased security awareness, a number of laws were enacted to address water supply systems within the U.S., including the Public Health, Security and Bioterrorism Preparedness and Response Act (PL 107-188) and the Homeland Security Act (PL 107-296). These acts resulted in renewed efforts by government agencies to develop new strategic plans for action that address their new homeland security responsibilities. Vulnerability assessments (VAs), such as Vulnerability Self-Assessment Tool (VSAT) (AMSA 2003) and Risk Assessment Methodology for Water Utilities (RAM-W) (AwwaRF 2002) have been developed to aid in the identification of areas of concern within water utilities that require strengthening against potential threats.

The common elements of a vulnerability assessment include (i) characterization of the water system along with its mission and objectives (planning); (ii) identification and prioritization of adverse consequences to avoid (site characterization); (iii) determination of critical assets that could be subjected to malevolent act (threat assessment); (iv) assessment of the likelihood of such malevolent acts (consequence management); (v) evaluation of existing countermeasures (system effectiveness); and (vi) analysis of current risk and development of risk reduction plan (risk management). Currently, these assessments do not address the vulnerability of the water distribution network to a variety of attacks, including physically destructive actions and/or chemical and biological contamination, even though water distribution systems represent one of the greatest security vulnerabilities due to the lack of understanding of fate and transport processes associated with potential contamination events (Danneels and Finley 2004).

Reports of accidental contamination events in water distribution systems are numerous, where illustration of two notable events may help illustrate the ease in which a system may be contaminated − through accidental or intentional acts. In our first example, an aqueous firefighting foam was unintentionally released into a Charlotte, North Carolina utility distribution system through a fire hydrant in September 1997 when a fire truck pump was turned on before a valve was closed. Due to the lack of a back-flow prevention device, the pump feeding the foam was able to produce more pressure than the water pressure in the system and the neighborhood's pipes were filled with more than 60 gallons of foam (Krouse 2001). A second example of a contamination event occurred in Gideon, Missouri in December 1993 when *Salmonella* was dispersed into the water distribution network from storage tanks. The tanks were both in disrepair and bird

droppings were present near holes in the roof where present near bird droppings. Rust, sediments, and bird feathers were found to be floating on the water inside the tank. Due to these conditions, it was determined that *Salmonella* had entered the distribution network from the fecal matter found in the storage water (Mays 2004). An adversary who has access to hazardous chemical or biological materials, and understands basic hydraulics, can fairly easily contaminate a water distribution system.

Almost every home and building has unprotected access to the local public water distribution system, so if the system is exposed to potentially harmful conditions, whether through accidental or intentional contamination events, the water supply system can quickly become contaminated without detection (Denileon 2001). Since vulnerability assessments that address both physical and chemical/biological forms of attack are lacking, further research is necessary to not only address system vulnerabilities, but to also evaluate possible consequences and corrective actions.

Development of consequence management techniques that address contamination events is necessary since few analytical tools are available to effectively analyze such problems (Danneels and Finley 2004). Though these types of events are relatively infrequent, it is still important to prepare emergency response solutions to help mitigate the consequences. Coupling system hydraulic models with water quality models can aid in the simulation of threat scenarios in order to assess the potential impacts of a contamination event and develop consequence mitigation strategies (Uber et al. 2004).

Information technologies such as geographic information systems (GIS) are now commonly employed in water distribution system modeling as a means to link spatial information with distribution system elements, enabling geospatial locations of specific

infrastructure features, including nodal demands and associated consumer information. Given this existing link, GIS-based information may easily be linked to sophisticated vulnerability assessment, thus assisting in the identification of populations at increased risk of exposure to contamination such as those in schools, hospitals, residential areas, or critical industries. Once areas of concern are identified, consequence management strategies may be employed to assist in minimizing risk.

Water utilities are required to create and maintain emergency response plans that delineate the response, recovery, and remediation actions associated with emergencies (Mays 2004). This research focuses on a component of emergency response planning, possessing the overarching goal of development of a comprehensive consequence management tool for water distribution networks which incorporates analysis of chemical/biological threats while addressing societal and economical concerns. The resulting activity from this research effort will produce a set of consequence management strategies that effectively addresses protocols to best isolate an event and manage response measures, including an assessment of how these strategies can affect the rest of the system.

In *Role in Water Security Research: The Water Security Research and Technical Support Action Plan*, the U.S. EPA states that new tools and technologies need to be developed in order to address potential attacks on drinking water systems. Research in this area will improve the "awareness, preparedness, prevention, response, and recovery" of drinking water systems against possible threats. The research completed here corresponds well with identified Action Plans, including "identifying drinking water threats, contaminants, and threat scenarios", "improving analytical methodologies and

monitoring systems for drinking water", and "containing, treating, decontaminating, and disposing of contaminated water and materials" (U.S. EPA 2004c).

1.2 Research Significance

Vulnerability assessment methodologies currently employed by water utilities lack capabilities to perform a thorough analysis of distribution networks and contamination events. In 2003, EPA's Office of Inspector General published a report which concluded "neither EPA nor the different (vulnerability assessment) methodologies adequately emphasized distribution system threats as the most susceptible components of water systems to include in vulnerability assessments" (U.S. EPA 2003). There exists a distinct need for a vulnerability assessment methodology that reflects the vulnerabilities of the distribution network to all types of attacks, including physical, chemical, and biological. The new methodology developed as a part of this effort will be able to provide a more thorough analysis of distribution systems as well as evaluation of the effects of contamination events on a network. Other areas of concern can also be addressed by the incorporation of GIS information that can assist in identifying populations at increased risk of exposure to contamination and thus will aid in public health risk assessment. Spatial information gathered from GIS can allow users to better define areas of concern, such as schools, hospitals, residential areas, or critical industries, by incorporating societal and economic issues. With this knowledge, water utility managers will be better prepared to mitigate attacks against the system. The managers will have knowledge of the spread of the contaminant and be able to initiate consequence management strategies. The resulting activity produces a set of strategies that effectively

addresses protocols to best isolate an event and manage the response measures. Overall, this modeling system will aid in the welfare of the public with respect to their drinking water supply. It will also assist in the public perception of the security of water distribution system infrastructure if water utilities are better equipped to respond quickly and effectively to such an event since emergency response plans were already developed.

The consequence management tool includes a coupling of hydraulic modeling software (i.e., EPANET (U.S. EPA 2002)) and optimization software (i.e., MATLAB (MathWorks 2006)). The tool will be useful for both planning emergency response scenarios and responding to an emergency in real-time. A variety of responses should be examined for the most optimal consequence management solution. Such actions may include (i) isolating the contaminated area, (ii) treating the contaminant *in situ* (e.g., Propato and Uber 2004); (iii) flushing the contaminated water into a sanitary sewer; or (iv) issuing "boil water" alerts to affected parties. While the response actions to a contamination event have been defined (Walski 2001), no overarching consequence management guidance currently exists.

1.3 Research Hypothesis

This research addresses the following hypotheses:

1. The incorporation of consequence management strategies along with spatial information provided by geographic information systems (GIS) within a vulnerability assessment tool will aid water utilities in better understanding the risks and vulnerabilities associated with their water distribution networks and enable them to manage and mitigate any adverse events.

2. The utilization of optimization techniques for consequence management strategies will aid in the identification of the optimal operational response during a contamination event.

1.4 Research Objectives

This research accomplished the following objectives: identification of areas of weakness in current vulnerability assessment methods; development of consequence management strategies for contamination events scenarios; and identification of societal and economical concerns and population exposure through the incorporation of GIS-based information. The following tasks were completed in an effort to accomplish the aforementioned objectives: (i) evaluation of system flushing; (ii) evaluation of system isolation valves; (iii) incorporation of GIS information through the application of weights in objective function; (iv) development of overall consequence management guidance; and (v) evaluation of proposed strategies through illustrative example applications.

1.5 Organization of the Dissertation

This dissertation is organized into six chapters. Chapter I includes an introduction to the research topic, its significance to the water utility community, and the hypotheses and objectives. Chapter II provides a literature review of the background related to consequence management strategies and optimization techniques. Chapters III, IV, and V represent archival journal article submissions, and thus are organized as stand-alone documents with contents similar to that contained in a journal manuscript. Chapter III describes the application of a Newton-Raphson method and parameter estimation (PEST)

techniques for the optimization of nodal flushing as a consequence management strategy.

Chapter IV presents the utilization of a genetic algorithm (GA) for consequence management strategies including system flushing and system isolation. Chapter V details the incorporation of GIS-based spatial information as weights on critical customers in the optimization objective function during optimal operational response. Chapter VI summarizes the primary conclusions from this dissertation and proposes areas of future research. Appendices A-W include programming codes utilized in Chapters IV and V.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

This chapter provides a detailed, state-of-the-art literature review of consequence management practices and optimization methods employed in water distribution system analysis and design. As a means of introduction, the chapter begins with definitions of the terminology associated with water distribution systems. The second portion reviews consequence management practices that have been applied to a variety of incidents which have affected the environment. The third portion describes the background of the optimization methods applied in this research. The final portion discusses the incorporation of geographic information systems in modeling.

2.2 Water Distribution System Terminology

Water distribution systems or networks are comprised of many components. A schematic of a simple water distribution network is given in Figure 2-1. The main components include junctions and links. A junction can be classified as a node, a reservoir, or a tank. A node represents the location where water is consumed in a hydraulic model, even though in reality water consumption is along a pipe main. This water consumption is generally referred to as the nodal demand. In hydraulic modeling, the demand is considered positive when it is removed from the system and negative when it is pumped into the network. A reservoir or tank serves to store water and also as a

potential energy reservoir to assist in maintaining pressures throughout a water network, especially during periods of high demand or in more remote locations. A link is a pipe which transports the water between junctions in a hydraulic model.

In terms of operational procedures to remove a contaminant from the network, two methods are generally performed: system flushing and system isolation. System flushing represents the process of transporting the undesired water out of the network through a desired node. System isolation involves the closure of isolation valves, usually located at the end of the pipes before a junction. Generally, there is one less valve than there are pipes at an intersection or node. Since isolation valves cannot be modeled in EPANET (U.S. EPA 2002), system isolation is achieved by turning the status of the desired pipe to off. For example, if a valve between Nodes 13 and 23 (Figure 2-1) needed to be closed, then Pipe 113 would be turned off in the system and water would no longer be transported along its length.
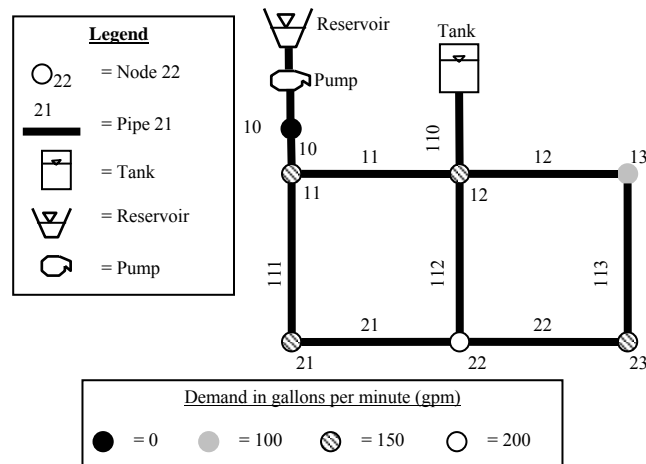
Figure 2-1. Schematic of simple network.

2.3 Consequence Management Techniques

A number of laws were enacted to address the security of water supply systems within the U.S., including the Public Health, Security and Bioterrorism Preparedness and Response Act (PL 107-188) and the Homeland Security Act (PL 107-296). These acts resulted in the need to develop new strategic plans for action that address new homeland security responsibilities. In *Role in Water Security Research: The Water Security Research and Technical Support Action Plan*, EPA states that new tools and technologies need to be developed in order to address the potential attacks on drinking water systems (U.S. EPA 2004c). In conjunction with addressing potential attacks on the water distribution network, response and recovery actions must be identified and explored. While the response actions to a contamination event have been defined (Walski 2001), no overarching consequence management guidance currently exists. Background information on risk assessments and consequence management strategies for other environmental media may give insight on how to develop similar procedures for water distribution systems.

Environmental accidents (e.g., chemical spills, nuclear releases, etc.), natural disasters (e.g., earthquakes, hurricanes, tornadoes, volcanic eruptions, etc.), and terrorist acts (e.g., chemical/biological releases) often have devastating effects on human life and property. The 1984 release of methyl isocynate at the Union Carbide plant in Bhopal, India killed more than 3,000 people and injured more than 100,000 (Murray and Goodfellow 2002). When Mount St. Helens erupted in 1980, over 50 people were killed (Murray and Goodfellow 2002). In 1995, terrorists released sarin and other chemicals in subways of Tokyo, Japan, which killed 12 people and injured more than 5,500 (Murray

and Goodfellow 2002). Though these types of events are relatively infrequent, it is still important to prepare emergency response solutions to help mitigate potential consequences. Numerous research efforts have focused on the development of risk assessment and consequence management for a variety of applications. Here, we reference 'risk' as a measure of the potential damage or loss of an asset based on the probability of an undesirable event, while risk assessment represents the process of analyzing potential threats against, and vulnerabilities of, a facility. The ability to perform rapid assessments of risks resulting from accidents or intentional acts is an important component of emergency response (Parris 2002), thus modeling is needed to aid in the decision process.

The majority of the modeling efforts to date have examined radioactive releases at nuclear power plants (e.g., (Andreev, Hittenberger et al. 1998), (Pechinger, Langer et al. 2001), (Galmarini, Bianconi et al. 2001), (Baklanov and Mahura 2004)) and chemical releases and fires at chemical manufacturing plants (e.g., (Chang, Wei et al. 1997), (Nivolianitou 1998), (Kirkpatrick, Howard et al. 2002), (Rigas and Sklavounos 2002), (Al-qurashi 2004)). Each of the assessments includes the following steps: (i) identification of hazards; (ii) release modeling; and (iii) consequence management. Murray and Goodfellow (2002) give a review of emergency response techniques to chemical incidents, which are grouped in a variety of categories including technical management for specific sites, computer-based systems for emergency management, and managerial procedures for chemical incidents. For a specific site, The American Institute of Chemical Engineers provides detailed guidelines for the prevention, preparedness, response, and recovery to a chemical incident (AIChE 1995). Many other government

agencies provide guidelines on emergency response, including the U.S. Department of Transportation (DOT), the U.S. Coast Guard, and state and federal emergency management agencies (i.e., FEMA). For example, U.S. DOT's 2004 *Emergency Response Guidebook* provides guidelines of isolation distances and fire control measures for a selection of chemicals which are transported by railroads and interstates (U.S. DOT 2004). Perhaps a better known example in the U.S. is the Coast Guard's Chemical Hazards Response Information System (CHRIS), which serves as an emergency response guideline available for chemicals transported on waterways.

A variety of computer-based models are available to aid in emergency response to chemical incidents. Rigas and Sklavounos (2002) utilized the software BREEZE HAZ PRO by Trinity Consultants (Dallas, Texas, USA) as its consequence management tool to model gas releases, fires, and explosions. Kirkpatrick (2002) used Science Applications International Corporation's (SAIC) (San Diego, California, USA) Consequence Assessment Tool Set (CATS) to predict the consequences associated with a natural or technological hazard. A popular simulation model is Computer-Aided Management of Emergency Operations (CAMEO), which integrates chemical databases, an air dispersion model, and a mapping program (U.S. EPA 2004d). Al-qurashi (2004) developed an emergency response system by integrating the SAFER Real-Time application by SAFER Systems (Edmonton, Alberta, Canada) and a GIS application. Through maps, real-time weather, chemical release specifics, and gas sensors data, SAFER displays immediate plume graphics, while GIS allows the effects of the plume to be analyzed in more detail. These are just a few of the emergency response simulation models available for chemical release accidents, but many other emergency response tools exist for coastal oil spills

(i.e., General NOAA Oil Modeling Environment (GNOME) (NOAA 2004)), river spills (e.g., Spill Management Information System (SMIS) (Martin, LeBoeuf et al. 2004), Riverine Emergency Management Model (Parris 2002), RiverSpill (SAIC 2003)), and groundwater contamination (i.e., Hydrocarbon Spill Screening Model (HSSM) (U.S. EPA 1997)). Recently, risk assessment simulation tools have been developed for water distribution utilities (e.g., PipelineNet (Bahadur et al. 2003), Threat Ensemble Vulnerability Assessment (TEVA) (Murray et al. 2004)). Coupling system hydraulic models with water quality models can aid in the simulation of threat scenarios in order to assess the potential impacts of a contamination event and develop consequence mitigation strategies (Uber, Murray et al. 2004).

Development of new water distribution system simulation tools represents an active area of research following the events of September 11th. Selected programs which have been developed include PipelineNet (Bahadur et al. 2003) and the Threat Ensemble Vulnerability Assessment (TEVA) (Murray et al. 2004). Science Applications International Corporation's (SAIC) PipelineNet possesses a variety of capabilities, such as consequence assessment, population exposure, risk assessment, and transport of contaminants through the incorporation of spatial information, but the program is unable to provide consequence management strategies for the system following a contamination attack. EPA's Threat Ensemble Vulnerability Assessment (TEVA) program is able to measure public health impacts, analyze water distribution system vulnerabilities, and evaluate consequence mitigation strategies (Murray et al. 2004). Similar to PipelineNet, this program, however, does not incorporate spatial information and does not determine the optimal operational response. Thus, a simulation tool which incorporates chemical

14

and biological vulnerabilities and provides a means for consequence management within a spatial framework is needed. Future water utility risk assessments could be improved through the integration of a contamination analysis within the risk assessment as well as improved response protocols (Danneels and Finley 2004).

Once a contamination threat to a network is established, the U.S. EPA's Response Protocol Toolbox (U.S. EPA 2003) provides recommendations for implementation of specific response actions to minimize the potential impact to the public. Steps in this protocol include detection, source identification, and consequence management. To aid in the detection and response time for contamination events, recent research efforts have focused on the placement of early warning detection systems within a water distribution network (Kumar et al. 1997; Kessler et al. 1998; Ostfeld and Salomons 2004; Berry et al. 2006; Propato 2006). Included in these efforts are optimization schemes to provide optimal placement of sensor systems to minimize population exposure, time to detection, volume of contaminated water consumed, and extent of contamination. After detection of a contaminant, the next step in the response protocol is the identification of the injection location. Researchers have established source identification methods (Laird et al. 2006; Preis and Ostfeld 2006) to identify contaminant injection locations as well as flow paths following successful detection of a contamination event. Once a contamination event has been detected and the injection location has been identified, optimal responses to mitigate and remediate contaminated systems must be evaluated. These consequence management strategies may include (i) isolation and containment of a contaminant through valve operations (U.S. EPA 2004a); (ii) public notification; (iii)

demand locations and quantities to "flush" the system (U.S. EPA 2004b); and (iv) any combinations of valving, notification, and flushing.

To date, limited research has focused on the application of optimization techniques to consequence management strategies in response to contamination events. Poulin et al. (2006) established a methodology to locate early warning detection sensors and to isolate contaminated zones utilizing operational rules. While representing an important contribution, this work is limited to system detection and isolation by minimizing the time required for valve and hydrant operations, and it does not incorporate flushing as an operational response. In addition, it is not currently incorporated into a programming code. The coupling of a hydraulic/water-quality model with an optimization method will assist in determining the optimal consequence management strategy following a contamination event.

2.4 Optimization Methods

Optimization typically involves searching for either the maximum or minimum value of an objective function, subject to restrictions or constraints. Many different categories of optimization techniques are available depending on the objective function and the constraints. For consequence management strategies, the optimization technique will provide both local (nodal) and global (network) minimization of the contaminant concentration subject to hydraulic operating constraints. Optimization categories can include constrained and unconstrained optimization, one-dimensional and multidimensional optimization, and any combination of these categories. For the problem of water distribution optimization, a wide range of methods have been applied

(Mays 2000), including simulated annealing (Cunha and Sousa 1999)., ant colony optimization (Maier et al. 2003), particle swarm optimization (Eusuff and Lansey 2003), and genetic algorithms (Savic and Walters 1997; Wu and Simpson 2001; Tolson et al. 2004; Ostfeld and Salomons 2004). The following sections review common optimization methodologies in water distribution design, and explore their use in consequence management strategies.

2.4.1 First-Order Reliability Method (FORM)

Monte Carlo simulation is a useful tool to aid in the analysis of systems with random variables that may possess a range of uncertainties. While recently employed to simulate the spread of a contaminant through a water distribution network (Nilsson et al. 2005), Monte Carlo simulations are often very computationally demanding. In the case of water distribution system consequence management, Monte Carlo simulations can be used to optimize the location and rate of "flushing" (or extra applied demand at specific notes) by simulating every possible combination of demand until the optimal demand schedule is determined. This procedure is very time consuming and computationally intensive, especially for large network systems. As such, employment of a more computationally efficient method such as FORM may yield improved performance relative to traditional Monte Carlo simulations. FORM is presently employed most often in structural reliability analysis, but recently was applied to water distribution system reliability (Xu et al. 2003; Tolson et al. 2004) and other water resources applications. The following section provides a brief overview of FORM, but the reader is referred to Haldar and Mahadevan (2000) for a more detailed description.

FORM finds the probability of failure based on a performance function. A performance function is generally expressed in terms of its load (demand) and resistance (capacity). For a water quality application, the system's load correlates to the pollution load, while the system's resistance correlates to a given water quality standard. The performance function, $g(\mathbf{X})$, is commonly written as the difference between the load (L) and the resistance (R) where $\mathbf{X}$ is the vector of random variables that influence the system. The performance function is formulated such that $g(\mathbf{X}) = 0$ defines the failure domain. Thus, the probability of failure, p_f, is defined by Equation 2-1, where $f_x(\mathbf{x})$ is the joint probability density function (PDF) of $\mathbf{X}$.

$$p_f = P[g(\mathbf{X}) < 0] = \int_{g(\mathbf{X})<0} f_{\mathbf{x}}(\mathbf{x})dx \tag{2-1}$$

In most applications, especially large dimensional problems, the above integral is difficult to compute, so FORM and other methods (Monte Carlo simulation, Second-order reliability method, etc.) were developed to approximate the solution. The objective of FORM is to approximate the above integral to determine the failure probability. FORM approximates the probability of failure by $p_f = \Phi(-\beta)$ where $\Phi(\ )$ is the standard normal cumulative distribution function (CDF) and β is the reliability index. The reliability index, β, represents the minimum distance between the design point on the failure surface and the origin in standard normal space. The design point is considered the most probable point (MPP) of failure. The determination of the design point and the β is a constrained nonlinear optimization problem. Various optimization algorithms are available, including the most widely used HL-RF algorithm, which was originally

developed in 1974 by Hasofer and Lind and then extended in 1978 by Rackwitz and
Fiessler. FORM is an optimization algorithm which uses a Newton-Raphson type
recursive formula to obtain the design point and the associated reliability. This algorithm
linearizes the performance function at each iteration point and uses the derivatives to find
the next iteration point. Compared to other nonlinear optimization algorithms, this
algorithm requires the least computational effort per step, since the only information
required to compute the next iteration point is the value and the gradient of the
performance function (Haldar and Mahadevan 2000). FORM obtains only an
approximation of the failure probability unless the performance function is linear, thus
the accuracy of FORM is dependent on the performance function's degree of nonlinearity
(Maier, Lence et al. 2001).

Initiation of a FORM analysis begins with the defining of the performance
function, $g(\mathbf{X})$, and the assumption of initial values of the random variables. If no prior
information is available, the mean values are generally used as the initial points. Once
the initial points have been assumed, the partial derivative, $\partial g / \partial X_i$, of the performance
function with respect to each of the random variables must be calculated. The next step
is to compute the new values for the design point using Equation 2-2, where $\nabla g(x_k'^*)$ is
the gradient vector of the performance function at $\mathbf{x}_k'^*$, the kth iteration point.

$$x_{k+1}'^* = \frac{1}{\left| \nabla g(x_k'^*) \right|^2} \left[\nabla g(x_k'^*)^t \, x_k'^* - g(x_k'^*) \right] \nabla g(x_k'^*) \qquad (2\text{-}2)$$

The new values for the design point in the original space are computed next using Equation 2-3.

$$x_i^* = \mu_{X_i} + \sigma_{X_i} x_i'^* \qquad (2\text{-}3)$$

Following determination of the new values for the design point, the reliability index, β, is calculated and the convergence criteria is evaluated. The new value of the performance function is then computed and the convergence criteria for $g(\mathbf{X})$ is evaluated. The iterative process continues until both convergence criteria are satisfied. FORM can aid in the identification of the minimum demand required to flush a contaminant out of the system, but other consequence management actions (i.e., utilizing isolation valves) need to be determined through the use of other optimization techniques.

2.4.2 Parameter Estimation (PEST)

One optimization technique capable of managing large numbers of variables is Parameter ESTimation (PEST) (Doherty 2004b). PEST possesses components which are able to interact with a variety of modeling software in order to estimate a number of model parameters, such as hydraulic conductivities. General application of PEST to water resources problems involves linking of the optimization scheme to the modeling software (e.g., MODFLOW) to assist in model calibration and predictive analysis of model parameters. PEST has been used for calibration of groundwater models (e.g., Doherty 2003), sensitivity analysis of soil and fertilizer properties, such as pH (Baginska et al. 2003), and predictive analysis for model uncertainty (Doherty and Johnston 2003).

Comprised of nonlinear parameter estimation and optimization modeling software, PEST is capable of estimating model parameters for an existing computer model without requiring access to the model's source code. PEST applies a robust Gauss–Marquardt–Levenberg algorithm, which combines the advantages of the Gauss-Newton method and the steepest descent method (Baginska et al. 2003). By adjusting model inputs, PEST minimizes the weighted sum of squared differences between the model generated values and observed measurements. At the beginning of each iteration, Taylor expansion about the current best parameter set is used to linearize the relationship between model parameters and observations. This expression is then solved for an improved parameter set evaluated by subsequent model runs. PEST determines whether additional iterations are required by comparing parameter change and objective function improvement achieved through the current iteration and previous iterations. A more detailed explanation of the methodology is provided by Doherty (2004a). For flushing consequence management strategy, PEST minimizes the contaminant concentration in each node. As with FORM, PEST can only aid in the identification of the nodal demand required to flush a contaminant out of the system, but the identification of nodes at which to alter demand, new demands for these nodes, and the location of pipe closures necessary to reduce the contaminant concentration during an incident, need to be determined through the use of other optimization techniques.

2.4.3 Combinatorial Optimization Techniques

Discrete variable optimization is also referred to as combinatorial optimization due to the fact that the optimal solution consists of a combination of discrete variables.

These techniques include natural optimization methods, which represent processes in nature that are successful at optimizing natural activities. Examples include simulated annealing, ant colony optimization, particle swarm optimization, genetic algorithm, and other evolutionary algorithms. Kirkpatrick, Gelatt, and Vecchi introduced the simulated annealing method in 1983, which simulates the annealing process where a substance is heated above its melting temperature and then is slowly cooled to produce a crystal structure and thus minimizes its energy. If the initial temperature of the system is not high enough or cooling is done too quickly, the system may form defects and have a higher optimal energy state. Thus, careful control of the change of temperate rate is very important. The algorithm begins with a random guess for the values of the function variables. The heating process is simulated by changing the variable values randomly, so higher heat refers to greater randomization. For each step, a new combination of variables is created and the function is evaluated. If the output from the function decreases, then the old variables are replaced with new variables. If not, then the old variables are used. The simulated annealing method has been used in the optimization of water distribution systems for determining pipe sizes which create the least-cost design (Cunha and Sousa 1999). An advantage of this approach is that it does not become trapped in a local optimal solution.

Another type of combinatorial optimization technique is the ant colony optimization (ACO) method. This technique is based on the fact that ants can find the shortest distance between a food source and their nest, even though ants are almost blind. Ants are able to do this because they leave pheromone trails wherever they travel and thus other ants are able to follow this trail of chemical cues. Paths which are shorter will

have greater levels of pheromone, since the ants are able to travel between locations faster. As the pheromone levels increase, the probability of another ant choosing that path increases and eventually all ants are utilizing the same path. Ant colony optimization was first applied to the traveling salesperson problem by Dorigo and others in 1996. The process begins with the ants randomly choosing a path and thus depositing pheromone along it. The next decision is selected by a weighted probability which is dependent on the strength of the pheromone on the path and the distance traveled along the path. Therefore, the shortest paths with the highest pheromone will have the greater probability of selection. Maier, Simpson, et al. (2003) have applied ant colony optimization to the least-cost design of water distribution system in order to determine the diameter of the pipes. For example, the ants have eight available paths (i.e. eight diameter sizes) for each of the five pipes, thus a wide variety of configurations are available for the network.

Particle swarm optimization (PSO) was inspired by the social behavior of schools of fish or flocks of birds. It is a population-based stochastic optimization method formulated by Edward and Kennedy in 1995. PSO is similar to evolutionary techniques, such as genetic algorithms, since it also begins with solutions of randomized populations and updates generations while searching for the optimal solution set. The particles move through the space by following the current optimal particles. Coordinates associated with the best solution for itself and neighboring particles are tracked by each particle. The velocity of each particle is changed towards the best solution coordinates. Some advantages of PSO are that it is easy to implement and that only a few parameters need to

be adjusted. The shuffled frog leaping algorithm, a form of particle swarm optimization, has also been applied to the least-cost optimization problem (Eusuff and Lansey 2003).

Another type of discrete variable optimization technique is the genetic algorithm (GA). GA is based on the principles of genetics and natural selection and was original proposed by Holland in 1975 (Holland 1975) and further developed by Goldberg in 1989 (Goldberg 1989). GAs represent one of the most commonly employed natural optimization techniques for design of water distribution networks as evidenced by use of GA for sizing of pipes (e.g., Savic and Walters 1997; Wu and Simpson 2001), evaluation of system reliability (e.g., Tolson et al. 2004), and placement of early warning detection sensors (e.g., Ostfeld and Salomons 2004). Genetic algorithms are applicable to a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear (Haestad 2003). GA can be utilized to identify the nodes at which to (i) alter the demand; (ii) the new demands for these nodes; and (iii) the location of pipe closures necessary to reduce the contaminant concentration during a contamination event in a water distribution network, since it is able to optimize discrete (valve is open or closed) or continuous variables (nodal demand). In addition, since GA does not require a gradient, it can be linked with the hydraulic/water-quality model.

The algorithm begins with random population of individuals in which each individual is represented by a binary string (i.e., chromosome) for one possible solution. For each population generation, a measure of the fitness in regards to the objective is calculated. Based on the fitness value, individuals are selected to create the next generation through the use of techniques such as inheritance, mutation, natural selection,

24

and recombination (crossover). Individuals with higher fitness values will have a greater probability of being selected to produce the next generation, thus on average the new generation will have a higher fitness value than the older population. The algorithm continues until one or more of the pre-established criteria (e.g., number of generations, time limit, fitness limit, stall generations, stall time limit, and fitness tolerance) are met.

2.5 Geographic Information Systems (GIS)

Proper planning, evaluation, and execution of consequence management necessitate a need to evaluate potential impacted areas. Thus, information management tools such as geographic information systems (GIS) can be employed to assist in the development of an intelligent or expert consequence management system. GIS combines common database operations with the unique visualization and geographic analysis benefits associated with maps (ESRI 2001). For a water utility, linking GIS with a hydraulic model can facilitate identification of junctions that are contained within a certain land use zone, identification of customers within a certain distance of a specific node, and identification of customers impacted by a water-main break or contamination event (Haestad 2003).

Following identification of vulnerable nodes with respect to contamination events, other less tangible concerns, such as societal and economic, should be addressed. Incorporation of GIS-based information will help highlight these areas of concerns, since it will be able to identify critical need consumers, such as hospitals and certain industries, in addition to considerations for daily population dynamics. For example, LandScan Population Databases allows the assessment, estimation, and visualization of populations

at risk by tracking population changes throughout the day. Dobson et al. (2000) utilized this tool to estimate ambient populations at risk to atmospheric release of contaminants. Currently, this tool is being integrated with transportation software, such as Transportation Routing Analysis GIS (TRAGIS), and atmospheric dispersion models, such as Hazard Prediction and Assessment Capability (HPAC) (ORNL 2002).

Many risk assessment applications of GIS exist in the water supply industry. For example, GIS has been utilized to identify locations in the water distribution network that are sensitive to contaminant intrusions based on risk contours (Sadiq et al. 2006). In addition, microbial monitoring of drinking water and records of incidents and outbreaks were incorporated within GIS for a water utility in Germany (Kistemann et al. 2001). To determine if gastrointestinal infections and drinking water sources were linked, spatial patterns were examined (Dangendorf et al. 2002). GIS was useful in analyzing population exposures and identifying the positive linkage between gastrointestinal disease and groundwater. Cech and Montera (2000) explored the spatial variation of total aluminum concentration in water distribution system around Houston, TX. With the incorporation of GIS, the researchers determined that the concentration of total aluminum was higher in the area serviced by the water treatment plant utilizing alum for water purification. Besides determining exposure risk, GIS coupled with a hydraulic model can be utilized to model pipe-breaks. A spatial decision support system was developed to analyze pipe-break susceptibility in South Africa (Sinske and Zietsman 2004). This decision support system allows water utilities to effectively implement preventative maintenance strategies. In summary, use of GIS will enable users to better identify areas

that are most critical to their mission. Further, it will aid in the quick and easy assessment of the populations at risk should a contamination event occur.

CHAPTER III

CONSEQUENCE MANAGEMENT OPTIMIZATION UTILIZING NEWTON-RAPHSON AND PEST

3.1 Introduction

On 11 September 2001, the concept of what constitutes a credible threat to the security of our nation's critical infrastructure changed. Threats that previously had been considered low risk are now being examined and incorporated into emergency plans and procedures. One environmental system at great risk of contamination by chemical and biological agents is the nation's water supply and distribution networks. Currently, the majority of vulnerability assessments (VAs) do not address potential attacks on water distribution networks which can include physically destructive actions and/or chemical and biological contamination. To our knowledge, VAs that address both physical and chemical/biological forms of attack are lacking, therefore further research is necessary to address not only system vulnerabilities, but to also evaluate possible consequences and corrective actions.

Development of consequence management techniques that address contamination events is necessary since few analytical tools are available to effectively analyze such problems (Danneels and Finley 2004). Though these types of events are relatively infrequent, it is still important to prepare emergency response solutions to help mitigate the consequences. The ability to perform rapid assessments of risks resulting from accidents or intentional acts is an important component of emergency response (Parris 2002), where modeling is requisite to aid in the decision process. Coupling system

hydraulic models with water quality models can aid in the simulation of threat scenarios in order to assess the potential impacts of a contamination event and develop consequence mitigation strategies (Uber et al. 2004).

Development of new water distribution system simulation tools represents an active area of research following the events of September 11th, though these tools do not incorporate consequence management guidance. A variety of techniques should be examined for the most optimal consequence management solution. Such actions may include (i) isolating the contaminated area (often not desirable due to loss of fire fighting capability in the affected area), (ii) treating the contaminant *in situ* (e.g., Propato and Uber 2004); (iii) flushing the contaminated water into a sanitary sewer; or (iv) issuing "boil water" alerts to affected parties. While the response actions to a contamination event have been defined (Walski 2001), no overarching consequence management guidance, however, currently exists.

Numerous recent research efforts have focused on the placement of chemical detection sensors within a water distribution network to aid vulnerability assessments associated with contamination events (Ostfeld and Salomons 2004; Kessler et al. 1998; Kumar et al. 1997); however, this research has not yet incorporated consequence management solutions once a contamination event is identified. These solutions may involve optimizing (i) valve operations (identifying best valves and timing of open/closure operations) to enhance contaminant isolation; (ii) demand locations and quantities to "flush" the system as expeditiously as possible; (iii) location and quantity of injection of chemical oxidants to react and potentially destroy the contaminant; and (iv) combinations of (i), (ii), and (iii). In an effort to illustrate use of optimization techniques

for consequence management, we choose to utilize two relatively common methodologies, Newton-Raphson and Parameter ESTimation (PEST), to assist in the determination of optimal demand for contaminant detection and isolation. Newton-Raphson has been utilized in first-order reliability methods (FORM) to find the minimum distance to the most probable failure point. FORM is presently employed most often in structural reliability analysis, but recently was applied to water distribution system reliability (Xu et al. 2003; Tolson et al. 2004) and other water resources applications. General application of PEST to water resources problems involves linking of the optimization scheme to the modeling software (e.g., MODFLOW) to assist in model calibration and predictive analysis of model parameters. A brief description of the methodologies and two examples are provided in the following sections.

3.2 Newton-Raphson Method

Monte Carlo simulation is a useful tool to aid in the analysis of systems with random variables that may possess a range of uncertainties. While recently employed to simulate the spread of a contaminant through a water distribution network (Nilsson et al. 2005), Monte Carlo simulations are often very computationally demanding. As such, employment of a more computationally efficient method such as FORM, may yield improved performance relative to traditional Monte Carlo simulations. The following section provides a brief overview of FORM, but the reader is referred to Haldar and Mahadevan (2000) for a more detailed description.

FORM determines the probability of failure based on a performance function. For water distribution systems, the performance function is generally expressed in terms

30

of its load (demand) and resistance (capacity). For water quality applications, the system's load correlates to the contaminant load, while the system's resistance correlates to a given water quality standard. The performance function, $g(\mathbf{X})$, is commonly written as the difference between the load (L) and the resistance (R), where $\mathbf{X}$ is the vector of random variables that influence the system. The performance function is formulated such that $g(\mathbf{X}) = 0$ defines the failure domain. Since FORM determines the failure probability of a performance function equal to zero, a similar procedure was utilized in this work to evaluate whether the concentration at a particular node is smaller than the target water quality standard.

FORM approximates the probability of failure by $p_f = \Phi(-\beta)$, where $\Phi(\ )$ is the standard normal cumulative distribution function (CDF) and β is the reliability index. The reliability index, β, represents the minimum distance between the design point on the failure surface and the origin in standard normal space, and the design point is considered the most probable point (MPP) of failure. Determination of β and the design point represents a constrained nonlinear optimization problem. FORM uses a Newton-Raphson type recursive formula proposed in 1978 by Rackwitz and Fiessler (1978) to obtain the design point and the associated reliability. This algorithm linearizes the performance function at each iteration point and uses the derivatives to find the next iteration point. Compared to other nonlinear optimization algorithms, this algorithm requires the least computational effort per step, since the only information required to compute the next iteration point is the value and the gradient of the performance function (Haldar and Mahadevan 2000). FORM obtains only an approximation of the failure

probability unless the performance function is linear, thus the accuracy of FORM is dependent on the performance function's degree of nonlinearity (Maier et al. 2001).

FORM analysis and our application of a Newton-Raphson method is initiated by defining a performance function, $g(\mathbf{X})$, and assumption of initial values of the random variables. If no prior information is available, the mean values are generally used as the initial points. The mean and standard deviation at the design point of the equivalent normal distribution need to be computed using Equations 3-1 and 3-2, where $\Phi^{-1}(\ )$ is the inverse CDF of the standard normal distribution N $(0,1)$, F_{Xi} (x^*_i) is the CDF of the original nonnormal variable, f_{Xi} (x^*_i) is the probability distribution function (PDF) of the original nonnormal variables, $\phi(\ )$ is the PDF of the standard normal, x^*_i is the nonnormal variable, μ^N_{Xi} and σ^N_{Xi} are the mean and standard deviation of the equivalent normal variable. In the unconstrained Newton-Raphson method analysis, the CDF and PDF of the normal random variables are determined from the normal distribution. The PDF and CDF of truncated normal random variables, used in the constrained Newton-Raphson method analysis, are given by Equations 3-3 and 3-4, where a and z are the upper bound and lower bounds and μ and σ are the mean and standard deviation of the truncated normal random variables.

$$\mu^N_{X_i} = x^*_i - \Phi^{-1}[F_{X_i}(x^*_i)]\sigma^N_{X_i} \tag{3-1}$$

$$\sigma^N_{X_i} = \frac{\phi\{\Phi^{-1}[F_{X_i}(x^*_i)]\}}{f_{X_i}(x^*_i)} \tag{3-2}$$

$$f_{X_i}(x) = \frac{1}{\sqrt{2\pi}\sigma} \frac{e^{\frac{-1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}}{\Phi\left(\frac{z-\mu}{\sigma}\right) - \Phi\left(\frac{a-\mu}{\sigma}\right)}$$ (3-3)

$$F_{X_i}(x) = \frac{\Phi\left(\frac{x-\mu}{\sigma}\right) - \Phi\left(\frac{a-\mu}{\sigma}\right)}{\Phi\left(\frac{z-\mu}{\sigma}\right) - \Phi\left(\frac{a-\mu}{\sigma}\right)}$$ (3-4)

Once calculated, the coordinates of the design point in the equivalent standard normal space are defined by $x_i^{'*} = (x_i^* - \mu_{X_i}^N)/\sigma_{X_i}^N$. The partial derivative, $\partial g/\partial X_i$, of the performance function, with respect to each of the random variables, is then evaluated at the design point. When the performance function is implicit, a finite difference scheme may be required to determine the derivative of the performance function. The chain rule of differentiation is then used to compute the partial derivatives $\partial g/\partial X_i'$ in the equivalent standard normal space by $(\partial g/\partial X_i)*\sigma_{X_i}^N$. Next, new values for the design point, $\mathbf{x}_{k+1}'^*$, are computed using Equation 3-5, where $\nabla g(x_k'^*)$ is the gradient vector of the performance function at $\mathbf{x}_k'^*$, the kth iteration point and $\left|\nabla g(x_k'^*)\right|$ is the norm of the gradient vector.

$$x_{k+1}'^* = \frac{1}{\left|\nabla g(x_k'^*)\right|^2}\left[\nabla g(x_k'^*)^t x_k'^* - g(x_k'^*)\right]\nabla g(x_k'^*)$$ (3-5)

The new values for the design point in the original space are then evaluated using $x_i^* = \mu_{X_i}^N + \sigma_{X_i}^N x_i'^*$. Following determination of the new design point value, the reliability

index, β, is calculated and its convergence criteria, δ, is checked. The new value of the performance function is then computed and evaluated using its convergence criteria, ε. The iterative process continues until both convergence criteria are satisfied, usually $\leq$ 0.001. The Newton-Raphson method utilized in FORM can aid in the identification of the minimum demand required to flush a contaminant out of the system. In this study, the random variables are the demand at the nodes, x, and the performance function, $g(x)$, is defined in terms of the target water quality standard minus the concentration value at the node and time of consideration. The reliability index was not calculated for this application, since the objective was to determine the most probable point where the performance function equals zero. WaterCAD$^{\circledR}$ was utilized to determine the derivative of the performance function with respect to the random variables by utilizing a finite difference scheme.

3.3 Parameter ESTimation (PEST)

Optimization typically involves searching for either the maximum or minimum value of an objective function, subject to restrictions. Many different categories of optimization techniques are available depending on the objective function and the constraints. The categories can include constrained and unconstrained optimization, one-dimensional and multidimensional optimization, and any combination of these categories. For the problem of water distribution optimization, a wide range of methods have been applied (Mays 2000).

One optimization technique capable of managing large numbers of variables is Parameter ESTimation (PEST) (Doherty 2004b). PEST possesses components which are

able to interact with a variety of modeling software in order to estimate a number of model parameters, such as hydraulic conductivities. PEST has been used for calibration of groundwater models (e.g., Doherty 2003), sensitivity analysis of soil and fertilizer properties, such as pH (Baginska et al. 2003), and predictive analysis for model uncertainty (Doherty and Johnston 2003). Comprised of nonlinear parameter estimation and optimization modeling software, PEST is capable of estimating model parameters for an existing computer model without requiring access to the model's source code. PEST applies a robust Gauss–Marquardt–Levenberg algorithm, which combines the advantages of the Gauss-Newton method and the steepest descent method (Baginska et al. 2003). By adjusting model inputs, PEST minimizes the weighted sum of squared differences between the model generated values and observed measurements. At the beginning of each iteration, Taylor expansion about the current best parameter set is used to linearize the relationship between model parameters and observations. This expression is then solved for an improved parameter set evaluated by subsequent model runs. PEST determines whether additional iterations are required by comparing parameter change and objective function improvement achieved through the current iteration and previous iterations.

Initiation of PEST begins with defining a set of model parameters for which the model-generated observations are close to the field observations in the least squares sense. Thus, PEST will determine a parameter set in which the objective function, Ω, is a minimum. The objective function for nonlinear parameter estimation is defined by Equation 3-6, where c is the experimental observation vector, c_0 is the field observation vector, b is the parameter vector that is slightly different than b_0, J is the Jacobian matrix

35

composed of the derivatives of the observations with respect to the parameters, and Q is a diagonal matrix composed of the square of the weight attached to each observation. The derivatives of the observations with respect to parameters for the Jacobian matrix are calculated using finite difference. The parameters are altered by utilizing the parameter upgrade vector, u, defined by Equation 3-7, which forms the basis of the nonlinear weighted least squares parameter estimation, where α is the Marquardt parameter, I is the identity matrix, and r is the residuals vector. To help reduce the roundoff errors of Equation 3-7, a scaling matrix, S, may be used (Equation 3-8). The scaling matrix, S, is a square, $n \times n$ matrix with diagonal elements only, where the ith diagonal element of S is given by $S_{ii} = (J^t Q J)_{ii}^{-1/2}$. The largest element of $\alpha S^t S$ is referred to as the Marquardt lambda, λ. PEST solves Equation 3-8 for u, using the initial value of λ supplied by the user. It then upgrades the parameter set, b, using $b = b_0 + \chi u$, where χ is given by Equation 3-9, and w_i is the weight association with observation i.

$$\Omega = (c - c_0 - J(b - b_0))^t Q(c - c_0 - J(b - b_0)) \tag{3-6}$$

$$u = (J^t Q J + \alpha I)^{-1} J^t Q r \tag{3-7}$$

$$S^{-1}u = ((JS)^t QJS + \alpha S^t S)^{-1} (JS)^t Q r \tag{3-8}$$

$$\chi = \frac{\sum_{i=1}^{m} (c_i - c_{0_i}) w_i^2 J u_i}{\sum_{j=1}^{m} (w_i J u_i)^2} \tag{3-9}$$

The new set of parameters contained in b is then used to calculate the value of the objective function, Ω. PEST then examines a lower value of λ and compares the values of Ω calculated from both λ values. If the second Ω value is lower, then λ is lowered again, otherwise λ is raised above the initial λ value. PEST tests a maximum of 10 lambdas before moving to the next optimization iteration, repeating the procedure by using the lambda value corresponding to the lowest Ω value as the starting point in determining the next parameter upgrade vector until a global minimum is reached. A more detailed explanation of the methodology is provided by Doherty (2004a). In this study, the objective is to reduce the contaminant concentration at each node to a target water quality standard by altering the demand at each node. Therefore, b, c_0, and c represent the demand at each node, target water quality standard, and contaminant concentration at each node, respectively.

3.4 Applications

The scenario examined in this research addresses the injection of a contaminant within a water distribution network, with the objective to minimize the impact of the contamination on the system once detection has occurred. Example 1 represents a modified version of EPANET Example 1 (Rossman 2000) and Example 2 is Anytown U.S.A. (Walski et al. 1987), which were previously optimized for sensor location within the network (Ostfeld and Salomons 2004).

Example 1

The Example 1 network, EPANET Example 1, consists of 12 pipes, a source, a pumping station, an elevated storage tank, and eight demands (Figure 3-1). The demands at Nodes 10 and 12 are random variables, while all other demands of the system possess a fixed demand pattern. A hydraulic and constituent time step of five minutes was used for a 24-hr simulation period. For purposes of simulation, a contaminant of 2.0 mg/L is injected into Node 11 at minute 5 in the simulation. The contaminant is considered conservative and thus is not reactive with system constituents. Once the contaminant is injected, the simulation is run until a sensor detects it (detection is defined as concentration greater than 10^{-3} mg/L). Here, sensors were located at the reservoir, and at Nodes 12, 21, and 32. The first sensor to detect the contaminant was Node 12 at minute 35 with a concentration of 0.28 mg/L, followed by the second detection at Node 21 at minute 45 with a concentration of 0.075 mg/L. The minimum demands at the nodes were calculated every five minutes following sensor detection using the contaminant concentration at every node. These demands were only changed for time periods under investigation so that the altered demands did not affect concentration levels in other time segments.
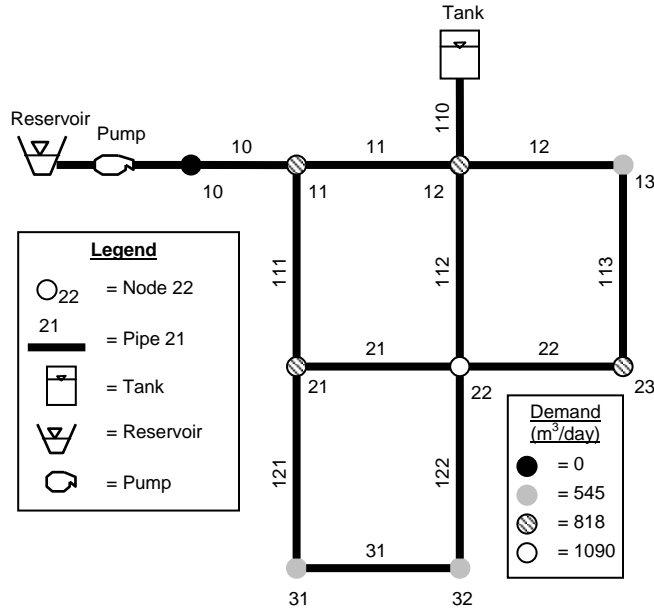
Figure 3-1. Schematic of Example 1, EPANET Example 1.

Following detection, the nodal demands were changed using three different optimization methods in order to minimize contamination spread. For the first method, a commercially-available software package, WaterCAD®, (Bentley Systems 2003) was coupled with an unconstrained Newton-Raphson method to determine the demands necessary to limit the spread of the contaminant during an incident. The second method, constrained Newton-Raphson method, also utilized WaterCAD®, while the final method linked EPANET (U.S. EPA 2002) with PEST. The properties of the three optimization methods are summarized in Table 3-1. For the Newton-Raphson method analyses, the means and standard deviations of the variables are utilized. The demands at Nodes 10 and 12 are considered as normal random variables with means of 0 m³/day and 818 m³/day, respectively, and a standard deviation of 164 m³/day for the first scenario. For the constrained Newton-Raphson method the demands are truncated normal random variables with the same distribution parameters, but with a lower bound of -2730 m³/day

and an upper bound of 10900 m^3/day for Node 10 and 10100 m^3/day for Node 12. PEST uses the same upper and lower bounds as the Newton-Raphson method analysis. The Newton-Raphson method analyses adjust only the two nodal demands of combination Node 10 and 12, whereas the PEST analysis adjusts every combination of two nodal demands for a total of 36 and then all nodes together. The different combinations of nodal demands were examined to determine which combination resulted in a greater reduction in contaminant concentration.

The performance function for this application of a Newton-Raphson method was defined as $g(\ ) = Conc_{desired} - Conc_{exp}$, where $Conc_{desired} = 0.001$ mg/L and $Conc_{exp} =$ contaminant concentration calculated by WaterCAD®. Convergence criteria for $g(\ )$ was 0.001. The field observation data, c_0, for PEST consisted of the target water quality standard for the nodes, which was assumed to be equal to 0.001 mg/L. All other PEST parameters were assigned typical values as noted in Doherty (2004a).

Table 3-1. Characteristics of Employed Optimization Methods.

Unconstrained Newton-Raphson	Constrained Newton-Raphson	Parameter ESTimation (PEST)
- Unbounded normal random variables - Two nodal demands optimized (N10, N12) - WaterCAD® analysis - Derivatives calculated by forward difference	- Truncated normal random variables - Two nodal demands optimized (N10, N12) - WaterCAD® analysis - Derivatives calculated by central difference	- Parameters with upper and lower bounds - Every combination of two nodal demands optimized - All nodal demands optimized - EPANET analysis - Able to switch derivative calculation between forward and central difference

Each Node at Each Time Analysis

The contamination of Example 1 network nodes occurred in the following order: (i) Node 21 at 45 minutes, (ii) Node 31 at 140 minutes, (iii) Node 22 at 160 minutes, (iv) Node 13 at 195 minutes, and (v) Node 32 at 285 minutes. Node 23 is not contaminated until the tank begins to drain at 420 minutes. Contaminants generally remain in the nodes for about four time steps and then reappear when the contaminated water in the elevated storage tank drains and redistributes the contaminant.

Demand at Nodes 10 and 12 were adjusted in order to reduce the contaminant concentration levels to 0.001 mg/L in each of the nodes at each time step for the first two analysis scenarios. Table 3-2 provides a summary of the simulation results for unconstrained and constrained Newton-Raphson methods. Based on the unconstrained and constrained Newton-Raphson method analyses, the demand at Node 10 appears to control overall system response as illustrated by its large fluctuation and the relative consistency of Node 12 demand near its mean value. PEST analysis provided similar results as the constrained Newton-Raphson method analysis for the nodal combination of 10 and 12. Other nodal combinations produced similar results as the nodal combination of 10 and 12, especially for time periods when the contaminant concentrations were relatively low. Time periods with higher contaminant concentrations resulted in varying degrees of percent reduction in contaminant concentration especially for Nodes 31 and 32, which are farthest from the injection node. Figure 3-2 shows the fluctuations in the contaminant reduction percentages for Node 21 at minute 55, in that the nodal combinations which contain Nodes 31 or 32 reduced the contaminant concentration by approximately 100%, while combinations which contain Node 21 achieved 66%

41

reduction in contaminant concentration. When examining the combination in which all nodes were adjusted together, changes in the demand were able to reduce the contaminant concentration to 0.001 mg/L or less for almost all cases. The demands for each of the nodes varied greatly for each time period, besides Node 12 which remained near the average demand. When comparing all of the nodal combinations from the PEST analysis, the combination of Nodes 12 and 32 appears to be the best choice for system response, since the Node 12 demand remains near average, and the reduction in contaminant concentration is relatively high for all time periods.

Table 3-2. Demand Results for Each Node and Time Step from Newton-Raphson Method Analysis of EPANET Example 1.

Node	Time (min.)	Unconstrained Newton-Raphson				Constrained Newton-Raphson			
		Demand at Node 10 (m³/day)	Demand at Node 12 (m³/day)	Conc. (mg/L)	% Reduced	Demand at Node 10 (m³/day)	Demand at Node 12 (m³/day)	Conc. (mg/L)	% Reduced
13	195	-829	818	0.001	91.72	-832	872	0.001	91.73
13	200	-57800	818	0.001	99.74	-2730	818	0.278	26.76
13	205	490000	818	0.001	99.95	10900	-2730	1.912	3.50
13	210	469000	818	0.001	99.94	10900	-2730	1.119	29.57
21	45	561	818	0.001	98.66	562	818	0.001	98.55
21	50	178000	818	0.001	99.95	10900	-2730	1.591	20.44
21	55	178000	818	0.001	99.95	-2730	10100	1.520	22.02
22	160	4900	818	0.001	96.53	4900	818	0.001	96.47
22	165	6210	818	0.001	99.87	6190	818	0.001	99.86
22	170	6380	812	0.001	99.89	6360	818	0.001	99.93
22	175	6340	818	0.001	99.65	6340	818	0.001	99.68
22	190	-140	818	0.001	71.91	-139	818	0.001	71.54
22	195	-7680	845	0.001	99.51	-2730	10100	0.094	53.97
22	200	-7740	845	0.001	99.90	-2730	10100	0.674	34.86
22	205	-7740	818	0.001	99.87	-2730	10100	0.590	24.95
31	140	19900	720	0.001	96.16	10900	-2730	0.021	17.72
31	145	263000	-486	0.001	99.86	10900	-2730	0.619	16.27
31	150	385000	818	0.001	99.95	-2730	10100	1.981	0.10
31	155	-218000	818	0.001	99.92	-2730	10100	1.216	5.80
32	285	-4670	818	0.001	81.62	-2730	10100	0.003	44.30
32	290	-5610	818	0.001	99.37	-2730	10100	0.095	39.51
32	295	45500	818	0.001	99.80	-2730	10100	0.414	15.97
32	300	41100	818	0.001	99.77	-2730	10100	0.412	5.46
32	305	12900	818	0.001	99.11	0	818	0.112	0.00
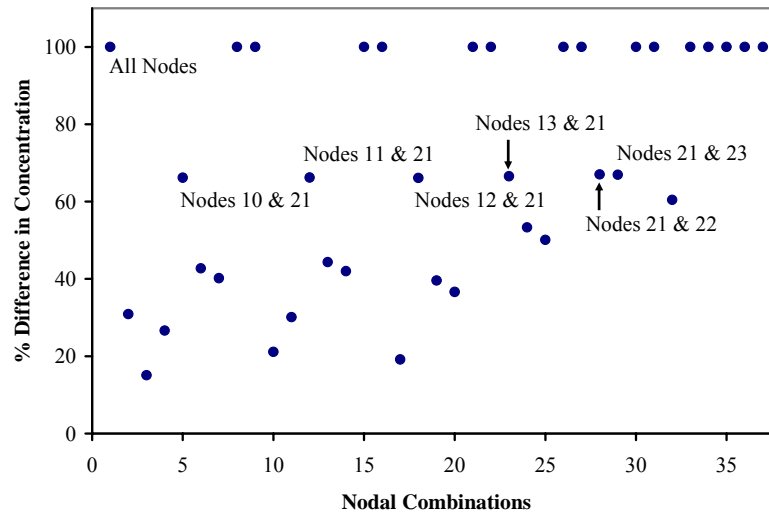
Figure 3-2. Contaminant Percent Reduction from PEST Analysis for Node 21 at Minute 55 of EPANET Example1.

All of the Nodes at All Times Analysis

The above analysis examined the optimal demand for each node at each time, since a delay in responding to an incident may be present. The situation where an operator can respond quickly needs to also be analyzed, as well as the effects of spreading the contaminant into nodes previously uncontaminated. All of the nodes and time periods following the second detection were utilized to optimize the nodal demands necessary to flush the contaminant from the entire network. The different combinations of nodal pairs and the combination of all nodes together produced a variety of total concentration reductions, which ranged from an increase in concentration to a decrease of approximately 35% (Figure 3-3). As expected the alternative in which all nodes were adjusted together resulted in one of the highest reduction percentages, but it also required a 56% change in the total network demand. The majority of the alternatives remained around the original total demand as shown by the small number of extreme points (Figure

44

3-4).   Comparing the two figures, it can be seen that the combinations with the best

reduction in contaminant concentration required the greatest change in demand.   It also

shows that a one percent reduction in concentration required approximately a one percent

change in demand.
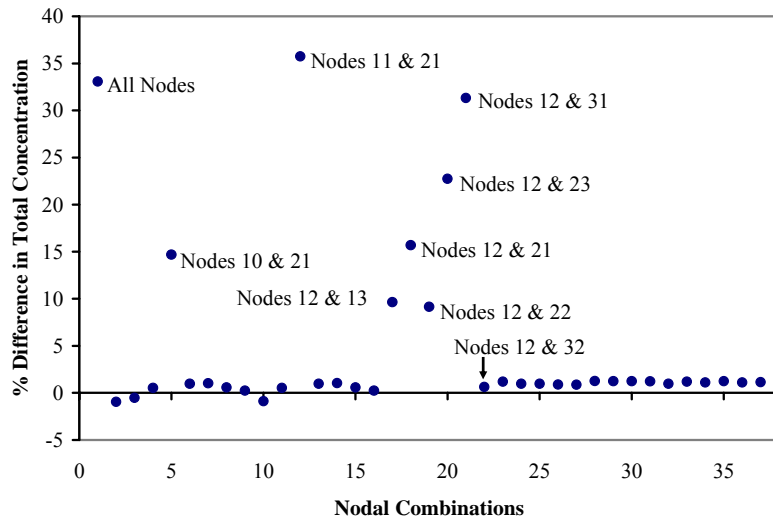
Figure 3-3. Percent Difference in Total Concentration of EPANET Example 1.
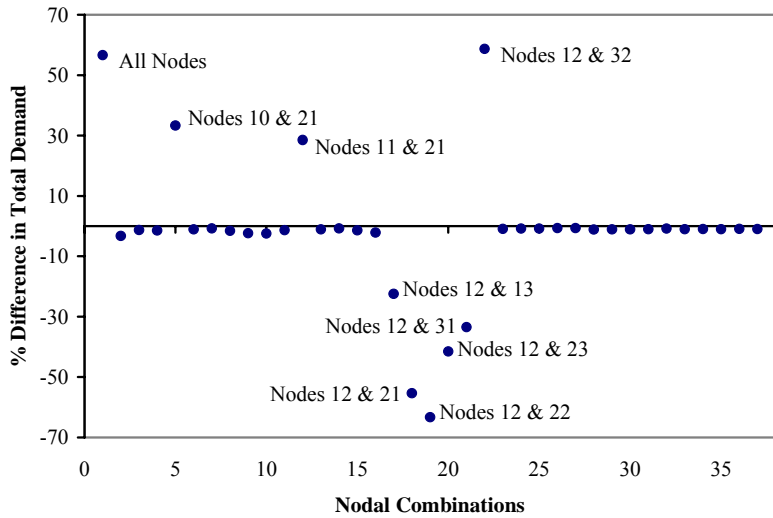
Figure 3-4. Percent Difference in Total Demand of EPANET Example 1.

Example 2

The Example 2 network, Anytown, consists of 34 pipes, 16 consumer nodes, two 1,136 m^3 capacity elevated storage tanks, one pumping station, and one well (Figure 3-5). The pipes, nodes, tanks, and pumping station characteristics represent those used in a previous application of Anytown (Walski et al. 1987). A hydraulic and constituent time step of five minutes was used for a 24-hr simulation period. For nodes that were not utilized in the nodal combination under consideration, the demands were fixed. The observations were for all of the nodes and time periods experiencing contaminant concentrations, including two time steps following a contamination event to ensure that the contamination was not distributed into later time periods. In this example, a conservative contaminant of 2.0 mg/L was injected into Node 30 at minutes 5 and 10 in the simulation. Four sensors were located at Nodes 70, 80, 90, and 160 as noted in Ostfeld and Salomons (2004). Nodes 80 and 90 at minute 180 represented the first two sensors to detect (detection is defined as concentration greater than 10^{-3} mg/L) the contaminant with concentrations of 0.028 mg/L and 0.067 mg/L, respectively.
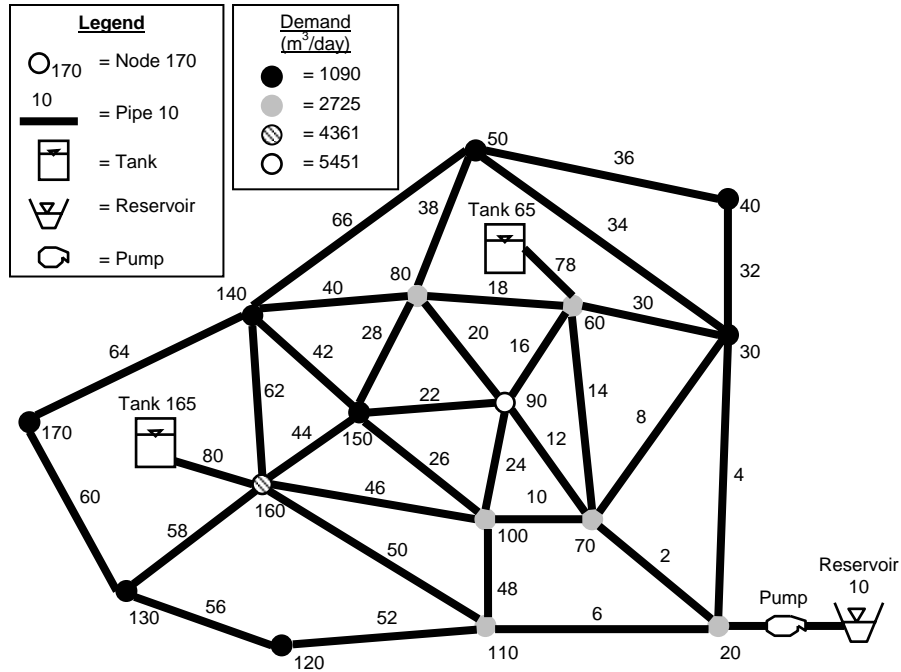
Figure 3-5. Schematic of Example 2, Anytown U.S.A.

Demands were optimized using EPANET linked with PEST. The demands had a lower bound of -2730 m³/day and an upper bound of 10900 m³/day. The field observation data, c_0, for PEST consisted of the target water quality standard for the nodes, which was assumed to be equal to 0.0 mg/L. All other PEST parameters were assigned typical values as noted in Doherty (2004a). The PEST evaluation included two sets of analyses: (i) optimization of every combination of two nodal demands for a total of 120 combinations; and (ii) optimization of all nodes together. The different combinations of two nodal demands and the combination of all nodes together were examined to determine which alternative resulted in a greater reduction in contaminant concentration of the entire network.

Each of the alternatives was able to reduce the contaminant concentration in the entire network to lower than the original concentration following optimization of the

demands. The range of total concentration reductions are shown in Figure 3-6. Approximately 83% of the alternatives resulted in concentration percentage reductions of 20% or less. Optimizing all of the nodal demands produced the greatest reduction in total contaminant concentration of 90%, but caused the largest difference in total network demand of -58% (Figure 3-7). Comparing Figures 3-6 and 3-7, only five of the alternatives produced a reduction of contaminant concentration greater than 20% while requiring a change in demand of 5% or less. The best alternative to flush the contamination out of the network was the nodal combination of Nodes 80 and 100, since this combination resulted in a contaminant reduction percentage greater than 50% and a change in demand of less than 5%.
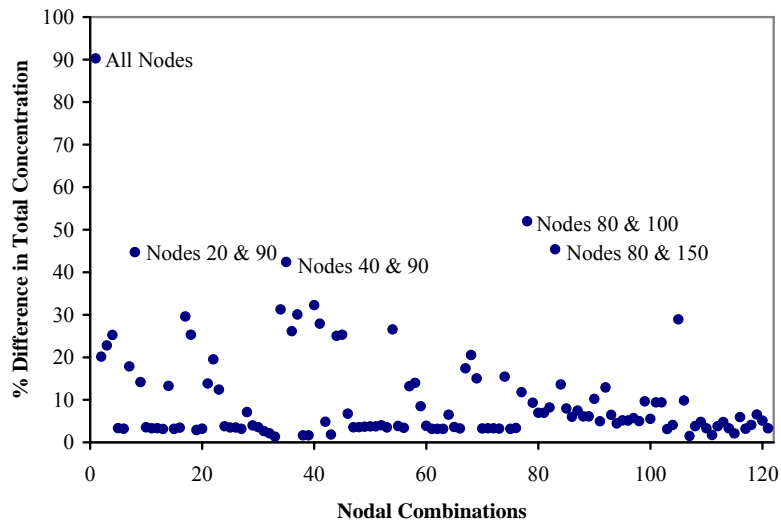
Figure 3-6. Percent Difference in Total Concentration of Anytown.
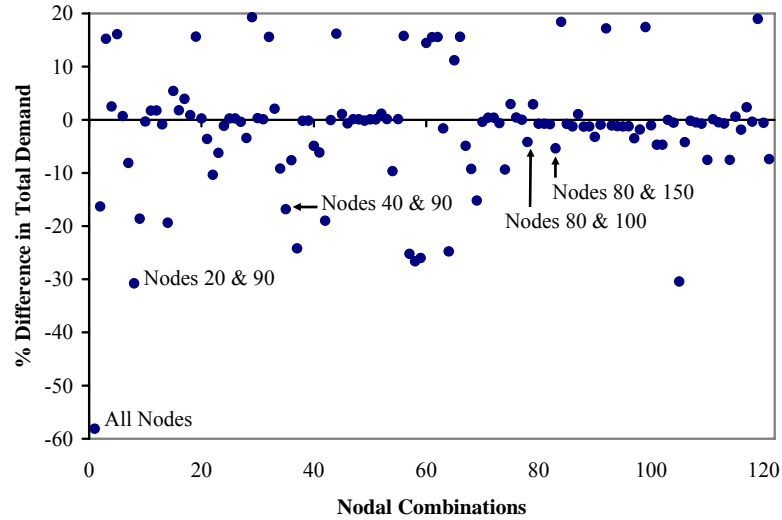
Figure 3-7. Percent Difference in Total Demand for Anytown.

3.5 Conclusion and Future Work

Beginning with a water distribution system with optimal sensor placement, results from this research illustrate the usefulness of unconstrained and constrained FORM to provide an optimal initial solution to minimize the impact of further contamination to a water distribution network through changes in demand at target nodes. Because of convergence challenges associated with the Newton-Raphson method, a more robust optimization technique, PEST, was employed.

As with any model application and analysis, there are limitations to each of the optimization methods presented for this application. An obvious limitation of the unconstrained Newton-Raphson method analysis was the lack of bounds applied to the demand. Another concern was the efficiency of the method, since typically 10 or more iterations were required to reach the desired solution. In the constrained Newton-Raphson method analysis, difficulties arose when the solution demands neared the upper and lower limits, since the formulas for the mean and standard deviations in standard

49

normal space cannot be calculated at the bounds. An observation of the PEST analyses involved difficulty in convergence to an optimal solution at high contaminant concentrations. In select cases, PEST required that the initial demand values be near the optimal value, causing obvious difficulties if the optimal solution is not known prior to initiation of simulations. A comparison between the two methodologies used in the analysis is illustrated in Table 3-3.

Table 3-3. Comparison of Newton-Raphson and PEST.

Newton-Raphson	Parameter ESTimation (PEST)
- Utilizes Newton-Raphson method - Utilizes distribution parameters for random variables - Utilizes performance function - EPANET executes separate from analysis - Can possess convergence problems - Can possess difficulties in obtaining global optimization (e.g., this application)	- Utilizes Gauss–Marquardt–Levenberg algorithm - Requires upper and lower bounds of parameters - Requires field observations values - Integrates automated executions of EPANET - Converges within 5 to 6 iterations for small applications - Obtains global optimization when starting point is near optimal

The primary objective of this study was to demonstrate how common optimization techniques, i.e., Newton-Raphson method and PEST, can be employed for consequence management of water distribution networks to flush a contaminant out of the network. Although each of the techniques employed in this study performed well, it would be beneficial for future studies to examine the applicability of other optimization techniques, such as genetic algorithms, in determining the optimal demand to reduce contaminant concentrations. These methods may be able to provide improved versatility in the selection of nodal combinations (e.g., genetic algorithms allow use of additional constraints, enhancing flexibility in the selection of nodal demands), further enabling the

exploration of more complex networks and use of additional nodal combinations (e.g., three, four, or five nodes) to optimize overall system response. Future work will further incorporate costs for altering the demand and weights for nodes of greater concern, such as those associated with hospitals or schools. Coupled with these techniques can be evaluation of valve operations, including prioritization of valve shutoff locations. Armed with this knowledge, a water distribution system operator may be able to identify valves to close and which nodal demands should be altered to minimize the spread of contamination within the network, and to eventually expedite removal of contaminant from the network.

Other future work may benefit from inclusion of a probability of risk. For example, given an acceptable risk of 10 percent, what actions are necessary to achieve this level of risk? By assuming different levels of risk, a variety of demand scenarios may be determined. Thus, a decision-based matrix could be developed to aid consequence management efforts. Further, information management tools such as geographic information systems (GIS) may be employed to assist in the development of an intelligent consequence management system. For example, incorporation of a GIS-based system may assist in highlighting societal and economic areas of concerns, since such systems will be able to identify critical need consumers, such as hospitals, schools, and certain industries, in addition to considerations for daily population dynamics (e.g., Oak Ridge National Laboratory's LandScan system (ORNL 2000)).

CHAPTER IV

CONSEQUENCE MANAGEMENT UTILIZING GENETIC ALGORITHM

4.1 Introduction

Following the events of September 11, 2001, the nation's water supply and distribution utilities began to examine threats that had been previously considered low risk. As a component of the Public Health, Security, and Bioterrorism Preparedness and Response Act (PL 107-188), water utilities are now required to perform vulnerability assessments which aid in the identification of areas within the water utility requiring hardening against potential threats. Accompanying the vulnerability assessment is the emergency response protocol that explores possible consequences and corrective actions following a physical/chemical/biological attack.

Once a contamination threat to a network is established, the U.S. Environmental Protection Agency's (EPA's) Response Protocol Toolbox (U.S. EPA 2003) provides recommendations for implementation of specific response actions to minimize the potential impact to the public. Steps in this protocol include detection, source identification, and consequence management. To aid in the response time for contamination events, recent research efforts have focused on the placement of early warning detection systems within a water distribution network (Kumar et al. 1997; Kessler et al. 1998; Ostfeld and Salomons 2004; Berry et al. 2006; Propato 2006). Other researchers have established source identification methods (Laird et al. 2006; Preis and Ostfeld 2006) to identify contaminant injection locations as well as flow paths following

successful detection of a contamination event. Optimal responses to remediate contaminated systems must then evaluate possible consequences and corrective actions. These consequence management strategies may include (i) isolation and containment of a contaminant through valve operations (EPA 2004a); (ii) public notification; (iii) demand locations and quantities to "flush" the system (EPA 2004b); and (iv) any combinations of valving, notification, and flushing.

To date, limited research has focused on the application of optimization techniques to consequence management strategies in response to contamination events. Baranowski and LeBoeuf (2006) previously explored this concept in order to determine the most favorable demand to minimize contaminant concentration within a network. In that work, three different gradient-based optimization techniques were utilized to determine the optimal demand required to minimize total system contaminant concentration following detection by early warning detection sensors. While results from that effort produced optimal solutions, employment of gradient-based methods led to computational inefficiencies, especially for larger water distribution systems. Poulin et al. (2006) established a methodology to locate early warning detection sensors and to isolate contaminated zones utilizing operational rules. While representing an important contribution, this work is limited to system detection and isolation by minimizing the time required for valve and hydrant operations, and it does not incorporate flushing as an operational response. In addition, that work is not currently incorporated into a programming code. In this current effort, we apply a non-gradient based optimization technique, a genetic algorithm, to determine the optimal flushing and valving operations to reduce the total network contaminant concentration following sensor detection. We

begin our presentation with a brief description of the methodology employed, followed by illustration through example applications.

4.2 Methodology

This research addresses the scenario in which a contaminant is injected within a water distribution network, with the objective of minimizing the impact of the contamination on the system following successful detection via previously placed sensors. EPANET (U.S. EPA 2002) was employed as the hydraulic model, while a genetic algorithm (GA) (MathWorks 2006) was utilized to identify the nodes at which to (i) alter the demand; (ii) the new demands for these nodes; and (iii) the location of pipe closures (e.g., valving operations) necessary to reduce the contaminant concentration during an incident.

Genetic Algorithm

GA represents a discrete variable optimization technique based on the principles of genetics and natural selection. Originally proposed by Holland in 1975 (Holland 1975), and further developed by Goldberg in 1989 (Goldberg 1989), GAs represent one of the most commonly employed natural optimization techniques for design of water distribution networks as evidenced by use of GA for sizing of pipes (e.g., Savic and Walters 1997; Wu and Simpson 2001), evaluation of system reliability (e.g., Tolson et al. 2004), and placement of early warning detection sensors (e.g., Ostfeld and Salomons 2004). Genetic algorithms are applicable to a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the

54

objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear (Haestad 2003). Advantages of this method include the ability to (i) optimize discrete or continuous variables; (ii) search a wide area of the design space; and (iii) address a large number of variables without requiring objective function derivative information (Haestad 2003).

Briefly, the GA algorithm is initiated with a random population of individuals in which each individual is represented by a binary string (i.e., chromosome) for one possible solution. For each population generation, a measure of the fitness with respect to an objective function is calculated. Based on this fitness value, individuals are selected to create the next generation through the use of techniques such as inheritance, mutation (random changes to a single parent), natural selection (elite), and crossover (combines a pair of parents). Individuals with higher fitness values will possess a greater probability of being selected to produce the next generation; thus, on average, the new generation will possess a higher fitness value than the older population. The algorithm continues until one or more of the preestablished criteria (e.g., number of generations, time limit, fitness limit, stall generations, stall time limit, and fitness tolerance) are met. The optimization problem solved by the GA is the minimization of an objective function (Equation 4-1) subject to constraints (Equations 4-2 – 4-6). The nonlinear constraints are given by Equations 4-2 and 4-3, where $C(x)$ represents the nonlinear inequality and equality constraints, m is the number of inequality constraints, and mt is the total number of nonlinear constraints. The linear constraints are given by Equations 4-4 and 4-5, where A and A_{eq} are matrices of size number of linear equalities/inequalities by number of variables and b and b_{eq} are vectors of length of the number of linear

equalities/inequalities. The bounds of the variables are given by Equation 4-6, where *LB*

is the lower bound and *UB* is the upper bound of the variables.

$$\underset{x}{Minimize}\ f(x) \tag{4-1}$$

$$C_i(x) \le 0, i = 1...m \tag{4-2}$$

$$C_i(x) = 0, i = m+1...mt \tag{4-3}$$

$$Ax \le b \tag{4-4}$$

$$A_{eq}x \le b_{eq} \tag{4-5}$$

$$LB \le x \le UB \tag{4-6}$$

4.3 Applications

Two example networks previously optimized for sensor placement (Ostfeld and

Salomons 2004) were utilized as illustrated applications of this method. Application 1

represents a modified version of EPANET Example 1 (Rossman 2000), while

Application 2 represents a more complex network as depicted in Anytown U.S.A.

(Walski et al. 1987). The network of Application 1 consists of eight consumer nodes, one

source, a pumping station, an elevated storage tank, and 12 pipes (Figure 4-1). A

hydraulic and constituent time step of 30 minutes was used for a 24-hr simulation period.

For purposes of simulation, a conservative contaminant with concentration of 2.0 mg/L

was injected into Node 11 at minute 30 in the simulation. Following injection, the

simulation runs until a sensor detects a concentration greater than zero. The sensors were

located at the reservoir, and at Nodes 12, 21, and 32. In this injection scenario, the

sensors at Nodes 12 and 21 detected the contaminant at hour one with a concentration of 1.72 and 1.02 mg/L, respectively.
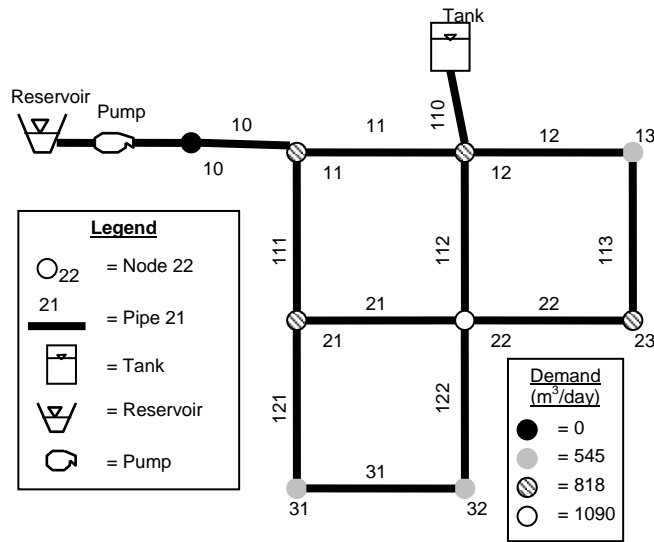
Figure 4-1. Schematic of Application 1, EPANET Example 1.

The Application 2 network consists of 16 consumer nodes, one well, a pumping station, two 1,136 m^3 capacity elevated storage tanks, and 34 pipes (Figure 4-2). The characteristics of the nodes, pumping station, tanks, and pipes represent those used in a previous application of Anytown (Walski et al. 1987). Again, a hydraulic and constituent time step of 30 minutes was used for a 24-hr simulation period. For this application, a conservative contaminant with concentration of 2.0 mg/L was injected thirty minutes into the simulation at Node 30. As noted in Ostfeld and Salomons (2004), four sensors were located at Nodes 70, 80, 90, and 160. The first two sensors to detect the contamination were Nodes 80 and 90 at hour three of the simulation, with contaminant concentrations of 0.023 mg/L and 0.012 mg/L, respectively. Following

detection, nodal demands and pipe closures were altered through use of GA in order to minimize system contamination until the end of the 24-hour simulation period.
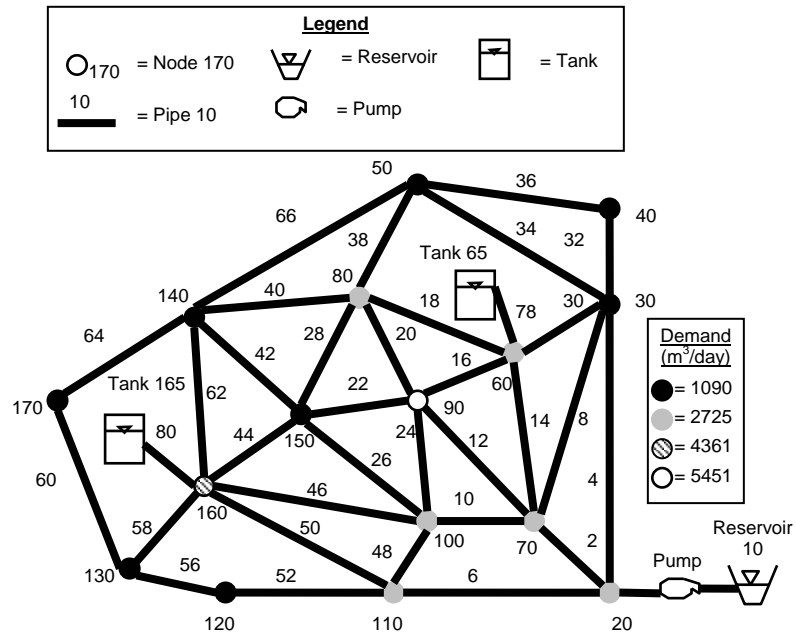
Figure 4-2. Schematic of Application 2, Anytown.

To begin a GA optimization, the fitness function and the number of variables must be identified. Since an equation that directly relates total network contamination concentration to nodal demands is not available, a response surface or a link to EPANET can be utilized. A response surface is created by evaluating the total concentration achieved through a variety of different demands, exhausting every possible solution, and then fitting a polynomial to all of the data. To obtain a better representation of the actual network, EPANET can be called to compute the objective function. Armed with this information, the GA can then determine the optimal response in order to reduce the total network contaminant concentration. For these applications, the fitness value is calculated

as the total contaminant concentration in all nodes from all times after the dectection (Equation 4-7) or from all times after response (Equation 4-8) until the end of the simulation, where i is the node number, j is time from time of detection, t_d, or time of response, t_r, until the end of the simulation, t_{end}.

$$TotalConcentration_{\det ection} = \sum_{\substack{i=1..N \\ j=t_d..t_{end}}} concentration_{i,j} \qquad (4\text{-}7)$$

$$TotalConcentration_{response} = \sum_{\substack{i=1..N \\ j=t_r..t_{end}}} concentration_{i,j} \qquad (4\text{-}8)$$

An initial population size of 20 was selected to ensure sufficient population diversification to enable search of the entire space of variables for the GA. The initial population had a lower bound based on the average base demand and an upper bound of 1000 for Application 1 and 1500 for Application 2. A generation size of 100 was used with a Gaussian mutation function, a scale and shrink parameter of one, a crossover fraction of 0.8, and an elite count of two. For this application, there are two elite, 14 crossover, and four mutation children in the next generation. The crossover children are determined by taking the population size minus the elite children, multiplying by the crossover fraction, and rounding to an even number. In addition to the GA requirements, constraints were employed to keep the solutions realistic. Here, linear constraints were set on the demands in order to avoid negative pressures in the network, while nonlinear constraints were used to maintain system connectivity. The flow path of the optimization methodology for these applications is given in Figure 4-3.
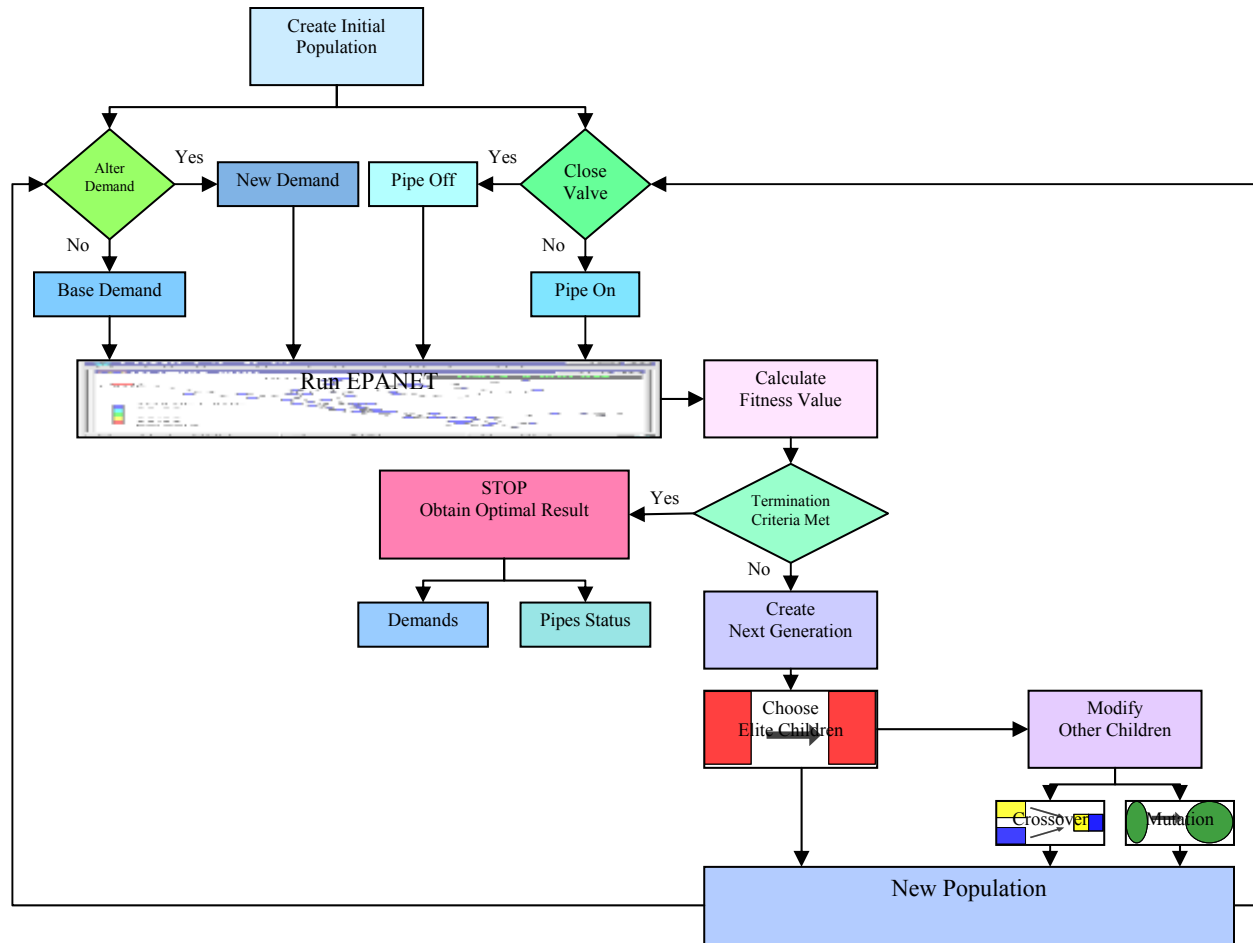
Figure 4-3. Optimization Flowchart.

60

4.4 Results and Discussion

Since consequence management strategies of a contamination event may include a variety of activities, different response scenarios were examined for each example network. Flushing (altering demand), valving (closing pipes), and combinations of flushing with valving were explored as possible response strategies. In addition to these scenarios, the response time to the contamination event was also investigated.

Application 1

For Application 1, the optimal solution was determined from each of the following response strategies: (i) Scenario 1: flushing using a response surface and EPANET for nodal pairs; (ii) Scenario 2: flushing for any combination of nodes; (iii) Scenario 3: valving for each pipe combination; (iv) Scenario 4: valving for any combination of pipes; (v) Scenario 5: valving with flushing for each pipe combination; and (vi) Scenario 6: flushing and valving for any combination of nodes and pipes. Starting in hour 2 of the simulation (an hour after sensor detection), the demands and valve positions were altered in order to reduce the total network contaminant concentration from 25.6 mg/L, which is the summation of the concentration in all nodes from one-hour after detection until the end of the 24-hr simulation. Appendices A-K include the MATLAB (MathWorks 2006) programming code for Application 1.

For Scenario 1, the GA evaluated 36 different combinations of nodal pairs to determine the greatest reduction in contaminant concentration of the entire network. Each combination of nodal pairs was examined using (i) a response surface or (ii) the actual network with EPANET serving as the objective function. Different combinations

of nodal demands produced a variety of reductions in the total network contamination concentration, while increasing the total network demand (Table 4-1). Examination of Table 4-1 (response surface objective function) suggests that the best solution for flushing the contaminant from the network with the smallest increase in network demand is provided through demand alteration at Nodes 11 and 31, which reduced the total contaminant concentration by 61.6% and increased the total network demand by 50%. However, the use of the EPANET-based objective function suggests that the combination of Nodes 11 and 32 provides the best solution, since it reduced the total network concentration by 71.5% while increasing the total network demand by approximately 59%. Altering the demands in Nodes 31 and 32 generally resulted in lowering the total network contaminant concentration. Thus, these nodes should be examined for possible corrective actions.

While flushing strategies may be limited to specific nodes which are flushable (as demonstrated above), a strategy where all nodes are flushable should also be investigated. In this scenario (Scenario 2), the GA determined which combination of nodes resulted in the greatest reduction of total network contaminant concentration. Altering the demand at Nodes 13 and 32 resulted in a 73.8% reduction of total network contamination concentration with a 68.2% increase of total network demand. This result is consistent with the results determined from the combination of nodal pairs (Table 4-1).

Since consequence management strategies are not limited to only flushing, valving alternatives were also explored. For Scenario 3, 104 combinations of pipe closures were examined to determine the optimal combination resulting in the greatest reduction of total network contaminant concentration. Closing Pipes 11, 112, and 121

resulted in an 81.5% reduction of total network contamination concentration (Figure 4-4). The greatest reduction in total network contamination concentration generally involved a combination of closing Pipes 11, 12, 21, 112, and 121. Thus, closure of these pipes should be examined for possible corrective actions. For Scenario 4 (valving for any combination of pipes), the GA determined the combination of pipes to close in order to minimize the total network concentration. By closing Pipes 11, 112, and 121, an 82.2% reduction of total network contamination concentration occurred. This result is consistent with the findings from Scenario 3, which helps verify that the GA is determining the optimal combination of pipe closures.
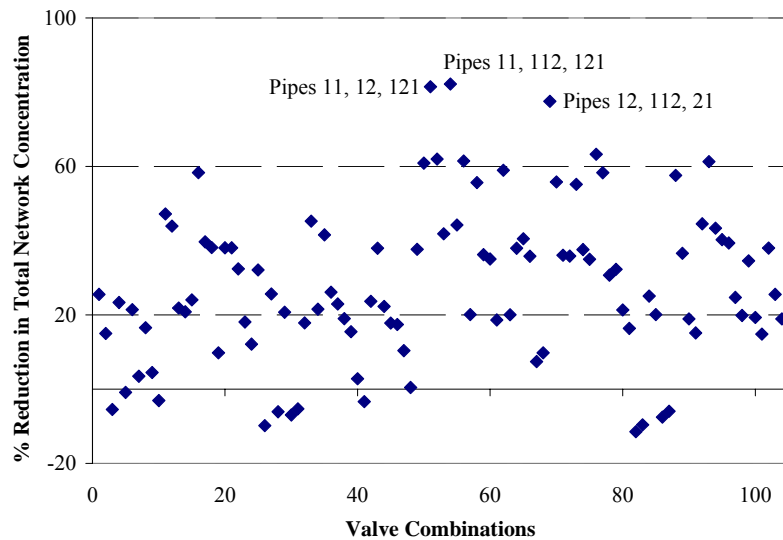
Figure 4-4. Percent Reduction in Concentration using Valve Combinations for Application 1.

Table 4-1. Nodal Pair Flushing Results for Application 1.

Nodal Pair	Node 1	Node 2	Response Surface – GA % Reduction Concentration	Response Surface – GA % Increase Demand	Response Surface - MINLP % Reduction Concentration	Response Surface - MINLP % Increase Demand	EPANET - GA % Reduction Concentration	EPANET - GA % Increase Demand
1	10	11	16.95	77.27	17.03	75.82	19.00	104.18
2	10	12	16.94	77.27	16.94	74.82	16.94	77.27
3	10	13	22.43	72.73	44.74	109.09	41.85	81.82
4	10	21	36.26	68.18	35.30	81.18	36.26	68.18
5	10	22	42.90	72.73	44.91	100.00	47.15	69.18
6	10	23	48.02	68.18	48.35	104.55	48.12	77.64
7	10	31	36.39	81.82	58.10	69.73	57.32	81.41
8	10	32	52.59	100.00	60.07	73.82	61.11	72.86
9	11	12	16.84	63.64	16.88	64.00	16.90	64.36
10	11	13	43.65	59.09	46.39	95.45	43.65	59.09
11	11	21	36.11	54.55	33.87	75.27	38.33	63.64
12	11	22	45.83	50.00	48.23	86.36	48.07	59.82
13	11	23	50.58	63.64	50.88	90.91	50.96	65.64
14	11	31	**61.64**	**50.00**	**63.04**	**67.36**	61.87	68.05
15	11	32	56.95	77.27	**62.51**	**63.45**	**71.49**	**59.18**
16	12	13	43.64	68.18	45.88	95.45	43.74	68.09
17	12	21	26.47	45.45	37.77	70.82	39.11	68.73
18	12	22	48.03	59.09	48.18	86.36	49.24	65.82
19	12	23	48.52	54.55	50.75	88.36	51.24	67.23
20	12	31	**62.04**	**68.18**	58.60	71.00	62.04	68.18
21	12	32	**61.00**	**95.45**	**62.52**	**66.91**	**71.06**	**67.36**
22	13	21	43.85	59.09	38.95	84.73	43.85	59.09
23	13	22	43.58	63.64	49.44	85.73	50.92	67.11
24	13	23	49.47	68.18	48.23	95.45	50.35	67.36
25	13	31	50.48	72.73	61.81	77.36	63.74	67.73
26	13	32	**66.82**	**100.00**	63.51	73.00	**74.07**	**73.00**
27	21	22	47.81	59.09	47.45	86.00	49.50	66.70
28	21	23	50.69	63.64	50.51	83.55	51.19	66.55
29	21	31	48.96	68.18	60.08	72.55	60.87	68.18
30	21	32	56.87	95.45	**64.49**	**69.82**	71.71	68.11
31	22	23	47.09	59.09	49.11	85.64	49.71	75.82
32	22	31	56.78	90.91	60.01	72.55	59.81	63.45
33	22	32	**65.03**	**81.82**	60.38	65.82	**72.14**	**65.82**
34	23	31	56.33	68.18	58.14	77.09	69.05	79.32
35	23	32	**63.82**	**95.45**	57.84	69.91	**71.66**	**68.18**
36	31	32	56.15	100.00	60.43	68.55	**67.62**	**63.64**

The majority of consequence management strategies involve a combination of flushing and valving, so this strategy was explored as part of Scenarios 5 and 6. The 104 pipe closure combinations along with the GA-determined nodal demands were examined

to obtain the greatest reduction of total network contaminant concentration. Closing Pipes 12 and 21 and alerting demand at Node 32 resulted in a 95% reduction of total network contamination concentration, but a 50% increase in total network demand (Figure 4-5). Since the pipe closure combination of Pipes 111, 22, 121 with altered nodal demands caused an increase in total network concentration; it was removed from Figure 4-5. Depending on the amount of disruption to the network in terms of flushing, different strategies should be examined. For example, if only a 20% increase in demand was available for flushing, then the alternative of closing Pipes 11, 112, and 121 and altering demands at Nodes 13 and 31 should be considered for an 86% reduction in concentration. For Scenario 6 (flushing and valving for any combination of nodes and pipes), the GA determined which demands to alter and pipes to close in order to minimize the total network contaminant concentration. Thus, the optimal consequence management strategy for Application 1 is closing Pipes 12 and 112 and altering the demand at Node 32 to produce a 95% decrease in network concentration with a 73% increase in total network demand.
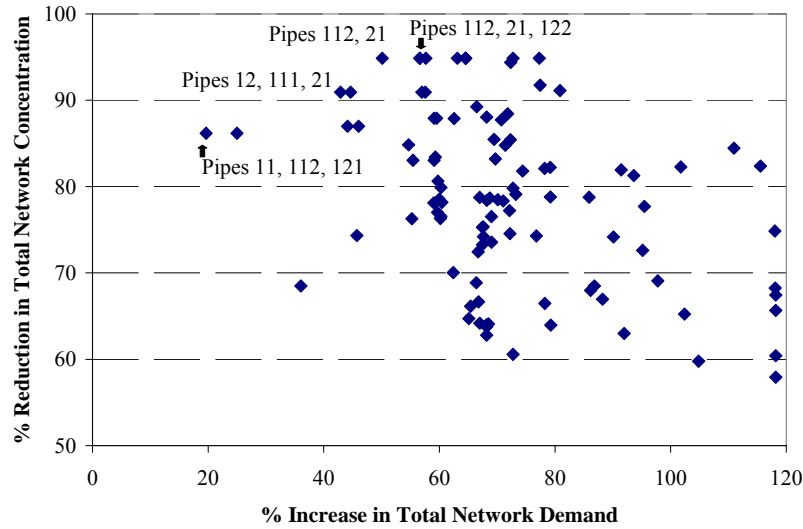
Figure 4-5. Valve Combinations with Flushing for Application 1.

Application 2

For Anytown, the optimal solution was determined from each of the following response strategies: (i) Scenario 1: flushing for each nodal pair; (ii) Scenario 2: flushing for any combination of nodes; (iii) Scenario 3: valving for any combination of pipes; and (iv) Scenario 4: flushing and valving for any combination of nodes and pipes. Starting at hour 4 of the simulation (an hour following sensor detection), demands and valves were altered in order to reduce the total network contaminant concentration from 4.83 mg/L (the summation of the concentration in all nodes from one-hour after detection until the end of the 24-hr simulation). Appendices L-X include the MATLAB (MathWorks 2006) programming code for Application 2.

For Scenario 1, the GA evaluated 120 different combinations of nodal pairs to determine which alternative resulted in a greater reduction in contaminant concentration of the entire network. The different combinations of optimal demand produced a variety of differences in the total network contamination concentration, while increasing the total

66

network demand (Figure 4-6). Examination of Figure 4-6 suggests that the best solution for flushing the contaminant out of the network with the smallest increase in network demand is the combination of Nodes 40 and 130, since the total contaminant concentration was reduced by 50.8% with only a total demand change of 14.4%. Altering the demands in Nodes 50 and 40 generally resulted in lowering the total network contaminant concentration, and thus should be examined for possible corrective actions. In Scenario 2 (where all nodes are flushable), altering the demand at Nodes 30, 50, 120, 140 or 150, and 170 resulted in a 25% decrease in network concentration, with a 15% increase in total network demand.
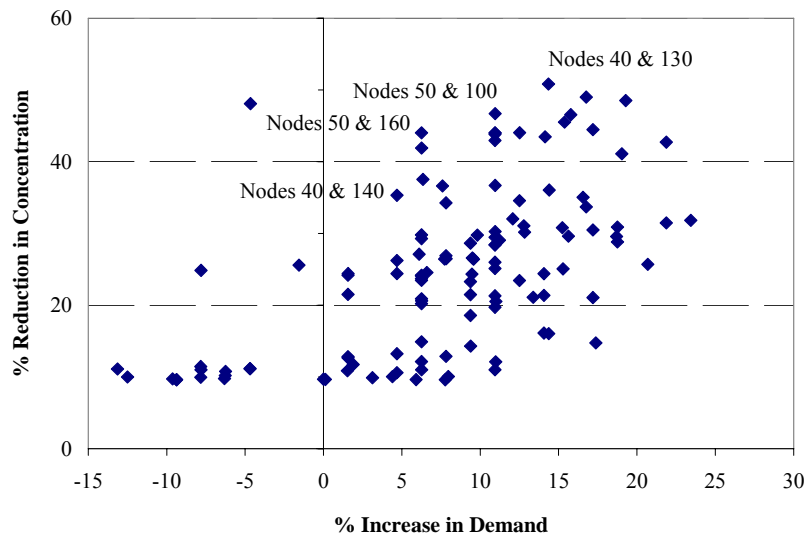
Figure 4-6. Nodal Combinations for Application 2.

For Scenario 3 (valving with any combination of pipes), 28% of the runs closed either Pipes 66 or 38, which produced a 31% or 24% reduction of total network contamination concentration, respectively. The greatest contaminant concentration reduction of 41% occurred when Pipes 22, 26, 38, and 66 were closed, but this situation

was selected in only 8% of the runs. Since Application 2 consists of 34 pipes and over 10^6 valve combinations, the scenario of valving for each pipe combination was not explored. In Scenario 4 (flushing and valving for any combination of nodes and pipes), the optimal consequence management strategy is altering the demand at Nodes 30, 50, 120, and 150, for a 12% increase in the total network demand, and closing Pipes 22, 26, 38, and 66 to produce a 54% decrease in network concentration.

4.5 Response Time Effects

When implementing any response strategy, time delays in the execution of remedial actions should be taken into account. Delay times can be attributed to confirmation of the contaminant in the network through multiple sensor triggers, identification of the contaminant in the system, location of the injection site, and operation of valve closures. Four different response times (2-hr, 4-hr, 8-hr, and 12-hr response delays) in addition to the original one hour delay were explored for the flushing and valving strategy. If a delay in the response time occurs, then the water utility may analyze the optimal operational response based on the contaminant concentration in the network at the time of detection or the concentration present in the network at the time of response. For example, the contaminant concentration in the entire network at time of detection is 25.6 mg/L, but after a four-hour response delay the concentration in the entire network is reduced to 12.4 mg/L through both consumption at nodes as well as system dilution. In order to investigate the relative impacts of response delay on overall system performance, the concentration to be minimized was explored at two different times: (i)

the contaminant concentration in the network at the time of detection; and (ii) the concentration present in the network at time of the response.

Application 1

Figure 4-7a displays the percent reduction in the total network contaminant concentration for a 1-hr, 2-hr, 4-hr, 8-hr, and 12-hr response delay for Application 1. As one would expect, delays in the response time results in smaller reductions in the total network concentration. Both curves exhibit an exponential relationship between the percent reduction and time delay. Each time scenario altered the demand at Node 32, which resulted in a 72% increase in the total network demand. Pipe 112 was closed for all of the time scenarios, whereas Pipe 12 was closed for each scenario, except the 4-hr delay for both concentration situations and the 8-hr delay for the detection concentration.

Application 2

The percent reduction in the total network contaminant concentration of each response time delay for Application 2 is shown in Figure 4-7b. In this case, an exponential function was observed between detection concentration and response delay, whereas a power function was observed for delay time concentration and response delay. The power function behavior was likely a result of the smaller delay time concentrations for the 2-hr, 4-hr, 8-hr, and 12-hr periods relative to the 1-hr delay concentration as illustrated in Figure 4-8. Each delay time scenario optimized solution resulted in the closure of Pipes 22, 26, 38, and 66, while alteration of demands at Nodes 30, 50, 120, and 150, resulted in a 12% increase in the total network demand.

(a)

(b)
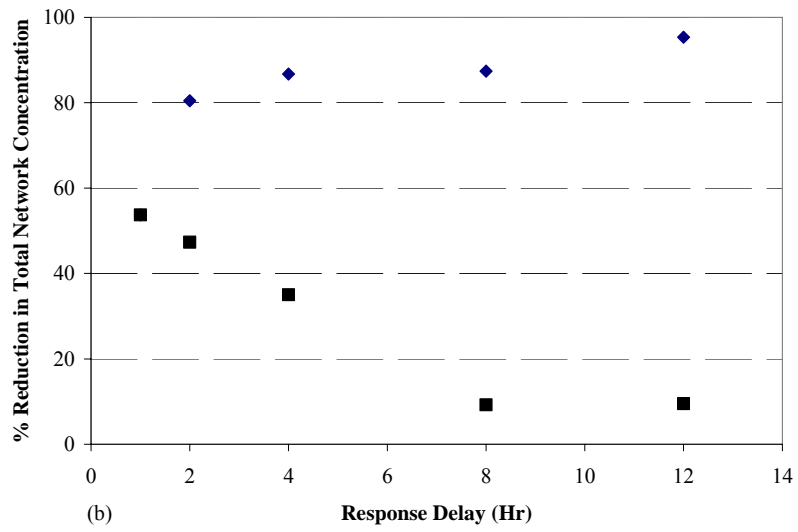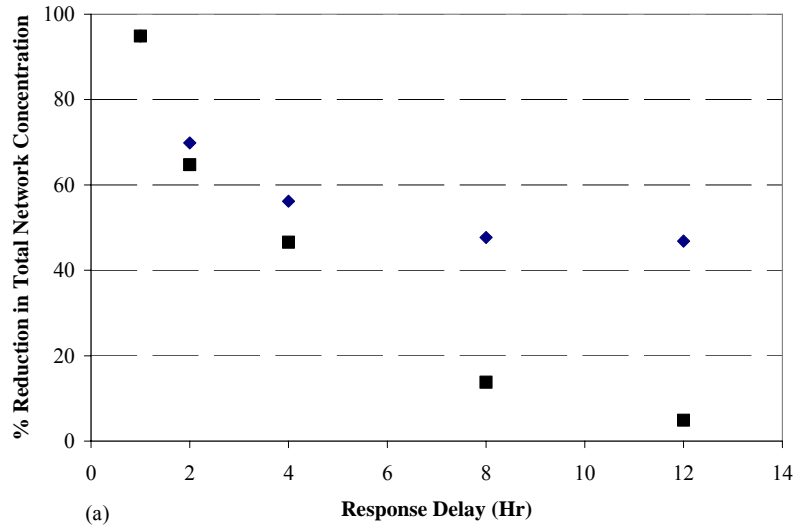
◆ Delay Time Concentration   ■ Detection Concentration

Figure 4-7. Percent Reduction in Concentration for Response Delays of (a) Application 1 and (b) Application 2.
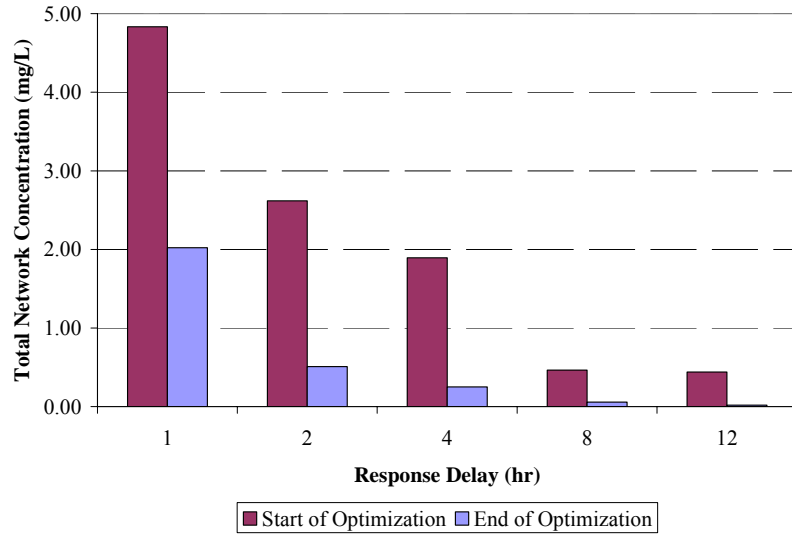
Figure 4-8. Total Concentration in Network at Response Time for Application 2.

4.6 Conclusion and Future Work

Given a scenario with optimal sensor placement, results from this research illustrate the usefulness of GA to provide an optimal solution to minimize the impact of further contamination to a water distribution network through nodal demand alterations and pipe closures. With this knowledge, a water distribution operator can identify valves to close and nodal demands to alter in order to minimize the spread of contamination and further assist in the eventual removal of the contaminant from the system.

Specific advantages of the GA method include the ability to search the entire design space and computation efficiency -- especially important for consequence management optimization in larger networks. Unfortunately, GAs are hampered by their inability to guarantee the identification of a global optimum solution. To help reduce the effects of local minimums, a number of steps may be taken. Since most optimization methods perform better when the initial population is near the optimum value, the GA was provided with an initial population created from results obtained through previous

71

runs. For instance, the nodal combinations and valve closures which created lower total concentrations were utilized to create the initial populations for subsequent simulations of both flushing and valving. Multiple simulations (minimum of 100) were also employed for each scenario to help reduce the effects of local minimums. In addition to these measures, the GA results derived from use of a response surface were compared to results obtained from a mixed-integer nonlinear programming (MINLP) method. Comparison of the results reported in Table 4-1 suggests that MINLP produced similar results to response surface-based solutions. (Since MINLP requires gradients of the objective function and constraints, it could not be applied to EPANET-based objective functions).

Future efforts in water distribution system consequence management optimization will incorporate weights for nodes of greater concern, such as those connected to hospitals or schools, which may be obtained from information management tools such as geographic information systems (GIS). Incorporation of GIS-based information will assist in highlighting societal and economic areas of concerns, including zoning regions to identify industrial, commercial, and residential areas. This information, combined with consumer consumption patterns, may enable faster response times for areas with the highest water consumption rates, especially when the water consumption is primarily linked to drinking water supplies (versus consumption for non-potable applications).

CHAPTER V

INCORPORATING SPATIAL INFORMATION FOR CONSEQUENCE MANAGEMENT

5.1 Introduction

In emergency response scenarios, simulation models can aid in the development of risk assessments and consequence management strategies. A variety of industries can benefit from the application of these models when determining consequences of an emergency as well as the effects of mitigation strategies. A few of the emergency response simulation models available for chemical release accidents include the Consequence Assessment Tool Set (CATS) developed by Science Applications International Corporation (SAIC) and SAFER Real-Time developed by SAFER Systems. CATS was used to predict the consequences associated with a natural or technological hazard (Kirkpatrick 2002), while SAFER was integrated with geographic information system (GIS) to display the immediate plume of a chemical release (Al-qurashi 2004). Other emergency response tools exist for coastal oil spills (i.e., General NOAA Oil Modeling Environment (GNOME) (NOAA 2004)), river spills (e.g., Spill Management Information System (SMIS) (Martin et al. 2004), Riverine Emergency Management Model (Parris 2002), RiverSpill (SAIC 2003)), and groundwater contamination (i.e., Hydrocarbon Spill Screening Model (HSSM) (U.S. EPA 1997)).

Recently, risk assessment simulation tools have been developed for water distribution utilities. Coupling system hydraulic models with water quality models can aid in the simulation of threat scenarios in order to assess the potential impacts of a

contamination event and develop consequence mitigation strategies (Uber et al. 2004).

Water distribution simulation tools, such as PipelineNet (Bahadur et al. 2003) and the

Threat Ensemble Vulnerability Assessment (TEVA) (Murray et al. 2004), have been

developed to aid the assessment of water distribution systems after a contamination

event. Consequence assessment, population exposure, risk assessment and transport of

contaminants through the incorporation of spatial information are some capabilities of

Science Applications International Corporation's (SAIC) PipelineNet. EPA's Threat

Ensemble Vulnerability Assessment (TEVA) program is able to measure public health

impacts, analyze water distribution system vulnerabilities, and evaluate consequence

mitigation strategies, such as sensor placement (Murray et al. 2004). Currently, both

tools are unable to evaluate planning and response actions, such as isolation and

containment, for the system following a contamination attack.

The U.S. EPA's Response Protocol Toolbox (U.S. EPA 2003) provides

recommendations of specific response actions to minimize the potential impact to the

public after a contamination threat to the network has been established. Detection, source

identification, and consequence management are the major steps in this protocol. To aid

in first step of the protocol for contamination events, recent research efforts have focused

on the placement of early warning detection systems within a water distribution network

(Kumar et al. 1997; Kessler et al. 1998; Ostfeld and Salomons 2004; Berry et al. 2006;

Propato 2006). Other researchers have established source identification methods (Laird

et al. 2006; Preis and Ostfeld 2006) to identify contaminant injection locations following

successful detection of a contamination event to address the second step of the protocol.

Finally, in the third step, consequence management, optimal operational responses to

remediate contaminated systems must then evaluate possible corrective actions. These consequence management strategies may include (i) isolation and containment of a contaminant through valve operations (U.S. EPA 2004a); (ii) public notification; (iii) demand locations and quantities to "flush" the system (U.S. EPA 2004b); and (iv) any combinations of valving, notification, and flushing.

To date, limited research has focused on the application of optimization techniques to consequence management strategies in response to contamination events. Baranowski and LeBoeuf (2006) previously explored this concept in order to determine the most favorable demand to minimize contaminant concentration within a network. In that work, gradient-based optimization techniques were employed to determine the optimal demand required to minimize total system contaminant concentration following detection. While results from that effort produced optimal solutions, employment of gradient-based methods led to computational inefficiencies, especially for larger water distribution systems. A methodology to place detection sensors and to isolate contaminated zones utilizing operational rules was recently developed (Poulin et al. 2006). While representing an important contribution, this work is limited to system detection and isolation by minimizing the time required for valve and hydrant operations, and it does not incorporate flushing as an operational response. In our recent work (Baranowski and LeBoeuf, *in review*), we applied a genetic algorithm to determine the optimal flushing and valving operations to reduce the total network contaminant concentration following sensor detection. In our current research effort, we examine additional operational constraints and incorporate spatial information to determine critical

75

customers. We begin our presentation with a brief description of the methodology employed, followed by illustration through example applications.

5.2 Methodology

The objective of this research is to minimize the impact of a contamination event on a water distribution network following successful detection and source identification while addressing additional constraints and critical customer concerns. EPANET (EPA 2002) was employed as the hydraulic/water-quality model, while a genetic algorithm (GA) (MathWorks 2006) was utilized to identify the operational response (system isolation and flushing) necessary to reduce the contaminant concentration after detection via optimally placed early warning detection sensors.

Genetic Algorithm (GA)

GA represents an optimization technique based on the principles of genetics and natural selection. Originally proposed by Holland (Holland 1975), and further developed by Goldberg (Goldberg 1989), GAs represent one of the most commonly employed optimization techniques for design of water distribution networks since they have been employed for sizing of pipes (e.g., Savic and Walters 1997; Wu and Simpson 2001), evaluation of system reliability (e.g., Tolson et al. 2004), and placement of early warning detection sensors (e.g., Ostfeld and Salomons 2004). Genetic algorithms are applicable to a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear (Haestad 2003). GA can be utilized to

identify the nodes at which to (i) alter the demand; (ii) the new demands for these nodes; and (iii) the location of pipe closures necessary to reduce the contaminant concentration during a contamination event in a water distribution network, since it is able to optimize discrete (valve is open or closed) or continuous variables (nodal demand). In addition, since a GA does not require a gradient, it can be linked with the hydraulic/water-quality model.

The optimization problem solved by the GA is the minimization of an objective function (Equation 5-1) subject to constraints (Equations 5-2 – 5-6). The nonlinear constraints are given by Equations 5-2 and 5-3, where $C(x)$ represents the nonlinear inequality and equality constraints, m is the number of inequality constraints, and mt is the total number of nonlinear constraints. The linear constraints are given by Equations 5-4 and 5-5, where A and A_{eq} are matrices of size number of linear equalities/inequalities by number of variables and b and b_{eq} are vectors of length of the number of linear equalities/inequalities. The bounds of the variables are given by Equation 5-6, where LB is the lower bound and UB is the upper bound of the variables.

$$\underset{x}{Minimize}\ f(x) \qquad (5\text{-}1)$$

$$C_i(x) \leq 0, i = 1...m \qquad (5\text{-}2)$$

$$C_i(x) = 0, i = m + 1...mt \qquad (5\text{-}3)$$

$$Ax \leq b \qquad (5\text{-}4)$$

$$A_{eq}x \leq b_{eq} \qquad (5\text{-}5)$$

$$LB \leq x \leq UB \qquad (5\text{-}6)$$

The GA algorithm begins with a initial population of 20 individuals in which each individual represents one possible solution. The variables for this application include the nodes at which to alter the demand, the new demands for these nodes, and the location of pipe closures (e.g., valving operations) necessary to reduce the contaminant concentration during an incident. Bounds were placed on the demand variables to ensure the delivery of the average base demand as well as maintaining positive pressures in the system. For this application, the fitness value is calculated as the total contaminant concentration in all nodes from all times after response (Equation 5-7) until the end of the simulation, where i is the node number, j is time from time of response, t_r, until the end of the simulation, t_{end}.

$$TotalConcentration = \sum_{\substack{i=1..N \\ j=t_r..t_{end}}} concentration_{i,j} \qquad (5\text{-}7)$$

A measure of the fitness with respect to the objective function is calculated for each population. Individuals are then selected, based on this fitness value, to create the next generation through the use of techniques such as natural selection (elite), mutation (random changes to a single parent), and crossover (combines a pair of parents). Individuals with higher fitness values have a greater probability of being selected to produce the next generation, so on average the new generation will possess a higher fitness value than the older population. Thus, for this application, the individuals which result in the lowest total network concentration are chosen to more frequently to reproduce the next population. The algorithm continues until one or more of the preestablished criteria (e.g., number of generations, time limit, fitness limit, stall

generations, stall time limit, and fitness tolerance) are met. In addition to the GA requirements, constraints were employed to keep the solutions realistic. Here, linear constraints were set on the demands in order to avoid negative pressures in the network, while nonlinear constraints were used to maintain system connectivity. For a more detailed explanation of the GA utilized, see our previous work (Baranowski and LeBoeuf, *in review*).

Geographic Information Systems (GIS)

Information technologies such as geographic information systems (GIS) are now commonly employed in water distribution system modeling as a means to link spatial information with distribution system elements, enabling geospatial locations of specific infrastructure features, including nodal demands and associated consumer information. For a water utility, GIS linked with a hydraulic model can be used for determining junctions that are contained within a certain land use zone, identifying customers within a certain distance of a specific node, and identifying customers impacted by a water-main break or contamination event (Haestad 2003).

Many risk assessment applications of GIS exist in the water supply industry. For example, GIS has been utilized to identify locations in the water distribution network that are sensitive to contaminant intrusions based on risk contours (Sadiq et al. 2006). In addition, microbial monitoring of drinking water and records of incidents and outbreaks were incorporated within GIS for a water utility in Germany (Kistemann et al. 2001). In summary, use of GIS will enable users to better identify areas that are most critical to

their mission. Further, it will aid in the quick and easy assessment of the population at risk should a contamination event occur.

Proper planning, evaluation, and execution of consequence management necessitate a need to evaluate potentially impacted areas. Given this existing link, GIS-based information may easily be employed to assist in the development of intelligent consequence management system, thus identifying populations at increased risk of exposure to contamination such as those in schools, hospitals, residential areas, or critical industries. Once areas of concern are identified, consequence management strategies may be employed to assist in minimizing risk.

Spatial information obtained from GIS can be utilized to develop consequence management strategies dependent on the operational responses available as well as the critical customers. For example, GIS-based information can assist in the determination of which nodal demands and valves to alter for a consequence management strategy. In addition, critical customers can be identified with GIS-based information, which can then be utilized as weights in the objective function. Critical customers generally need higher quality water, so in the event of a contamination event it is important to remove the contaminant from their water source quickly. Thus, placing weights on these critical customers will help aid in the reduction of the contaminant concentration at these nodes during the optimization of the operational response. For these applications, the previous objective function (Equation 5-7) is altered to include weights on the critical customers (Equation 5-8), where w is the weight associated with node i. The flow path of the optimization methodology with the incorporation of GIS information is given in Figure 5-1.

$$TotalConcentration = \sum_{\substack{i=1..N \\ j=t_r..t_{end}}} w_i * concentration_{i,j} \qquad (5\text{-}8)$$
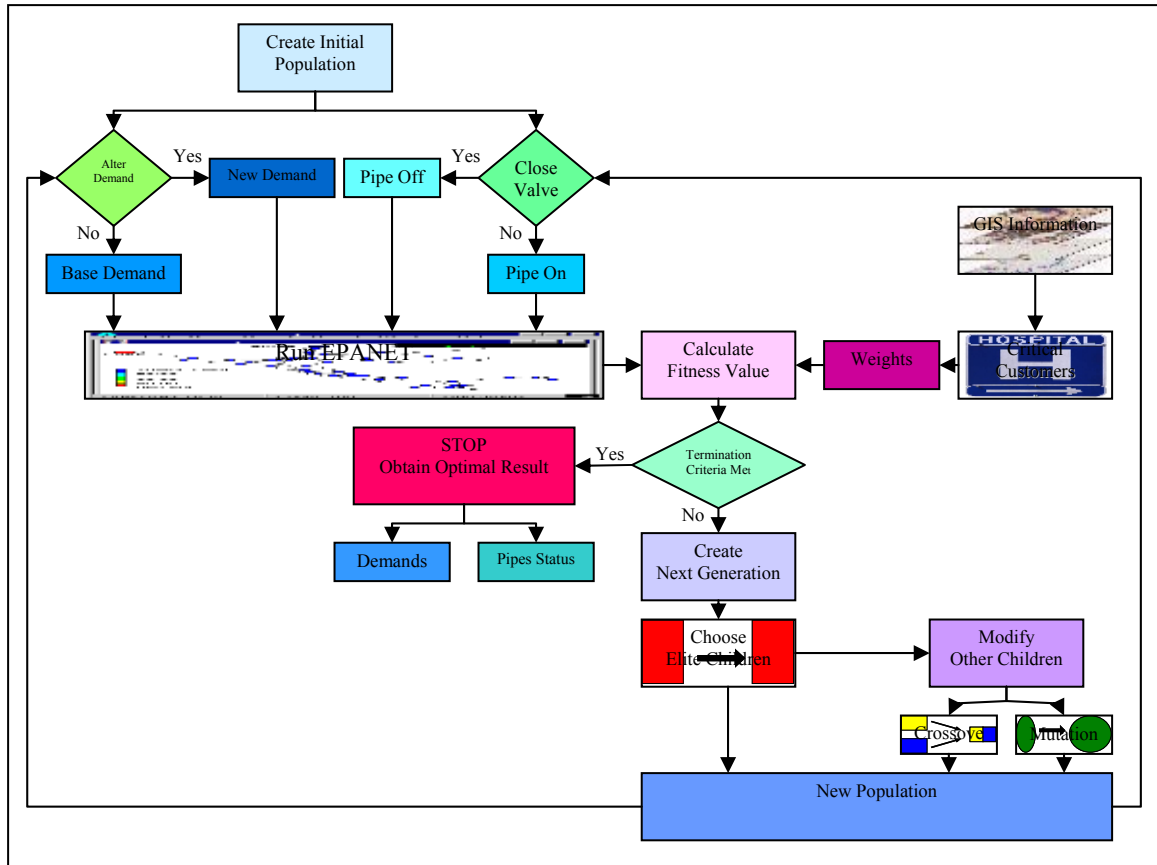
Figure 5-1. Incorporation of GIS Information in Optimization Procedure.

5.3 Applications

The two applications utilized in this work are derived from the two example networks previously optimized for sensor placement (Ostfeld and Salomons 2004). Application 1 represents a modified version of EPANET Example 1 (Rossman 2000), while Application 2 represents a more complex network as depicted in Anytown U.S.A. (Walski et al. 1987). The network of Application 1 consists of eight consumer nodes, one

source, a pumping station, an elevated storage tank, and 12 pipes (Figure 5-2). The Application 2 network consists of 16 consumer nodes, one well, a pumping station, two 1,136 m^3 capacity elevated storage tanks, and 34 pipes (Figure 5-3). The characteristics of the nodes, pumping station, tanks, and pipes represent those used in a previous application of Anytown (Walski et al. 1987).

A hydraulic and constituent time step of 30 minutes was used for a 24-hr simulation period. For purposes of simulation, a conservative contaminant with concentration of 2.0 mg/L was injected into Node 11 (Application 1) and Node 30 (Application 2) at minute 30 in the simulation. Following injection, the simulation runs until a sensor detects a concentration greater than zero. For Application 1, the sensors were located at the reservoir, and at Nodes 12, 21, and 32. As noted in Ostfeld and Salomons (2004), four sensors were located at Nodes 70, 80, 90, and 160 for Application 2. In the injection scenario for Application 1, the sensors at Nodes 12 and 21 detected the contaminant at hour one with a concentration of 1.72 and 1.02 mg/L, respectively. The first two sensors to detect the contamination for Application 2 were Nodes 80 and 90 at hour three of the simulation, with contaminant concentrations of 0.023 mg/L and 0.012 mg/L, respectively. Following detection, nodal demands and pipe closures were altered through use of GA in order to minimize system contamination until the end of the 24-hour simulation period.
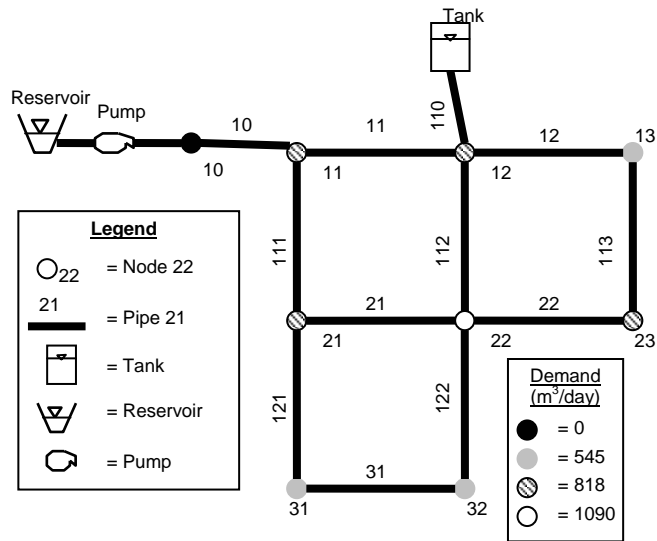
Figure 5-2. Schematic of Application 1, EPANET Example 1.
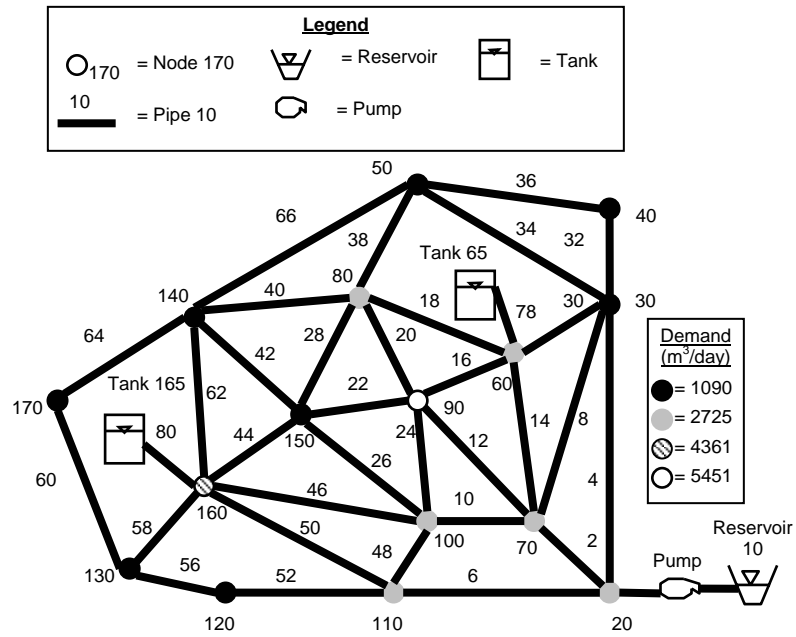
Figure 5-3. Schematic of Application 2, Anytown.

83

5.4 Results and Discussion

Consequence management strategies of a contamination event may include flushing (altering demand), valving (closing pipes), and combinations of flushing with valving. Since altering demand can affect the entire network and is associated with cost, constraints were placed on the percent increase in total network demand. In addition, weights were placed on critical customer to determine the effect on the network's optimal operational response.

Application 1

For Application 1, the optimal solution was determined for flushing and valving any combination of nodes and pipes. Starting in hour 2 of the simulation (an hour after sensor detection), the demands and valve positions were altered in order to reduce the total network contaminant concentration from 23.5 mg/L, which is the summation of the concentration in all nodes from hour 3 until the end of the 24-hr simulation. After the optimal solution was determined, the percent change in total network was constrained to less than the optimal value. The optimal consequence management scenario is altering the nodal demand at Node 32 and closing Pipes 12 and 112 for a reduction in total network contaminant concentration of 100% with a total increase of network demand of 72.7%. Thus, the percent increase in total network demand examined are 10%, 20%, 30%, 40%, 50%, 60%, and 70%. Figure 5-4 shows the comparison for these different scenarios. These alternatives allow the water utility to determine which optimal operational response is most cost-effective.
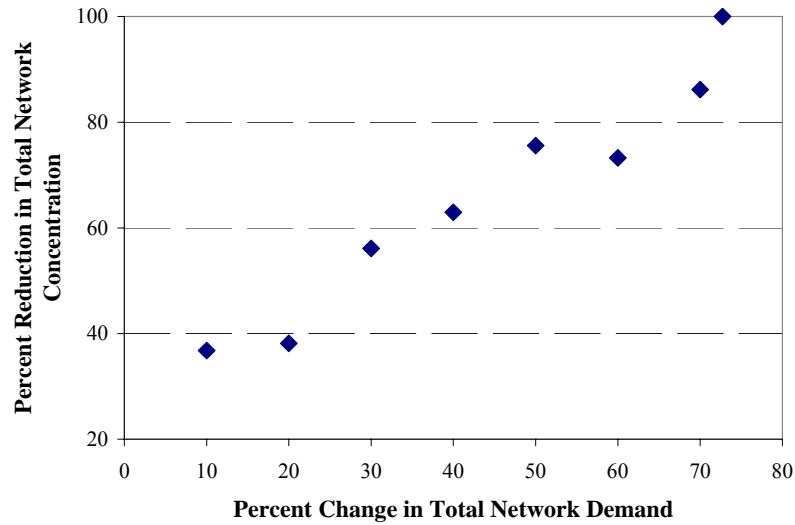
Figure 5-4. Comparison of Total Network Demand Constraints for Application 1.

The contaminant concentration in each of the nodes for the different demand constraints are given in Table 5-1. As the amount of total network demand is restricted, the contaminant concentrations in nodes increases, specifically Nodes 13, 22, and 32.

Table 5-1. Nodal Concentrations for Different Demand Constraints of Application 1.

	Contaminant Concentrations in Nodes (mg/L)									
Percent Increase in Total Network Demand	Node 10	Node 11	Node 12	Node 13	Node 21	Node 22	Node 23	Node 31	Node 32	Total Network Concentration
Original	0.00	0.35	0.60	4.65	0.24	4.68	4.70	3.61	4.64	23.46
Optimal - 72.73%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70%	0.00	0.00	0.00	0.19	0.00	1.26	0.94	0.00	0.85	3.24
60%	0.00	0.00	0.00	1.90	0.00	1.05	1.77	0.03	1.54	6.28
50%	0.00	0.15	0.21	0.71	0.10	1.52	1.21	0.21	1.64	5.73
40%	0.00	0.27	0.43	1.22	0.31	2.02	1.70	0.63	2.12	8.69
30%	0.00	0.35	0.49	1.56	0.39	2.25	1.85	0.99	2.43	10.30
20%	0.00	0.30	0.51	2.98	0.28	2.94	3.02	1.59	2.89	14.52
10%	0.00	0.43	0.57	2.48	0.39	2.81	2.47	2.48	3.21	14.83

Water utilities serve a variety of customers, including industrial, commercial, and residential consumers. Among these customers is a set of critical consumers, such as hospitals, nursing homes, and/or schools, who require high quality water at all times. As such, water utilities may provide special consideration to these critical customers when performing consequence management strategies. For example, in emergency situations, such as a contamination event, a water utility may desire to reduce the contaminant concentrations at these critical locations more quickly. In this regard, weights can be incorporated into the objective function to determine the optimal operational response for these critical consumers.

For Application 1, two separate critical customers were assigned to Node 13 and then to Node 23. To examine the effects of the weighting, the consequence management scenario did not alter the demand at Node 32, since alteration of the nodal demand at Node 32 always resulted in the lowest concentrations in all nodes of the network despite weights on critical customers. Two different consequence management strategies were examined for the weighting scenario. The first strategy allowed alteration of all demands except Node 32, while the second strategy did not allow Nodes 31 or 32 to change. Both strategies were constrained by a 70% increase in total network demand. The optimal operational response for the first strategy without weights for critical customers involved the alteration of nodal demands at Node 31 and closing Pipes 12 and 112, for a reduction in total network contaminant concentration of 84%, and total increase of network demand of 70%. The nodal concentrations which resulted from the first weighting strategy are listed in Table 5-2. When Node 13 represents a critical consumer, the nodal concentration at this node was reduced from 4.65 mg/L to 0.26 mg/L by altering the

demand at Node 31 and closing Pipe 112, which is less than the 1.29 mg/L concentration obtained in the non-weighting optimal operational response. When a critical consumer is associated with Node 23, the optimal response alters the demand at Node 31 and closes Pipes 11, 12, and 112 to reduce the contaminant concentration in Node 23 from 4.70 mg/L to 1.02 mg/L, which is slightly less than the non-weighting optimal operational response concentration of 1.10 mg/L. Even though the weighting criteria were able to reduce the concentrations in the critical nodes, the overall total network concentration was increased.

Table 5-2. First Strategy - Concentrations in Nodes After Weighting for Application 1.

	Contaminant Concentration (mg/L)									
Weight	Node 10	Node 11	Node 12	Node 13	Node 21	Node 22	Node 23	Node 31	Node 32	Total Network
Original	0.00	0.35	0.60	4.65	0.24	4.68	4.70	3.61	4.64	23.46
None	0.00	0.00	0.00	1.29	0.00	0.04	1.10	0.20	1.10	3.72
Node 13	0.00	0.00	0.00	**0.26**	0.00	2.16	0.97	0.46	2.21	6.06
Node 23	0.00	0.00	0.04	1.28	0.89	0.20	**1.02**	1.05	1.03	5.50

The second optimal strategy without critical customer weights, where demand at Nodes 31 or 32 are no longer variables, alters the nodal demand at Node 23 and closes Pipes 12 and 112 for a reduction in total network contaminant concentration of 86% with a total increase of network demand of 68%. The nodal concentrations for the second weighting strategy are listed in Table 5-3. When Node 13 is assigned a critical consumer, the optimal response involves altering the demand at Node 23 and closing Pipes 12, 112, and 31 to reduce the concentration in Node 13 from 4.65 mg/L to 0.0 mg/L, while the non-weighting optimal response only reduced the concentration to 0.35 mg/L. Once again, when the critical consumers are incorporated in the optimal operational response, the total concentration in the network increases. Thus, water utility operators must

balance the objectives of the water utility to achieve the most beneficial consequence management strategy, considering the impacts to both critical consumers and overall network effects.

Table 5-3. Second Strategy - Concentrations in Nodes After Weighting for Application 1.

	Contaminant Concentration (mg/L)									
Weight	Node 10	Node 11	Node 12	Node 13	Node 21	Node 22	Node 23	Node 31	Node 32	Total Network
Original	0.00	0.35	0.60	4.65	0.24	4.68	4.70	3.61	4.64	23.46
None	0.00	0.00	0.00	0.35	0.00	0.16	0.34	0.54	1.84	3.23
Node 13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.02	0.00	5.02
Node 23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.90	2.83	4.73

Application 2

For Anytown, starting at hour 4 of the simulation (an hour following sensor detection), demands and valves were altered in order to reduce the total network contaminant concentration from 2.17 mg/L (the summation of the concentration in all nodes from hour 5 until the end of the 24-hr simulation). The optimal consequence management strategy alters the nodal demand at Nodes 30, 50, 120, and 150 and closes Pipes 22, 26, 38, and 66 for a reduction in total network contaminant concentration of 93% with a total increase of network demand of 11.8%. Once again, constraints were placed on the percent increase in total network demand, which are 5%, 10% and 11%. Comparing the alternatives shown in Figure 5-4 will assist the water utility in determining which optimal operational response is most cost-effective. The contaminant concentration in each of the nodes for the demand constraints are given in Table 5-4.

Table 5-4. Nodal Concentrations for Different Demand Constraints of Application 2.

Contaminant Concentration (mg/L)

% Increase in Total Network Demand	Node 20	Node 30	Node 40	Node 50	Node 60	Node 70	Node 80	Node 90	Node 100	Node 110	Node 120	Node 130	Node 140	Node 150	Node 160	Node 170	Total Network
Original	0.00	0.00	0.00	0.05	0.00	0.00	0.64	0.29	0.00	0.00	0.00	0.00	1.19	0.00	0.00	0.00	2.17
Optimal - 11.8%	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15
11%	0.00	0.00	0.00	0.59	0.01	0.04	0.00	0.16	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83
10%	0.00	0.00	0.00	0.95	0.01	0.04	0.00	0.16	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18
5%	0.00	0.00	0.00	0.95	0.01	0.04	0.00	0.16	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.18
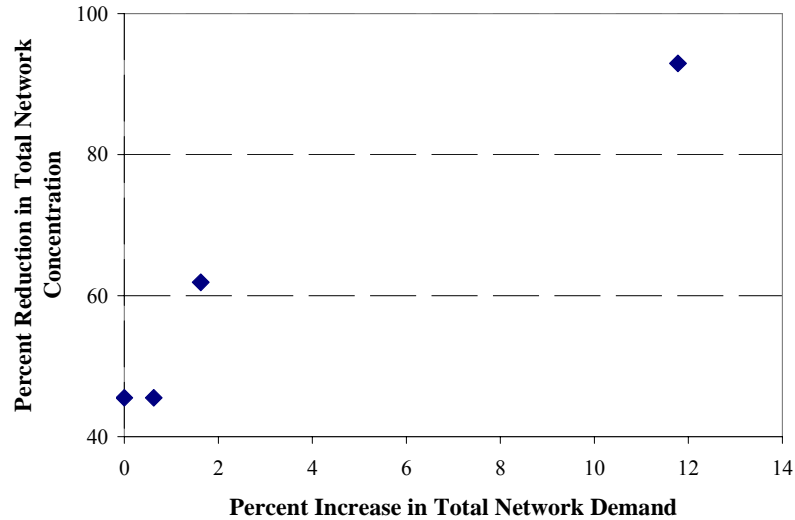
Figure 5-5. Comparison of Total Network Demand Constraints for Application 2.

5.5 Conclusion and Future Work

Results from this research illustrate the influence of weighting criteria in consequence management optimization in order to provide an optimal solution to minimize the impact of further contamination to a water distribution network through nodal demand alterations and pipe closures. With this knowledge, a water distribution operator can identify nodal demands to alter and valves to close in order to minimize the spread of contamination and further assist in the eventual removal of the contaminant from the system.

Additional constraints on the network demand were utilized in order to provide the water utility with alternatives of optimal operational responses based on cost concerns. GIS-based information provided the location of nodes of greater concern, such as those connected to hospitals or schools, which were weighted in the objective function in order to determine the optimal consequence management strategy for the water distribution system. Weighting may also be based on land use, nodal demand, or

population exposed. For land use, different weights can be assigned to industrial, commercial, and residential zones during a contamination event. For instance, the residential zone may be assigned a greater weight than a commercial zone, which may, in turn, possess a greater weight than an industrial zone. In addition, a system such as Oak Ridge National Laboratory's LandScan system (ORNL 2000) could be utilized to examine the influence of daily population dynamics on a contamination attack as well as consequence management strategies.

Future research efforts will include the use of GIS-based water hydraulic models, such as WaterGEMS (Bentley 2007) and H_2OMap Water (MWH Soft 2007), which will allow direct integration of GIS with consequence management strategies. With the incorporation of GIS, the water utility operator can interface with the Supervisory Control and Data Acquisition (SCADA) system and laboratory information system to aid in the development of consequence management strategies. Also GIS may also be useful in determining optimal vehicle routing and crew dispatch protocols when responding to contamination events.

Current research efforts include the application of these methods to a larger scale, more complex real-world network. In addition, current efforts are exploring a variety of different contamination events with respect to injection location, quantity, and type of contaminant to establish a 'playbook' of attack scenarios. This 'playbook' will aid the water utility in establishing base-case consequence management strategies to utilize during a real-time contamination event. The ability to accurately model the fate and transport of the contaminants within a network is an important consideration when analyzing consequence management strategies. Thus, hydraulic/water-quality models

that incorporate dispersion, such as those proposed by Axworthy and Karney (1996), Islam and Chaudhry (1998), and Tzatchkov et al. (2002), are needed in order to accurately model the fate and transport of chemicals. In addition, the injection of reactive contaminants must also be explored. The utilization of the new multi-species EPANET, which is expected to be released in early 2007, will produce more real-world injection scenarios, since it possesses the capability to model interactions between two chemical species. For example, MS-EPANET will enable evaluation of the interactions between a chemical contaminant and chlorine.

CHAPTER VI

CONCLUSIONS AND FUTURE RESEARCH NEEDS

6.1 Overview

This dissertation details the development of a consequence management system for water utilities, providing an optimal operational response to a contamination event in a water distribution network. In order to develop an effective emergency response plan, water utilities need to explore different operational response actions for the most optimal strategy. By coupling an optimization methodology with a hydraulic and water-quality model, an optimal consequence management strategy can be identified for a specific contamination event. To determine the most appropriate optimization technique to couple with a hydraulic and water-quality model, a variety of optimization methodologies were examined. The set of consequence management strategies produced from this research identified protocols to best isolate an event and manage response measures. The newly developed system was applied to examine system flushing and isolating as an optimal operational response. With the incorporation of GIS-based information, an optimal consequence management strategy could be altered to address the concerns of critical customers. The effects of cost-constraints on the optimal operational response were also examined. The consequence management tool will be useful to water utilities for both planning emergency response scenarios and responding to an emergency in real-time. With this knowledge, water utility managers will be better prepared to mitigate attacks against the system. Important findings of this research are summarized in the

following paragraphs. Recommendations for future work are addressed at the end of this chapter.

6.2 Summary

A variety of optimization methodologies and consequence management strategies were examined in this research.   Three common optimization methodologies were applied to the consequence management problem. Chapter III utilized Newton-Raphson and parameter estimation (PEST) as the optimization methodologies, while Chapters IV and V applied a genetic algorithm (GA) to the problem. The consequence management strategies explored included different combinations of flushing and valving. Chapter III analyzed nodal flushing for a node-by-node basis and the entire network.   The consequence management strategies investigated in Chapter IV included nodal flushing for the entire network and system isolation. After the optimal operational response was determined, additional constraints and weights based on GIS information were incorporated in order to examine the effects in Chapter V.

6.2.1 Consequence Management Utilizing Newton-Raphson and PEST

Though response actions have been defined for contamination events, no guidance or methodology existed. To address this lack of methodology, we applied common optimization techniques to illustrate the usefulness of optimization techniques for consequence management strategies. Newton-Raphson and parameter estimation (PEST) were applied to the consequence management problem. The objective was to reduce the contaminant concentration in the nodes after a contamination attack had been

identified by optimally placed early warning detection sensors. In order to reduce the concentration, nodal flushing for a node-by-node basis and the entire network were analyzed as the response action. Results from this portion of the research illustrate the usefulness of common optimization techniques to provide an optimal initial solution to minimize the impact of further contamination to a water distribution network through changes in demand at target nodes.

6.2.2 Consequence Management Utilizing GA

Even though the previous methods provided optimal solutions, they did not represent the most efficient methodology since they required the computation of the gradient. In addition, only nodal flushing was addressed as the consequence management strategy. To address the computational inefficiencies of the previous optimization techniques, a non-gradient optimization technique, genetic algorithm (GA), was utilized. The hydraulic and water quality model (e.g., EPANET (U.S. EPA 2002)) was linked directly with the GA to determine the optimal flushing and valving operations to reduce the total network contaminant concentration following sensor detection..

Different consequence management strategies were examined for the optimal operational response. Flushing (altering demand), valving (closing pipes), and combinations of flushing with valving were explored as possible response strategies. Thus, the GA identified the nodes at which to (i) alter the demand; (ii) the new demands for these nodes; and (iii) the location of pipe closures (e.g., valving operations) necessary to reduce the contaminant concentration during an incident. The objective function for the GA minimized the total network concentration in all nodes for all time periods after

detection until the end of the 24-hr simulation. In addition to determining the optimal operational response, effects of response time to the contamination event were also investigated. Results for this portion of the research illustrate the usefulness of a GA in providing the optimal consequence management strategy for two example networks. Thus, with this knowledge, a water distribution operator can identify nodal demands to alter and valves to close in order to minimize the spread of contamination and further assist in the eventual removal of the contaminant from the system. Also, the delay in response time demonstrated the importance of initiating optimal operational responses measures as quickly as possible after detection.

6.2.3 Incorporation of GIS-based Information

Since proper planning, evaluation, and execution of consequence management strategies are necessary to evaluate potentially impacted areas, GIS-based information was incorporated to assist in the identification of populations at increased risk of exposure to contamination such as those in schools, hospitals, residential areas, or critical industries. Critical customers were identified based on GIS information in order to incorporate weights for these critical customers in the objective function. These weights aided in the reduction of the contaminant concentration at these nodes during the optimization of the operational response. Spatial information obtained from GIS was also utilized to develop consequence management strategies dependent on the operational responses. This information defined the availability of nodal demands and valves for a consequence management strategy. In addition, the increase in total network demand was constrained in order to provide the water distribution operator with alternative

consequence management strategies based on cost. Results for this portion of the research illustrate the incorporation of spatial information into consequence management strategies.

6.3 Recommendations for Future Work

The purpose of this research was to illustrate the usefulness of applying state-of-the-art optimization techniques in consequence management strategies. Since the scenarios and applications utilized in this work were applied to demonstrate proof-of-concept, many different scenarios could be explored in future work efforts. Only one injection scenario was examined in this research, so exploration of different injection locations and amounts would aid a water utility in creating a 'playbook' of attack scenarios with optimal operational responses. In addition, the ability to accurately model the fate and transport of contaminants within a network also represents an important research need for consequence management strategies. Fortunately, a variety of water-quality models are available to assist in this effort.

Early water quality models for water distribution systems only considered steady-state simulations, whereas present models provide for steady- and nonsteady-state analysis. For example, Rossman and Boulos (1996) compared different types of dynamic water quality models where transport is described by the classical one-dimensional advection equation. Currently available dynamic hydraulic simulation software, such as EPANET, model fate and transport of contaminants through advection only. Though advection dominates contaminant transport throughout the majority of components within a water distribution system, dispersion may contribute significantly to contaminant

transport in specific areas, such as low flow or dead-end pipes. For example, Tzatchkov et al. (2002) has shown that 25% of a network may be composed of dead-end pipes and that these pipes tend to service a high percentage of residential consumers. Methods that incorporate dispersion, such as those proposed by Axworthy and Karney (1996), Islam and Chaudhry (1998), and Tzatchkov et al. (2002), are needed in order to accurately model the fate and transport of chemicals. Fate and transport models that incorporate dispersion will aid in determination of which nodes are the most vulnerable to contamination events, since these nodes will most likely represent low flow or dead-end zones. Additional injection scenarios with reactive contaminants need to be explored to evaluate consequence management strategies. The new multi-species EPANET (MS-EPANET), which is expected to be released in early 2007, could be utilized to model the interaction between two contaminants or a contaminant and chlorine in order to produce more real-world injection scenarios. Thus, more realistic attack scenarios will generate more realistic consequence management strategies.

The use of GIS-water hydraulic models, such as WaterGEMS (Bentley 2007) and H_2OMap Water (MWH Soft 2007), will allow direct integration of GIS with other consequence management components. Since a water utility's hydraulic/water quality model may be skeletonized, the incorporation of GIS will enable improved identification of customers who have been aggregated into one nodal demand. A GIS database will also aid in the estimation of the nodal demand, since demand can be categorized by land use, type and number of dwellings, meter routes, and individual meter billing records (Mays 2000). With the incorporation of GIS, the water utility operator can interface with the Supervisory Control and Data Acquisition (SCADA) system and laboratory

information system to aid in the development of consequence management strategies. Also, GIS will be useful in determining vehicle routing and crew dispatch when responding to contamination events. For example, Poulin et al. (2006) utilized the travel time of responding crews to optimize the operational response to a contaminant event. Thus, the inclusion of travel route information through GIS can provide more realistic estimates for travel and response times, enabling the evaluation of more realistic consequence management scenarios for water utilities. In addition, a system such as Oak Ridge National Laboratory's LandScan system (ORNL 2000) could be incorporated to examine the influence of daily population dynamics on the contamination attack as well as consequence management strategies.

An important next step is the application of this methodology to a real-world network, since the networks analyzed in this research represent relatively simple networks. For water distribution systems larger than 10,000 links, the computational requirements for the implementation of this methodology may be great. However, larger networks of 10,000 links or more can generally be broken down into smaller regions or pressure zones. With the utilization of pressure zones during a contamination event, a water utility will be able to isolate a specific region to examine for consequence management strategies. In addition, the exploration of different contamination events in regards to contaminants, locations, and quantity will allow a water utility to establish a 'playbook' of attack scenarios. Further more, the water utility can examine consequence management strategies with regards to the maximum contaminant level (MCL) of different contaminants. Incorporation of MCLs in the consequence management strategies will aid the water utility in deciding the most appropriate operational response

based on specific contaminants of concern. Therefore, this 'playbook' of optimal operational responses may be utilized as a planning tool for water utilities, which can later be implemented real-time during actual contamination events.

The ability of the planning tool to be applied to non-terrorist type events will also make the methodology appealing to water utilities. Water quality represents a continual concern of water utilities with respect to disinfectant residual and age of the water in the network. Of importance to water utility is the water quality in their storage facilities (i.e., reservoirs and storage tanks). Chemical, microbiological, and physical represent the three main water quality categories of concerns at a storage facility. The major chemical concerns include the loss of disinfectant residual, formation of disinfectant by-products, development of taste and odor, increase in pH, corrosion, buildup of iron and manganese, and occurrence of hydrogen sulfide, while bacterial regrowth, nitrification, and worms/insects are the key microbiological concerns (Mays 2000). Therefore, the inclusion of storage tanks in the consequence management strategies will aid the water utility in the development of optimal operational responses to address these daily concerns. For example, a consequence management strategy could be applied to help flush stagnant water or water with high concentration of disinfectant byproducts from a storage tank out of the network. In addition to exploration of non-terrorist scenarios, the incorporation of a graphical user interface (GUI) would be necessary in order to make the methodology more beneficial to the water utility industry.

APPENDIX A

GENETIC ALGORITHM (GA) CODE FOR EPANET EXAMPLE 1 FLUSHING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Options for GA: initial population, initial population range
%StallGenLimit and StallTimeLimit are stopping criteria set to 100
%which means the optimization is stopped for StallGenLimit if the
%weighted average change in the fitness function value over Stall
%generations (100 for this application) is less than Function tolerance
%which means the optimization is stopped for StallTimeLimit if there
%is no improvement in the best fitness value for an interval of time
%in seconds specified by Stall time (100 for this application)
options = gaoptimset('InitialPopulation', [0 0 1 150 0 150 0 100 0 150 0 200 0 150 1 100
0 100; 1 500 1 500 0 200 0 200 0 150 0 250 0 150 0 175 0 125; 0 100 1 300 0 200 0 125
0 200 1 300 0 175 0 100 0 120; 0 100 0 150 0 200 0 100 1 800 0 200 0 200 0 100 1 150;
1 150 0 200 0 150 1 210 1 250 1 500 0 175 1 300 0 100; 0 200 0 160 0 200 1 300 1 500 0
200 0 200 0 150 1 400; 0 150 0 150 1 500 1 300 0 150 0 200 1 250 1 800 0 100; 1 200 0
200 0 200 1 200 1 250 0 210 1 260 1 300 0 100; 0 0 1 250 1 300 1 200 0 150 0 250 1 300
1 200 1 800; 1 300 0 200 0 150 0 100 1 300 0 200 0 150 1 200 1 600; 0 100 0 150 0 200
0 150 0 200 0 200 0 150 0 150 1 900; 0 10 0 150 0 200 0 125 1 400 0 200 0 150 0 100 1
500; 1 100 0 150 0 150 0 100 0 200 1 500 0 150 0 100 0 100; 1 120 1 400 0 150 0 100 0
150 0 200 0 175 1 800 0 100; 1 100 1 800 0 155 1 175 0 200 0 200 0 200 1 400 0 100; 0
125 1 600 0 150 0 100 0 150 0 200 0 150 1 550 0 100; 0 100 1 300 0 150 1 200 0 175 0
225 0 160 0 150 1 500; 0 0 1 600 0 150 0 125 0 150 0 200 0 150  1 450 0 125; 1 200 0
200 0 150 0 125 0 200 0 225 0 150 0 125 1 600; 0 0 1 500 0 200 0 150 0 175 0 225 0 200
1 600 1 200], 'PopInitRange', [0 0 0 150 0 150 0 100 0 150 0 200 0 150 0 100 0 100; 1
900 1 900 1 900 1 900 1 900 1 900 1 900 1 900 1 900 ], 'StallGenLimit', 100,
'StallTimeLimit', 100);

%Lower and upper bounds on demand variables
%For decision variables whether to alter demand lower bound is 0 and
%upper bound is 1, the new demand has a lower bound of the base average demand
%and an upper bound of 1000 gallons per minute (gpm)
LB = [0; 0; 0; 150; 0; 150; 0; 100; 0; 150; 0; 200; 0; 150; 0; 100; 0; 100];
UB = [1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000];

%Linear constraint d1+d2+d3+d4+d5+d6+d7+d8+d9<=2300
%Helps ensure that the total demand in the network does not cause negative
%pressures in the network
A = [0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1];
b = 2300;

%GA optimization call is in this form
%[x,fval] = ga(fitnessfcn,nvars,A,b,Aeq,beq,LB,UB,nonlcon,options)
%The output from the optimization will be the dem (the decision variables)
%and the fval, fitness function value, (the total concentration)
%The GA calls the file with the function to be minimized
%flushdec in is this case
%There are 18 variables, the inequality linear constraint information
```

%is contained in A and b, there are no equality linear constraint so [], the
%lower and upper bounds of the decision variables are given in LB and UB,
%there are no nonlinear constraints so []
%and the options file information is given by the variable options
%defined above
[dem,fval] = ga(flushdec,18,A,b,[],[],LB,UB,[],options);

%Writes decision variables and fitness function value to Excel file
% xlswrite('ExcelFileName',[dem,fval],'TabName', 'Cell')
%For example, the ExcelFileName is GAFlushResults,
%the TabName is Results, and the Cell is C3
xlswrite('GAFlushResults',[dem,fval],'Results', 'C3')

APPENDIX B

**FITNESS FUNCTION CODE FOR EPANET EXAMPLE 1 FLUSHING
RESPONSE**

```matlab
%MATLAB programming code version R2006a
%Creates the fitness function, where the
%output variable being minimized is concTot and
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the nodes at which to alter the demand; the new demands
%for these nodes;
function concTot = flushdec(dem)

%Process to determine if the nodal demand is going to change
%and the value of the nodal demand to utilize in the input file
%For example, if decision variable dem(1) is less than or equal to 0.5
%then the nodal demand will not be altered and the average base demand
%of 0 gallons per minute (gpm) will be used, otherwise the nodal
%demand will be altered and the value determined in decision
%variable dem(2) will be used in the input file

if dem(1)<=0.5
    %Demand at Node 10
    %Base demand for Node 10
    d1=0;
else
    %New demand for Node 10
    d1=dem(2);
end
if dem(3)<=0.5
    %Demand at Node 11
    %Base demand for Node 11
    d2=150;
else
    %New demand for Node 11
    d2=dem(4);
end
if dem(5)<=0.5
    %Demand at Node 12
    %Base demand for Node 12
    d3=150;
else
    %New demand for Node 12
    d3=dem(6);
end
if dem(7)<=0.5
    %Demand at Node 13
    %Base demand for Node 13
    d4=100;
else
```

```matlab
    %New demand for Node 13
    d4=dem(8);
end
if dem(9)<=0.5
    %Demand at Node 21
    %Base demand for Node 21
    d5=150;
else
    %New demand for Node 21
    d5=dem(10);
end
if dem(11)<=0.5
    %Demand at Node 22
    %Base demand for Node 22
    d6=200;
else
    %New demand for Node 22
    d6=dem(12);
end
if dem(13)<=0.5
    %Demand at Node 23
    %Base demand for Node 23
    d7=150;
else
    %New demand for Node 23
    d7=dem(14);
end
if dem(15)<=0.5
    %Demand at Node 31
    %Base demand for Node 31
    d8=100;
else
    %New demand for Node 31
    d8=dem(16);
end
if dem(17)<=0.5
    %Demand at Node 32
    %Base demand for Node 32
    d9=100;
else
    %New demand for Node 32
    d9=dem(18);
end

%Command to open the file that is going to be changed
fid = fopen('Base1.inp', 'wt');
```

%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f are replaced with the demand values and the pipe status
fprintf(fid, '\n[TITLE]\nEPANET Example Network
1\n\n[JUNCTIONS]\n;ID\tElev\tDemand\tPattern\n10\t710\t1\t3;\n11\t710\t1\t4;\n12\t70
0\t1\t5;\n13\t695\t1\t6;\n21\t700\t1\t7;\n22\t695\t1\t8;\n23\t690\t1\t9;\n31\t700\t1\t10;\n3
2\t710\t1\t11;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n9\t800;\n\n[TANKS]\n;ID\tElev
ation\tInitLevel\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n2\t850\t120\t100\t
150\t50.5\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughness\tMinorLos
s\tStatus\n10\t10\t11\t10530\t18\t100\t0\tOpen;\n11\t11\t12\t5280\t14\t100\t0\tOpen;\n12
\t12\t13\t5280\t10\t100\t0\tOpen;\n21\t21\t22\t5280\t10\t100\t0\tOpen;\n22\t22\t23\t5280
\t12\t100\t0\tOpen;\n31\t31\t32\t5280\t6\t100\t0\tOpen;\n110\t2\t12\t200\t18\t100\t0\tOp
en;\n111\t11\t21\t5280\t10\t100\t0\tOpen;\n112\t12\t22\t5280\t12\t100\t0\tOpen;\n113\t1
3\t23\t5280\t8\t100\t0\tOpen;\n121\t21\t31\t5280\t8\t100\t0\tOpen;\n122\t22\t32\t5280\t6
\t100\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n9\t9\t10\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\n
1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t
0\t0\n1\t0\t0\t0\t0\t0\t0\n;Demand
Change\n3\t0\t0\t0\t0\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%1
2.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t150\t150\t150\t1
50\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t150\t150\t150\t150\t%12.7f\t%12.
7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t100\t100\t100\t100\t%12.7f\t%12.7f\n6\t%12.7f\t%
12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%1
2.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n7\t150\t150\t150\t150\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t2
00\t200\t200\t200\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7
f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f

\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t150\t150\t150\t150\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t100\t100\t100\t100\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t100\t100\t100\t100\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t1500\t250\n\n[CONTROLS]\nLINK 9 OPEN IF NODE 2 BELOW 110\nLINK 9 CLOSED IF NODE 2 ABOVE 140\n\n[ENERGY]\nGlobal Efficiency\t75\nGlobal Price\t0\nDemand Charge\t0\n\n[QUALITY]\n;Node\tInitQual\n10\t0\n11\t0\n12\t0\n13\t0\n21\t0\n22\t0\n23\t0\n31\t0\n32\t0\n9\t0\n2\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n11\tFLOWPACED\t2\t1\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0\nRoughness Correlation\t0\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nMessages\tNo\nPage\t0\nNodes\t10 11 12 13 21 22 23 31 32;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1\nViscosity\t1\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d

```matlab
9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,
d9,d9,d9,d9,d9,d9,d9,d9,d9,d9);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Code to read the output file created from EPANET
%Establishes the variables: i is the starting row in the matrix
%l is the starting line to read in the output file
i = 1;
l = 81;
%This establishes the amount of times that the output file must be read
%n begins with the time that response occurs and ends with the end
%of the 24-hr simulation, n changes value in increments of 30
%For this simulation, n begins reading the output file at 3-hr
%(180 minutes) and changes by 30 minutes until the end of the 24-hr
%(1440 minutes)
for n = 180:30:1440
    %k is the number of nodes
    for k = 1:9
        %Establishes a variable conc which reads the output file for
        %the concentration in each node
        conc=textread('Base.rpt','%*f%f',1,'headerlines',l,'endofline','\r\n');
        conct(i)=conc;
        %Increases the i to the next row of the matrix
        i = i + 1;
        %Increases the text line to the next line to read
        l = l + 1;
    end
    %Increases text line to skip header information
    l = l + 7;
end
%Calculates the total concentration in all nodes for all times
concTot = sum(conct);
```

APPENDIX C

**EPANET INPUT FILE CREATED BY METHODOLOGY FOR EPANET
EXAMPLE 1 FLUSHING RESPONSE**

;EPANET input file created by optimization methodology
[TITLE]
EPANET Example Network 1

[JUNCTIONS]
;ID	Elev	Demand	Pattern
10	710	1	3;
11	710	1	4;
12	700	1	5;
13	695	1	6;
21	700	1	7;
22	695	1	8;
23	690	1	9;
31	700	1	10;
32	710	1	11;

[RESERVOIRS]
;ID	Head	Pattern
9	800;	

[TANKS]
;ID	Elevation	InitLevel	MinLevel	MaxLevel	Diameter	MinVol	VolCurve
2	850	120	100	150	50.5	0;	

[PIPES]
;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status
10	10	11	10530	18	100	0	Open;
11	11	12	5280	14	100	0	Open;
12	12	13	5280	10	100	0	Open;
21	21	22	5280	10	100	0	Open;
22	22	23	5280	12	100	0	Open;
31	31	32	5280	6	100	0	Open;
110	2	12	200	18	100	0	Open;
111	11	21	5280	10	100	0	Open;
112	12	22	5280	12	100	0	Open;
113	13	23	5280	8	100	0	Open;
121	21	31	5280	8	100	0	Open;
122	22	32	5280	6	100	0	Open;

[PUMPS]
;ID	Node1	Node2	Parameters
9	9	10	HEAD 1;

[PATTERNS]
;ID   Multipliers
;Injection Pattern

1	1	1	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0

;Demand Change
;Demand variables are placed in the %12.7f spots

3	0	0	0	0	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	150	150	150	150	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	150	150	150	150	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	100	100	100	100	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	150	150	150	150	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	200	200	200	200	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	150	150	150	150	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	100	100	100	100	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	100	100	100	100	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

[CURVES]
;ID   X-Value   Y-Value
;PUMP: Pump Curve for Pump 9
1   1500   250

[CONTROLS]
;Control for the closure of link 9 if the pressure at node 2 is above 140 psi,
;or open if below 110 psi
LINK 9 OPEN IF NODE 2 BELOW 110

LINK 9 CLOSED IF NODE 2 ABOVE 140

[ENERGY]
Global Efficiency   75
Global Price   0
Demand Charge   0

[QUALITY]
;Node InitQual
10   0
11   0
12   0
13   0
21   0
22   0
23   0
31   0
32   0
9   0
2   0

[SOURCES]
;Node Type   Quality (mg/L)   Pattern
11   FLOWPACED   2   1

[REACTIONS]
Order Bulk   0
Order Tank   0
Order Wall   0
Global Bulk   0
Global Wall   0
Limiting Potential   0
Roughness Correlation 0

[TIMES]
Duration   24:00:00
Hydraulic Timestep   0:30
Quality Timestep   0:30
Pattern Timestep   0:30
Pattern Start   0:00
Report Timestep   0:30
Report Start   0:00
Start ClockTime   12:00 AM
Statistic   None

[REPORT]

Status	No
Summary	No
Messages	No
Page	0
Nodes	10 11 12 13 21 22 23 31 32;
DEMAND	No
HEAD	No
PRESSURE	No
QUALITY	PRECISION 10
Links	None

[OPTIONS]

Units	GPM
Headloss	H-W
Specific Gravity	1
Viscosity	1
Trials	40
Accuracy	0.001
Unbalanced	Continue 10
Pattern	1
Demand Multiplier	1
Emitter Exponent	0.5
Quality	Chemical mg/L
Diffusivity	0
Tolerance	0.01

[END]

APPENDIX D

GENETIC ALGORITHM (GA) CODE FOR EPANET EXAMPLE 1 VALVING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Options for GA: initial population, initial population range
%StallGenLimit and StallTimeLimit are stopping criteria set to 100
%which means the optimization is stopped for StallGenLimit if the
%weighted average change in the fitness function value over Stall
%generations (100 for this application) is less than Function tolerance
%which means the optimization is stopped for StallTimeLimit if there
%is no improvement in the best fitness value for an interval of time
%in seconds specified by Stall time (100 for this application)
options = gaoptimset('InitialPopulation', [0 1 0 1 0 0 0 0 0 0; 0 0 0 1 0 1 0 0 0 0; 0 1 0 1 0
0 0 1 0 0; 0 1 0 1 0 0 0 0 0 1; 0 1 0 0 0 1 0 1 0 0; 0 0 0 1 0 1 0 1 0 0; 0 0 0 1 0 1 0 0 1 0; 0
0 0 1 0 0 0 1 0 0; 0 1 1 0 0 1 0 0 0 0; 0 1 1 0 0 0 0 1 0 0; 0 0 1 1 0 0 0 1 0 0; 0 0 0 1 0 1 0
0 0 1; 0 1 0 1 0 0 0 0 1 0; 0 1 0 0 0 1 0 0 0 1; 0 1 1 0 0 0 0 0 0 0; 0 0 0 1 1 0 0 1 0 0; 0 1 1
0 0 0 0 0 0 1; 0 0 1 1 0 0 0 0 0 1; 0 0 0 0 1 1 0 1 0 0; 1 1 0 0 0 0 0 1 0 0], 'PopInitRange',
[0 0 0 0 0 0 0 0 0 0; 1 1 1 1 1 1 1 1 1 1 ], 'StallGenLimit', 100, 'StallTimeLimit', 100);

%Lower and upper bounds on demand variables
%For decision variables whether to alter demand lower bound is 0 and
%upper bound is 1
LB = [0; 0; 0; 0; 0; 0; 0; 0; 0; 0];
UB = [1; 1; 1; 1; 1; 1; 1; 1; 1; 1];

%Assigns nonlinear constraint to call the nonlinear constraint function
%nonlcon in this case
ConstraintFcn=@nonlconvalve;

%GA optimization call is in this form
%[x,fval] = ga(fitnessfcn,nvars,A,b,Aeq,beq,LB,UB,nonlcon,options)
%The output from the optimization will be the dem (the decision variables)
%and the fval, fitness function value, (the total concentration)
%The GA calls the file with the function to be minimized
%flushdec in is this case
%There are 10 variables, there is no inequality linear constraint information so []
% there are no equality linear constraint so [], the
%lower and upper bounds of the decision variables are given in LB and UB,
%the nonlinear constraints are given by variable ConstraintFcn defined
%above, and the options file information is given by the variable options
%defined above
[dem,fval] = ga(valvedec,10,[],[],[],[],LB,UB,ConstraintFcn,options);

%Writes decision variables and fitness function value to Excel file
% xlswrite('ExcelFileName',[dem,fval],'TabName', 'Cell')
%For example, the ExcelFileName is GAValveResults,
%the TabName is Results, and the Cell is C3
xlswrite('GAValveResults',[dem,fval],'Results', 'C3')
```

117

APPENDIX E

**FITNESS FUNCTION CODE FOR EPANET EXAMPLE 1 VALVING
RESPONSE**

```matlab
%MATLAB programming code version R2006a
%Creates the fitness function, where the
%output variable being minimized is concTot and
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the location of pipes to close
function concTot = valvedec(dem)

%Set demands at base value for valving only scenario

%Base demand for Node 10
d1=0;
%Base demand for Node 11
d2=150;
%Base demand for Node 12
d3=150;
%Base demand for Node 13
d4=100;
%Base demand for Node 21
d5=150;
%Base demand for Node 22
d6=200;
%Base demand for Node 23
d7=150;
%Base demand for Node 31
d8=100;
%Base demand for Node 32
d9=100;

%Process to determine the status of the pipes
%For example, if decision variable dem(1) is less than or equal to 0.5
%then first pipe (Pipe 11) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(1)<=0.5
    %Status of Pipe 11
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(2)<=0.5
    %Status of Pipe 12
    v2o='OPEN';
    v2=v2o;
else
```

```matlab
    v2c='CLOSED';
    v2=v2c;
end
if dem(3)<=0.5
    %Status of Pipe 111
    v3o='OPEN';
    v3=v3o;
else
    v3c='CLOSED';
    v3=v3c;
end
if dem(4)<=0.5
    %Status of Pipe 112
    v4o='OPEN';
    v4=v4o;
else
    v4c='CLOSED';
    v4=v4c;
end
if dem(5)<=0.5
    %Status of Pipe 113
    v5o='OPEN';
    v5=v5o;
else
    v5c='CLOSED';
    v5=v5c;
end
if dem(6)<=0.5
    %Status of Pipe 21
    v6o='OPEN';
    v6=v6o;
else
    v6c='CLOSED';
    v6=v6c;
end
if dem(7)<=0.5
    %Status of Pipe 22
    v7o='OPEN';
    v7=v7o;
else
    v7c='CLOSED';
    v7=v7c;
end
if dem(8)<=0.5
    %Status of Pipe 121
    v8o='OPEN';
```

```matlab
        v8=v8o;
    else
        v8c='CLOSED';
        v8=v8c;
    end
    if dem(9)<=0.5
        %Status of Pipe 122
        v9o='OPEN';
        v9=v9o;
    else
        v9c='CLOSED';
        v9=v9c;
    end
    if dem(10)<=0.5
        %Status of Pipe 31
        v10o='OPEN';
        v10=v10o;
    else
        v10c='CLOSED';
        v10=v10c;
    end


%Command to open the file that is going to be changed
fid = fopen('Base1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f values are replaced with the demand and pipe status
fprintf(fid, '\n[TITLE]\nEPANET Example Network
1\n\n[JUNCTIONS]\n;ID\tElev\tDemand\tPattern\n10\t710\t1\t3;\n11\t710\t1\t4;\n12\t70
0\t1\t5;\n13\t695\t1\t6;\n21\t700\t1\t7;\n22\t695\t1\t8;\n23\t690\t1\t9;\n31\t700\t1\t10;\n3
2\t710\t1\t11;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n9\t800;\n\n[TANKS]\n;ID\tElev
ation\tInitLevel\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n2\t850\t120\t100\t
150\t50.5\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughness\tMinorLos
s\tStatus\n10\t10\t11\t10530\t18\t100\t0\tOpen;\n11\t11\t12\t5280\t14\t100\t0\tOpen;\n12
\t12\t13\t5280\t10\t100\t0\tOpen;\n21\t21\t22\t5280\t10\t100\t0\tOpen;\n22\t22\t23\t5280
\t12\t100\t0\tOpen;\n31\t31\t32\t5280\t6\t100\t0\tOpen;\n110\t2\t12\t200\t18\t100\t0\tOp
en;\n111\t11\t21\t5280\t10\t100\t0\tOpen;\n112\t12\t22\t5280\t12\t100\t0\tOpen;\n113\t1
3\t23\t5280\t8\t100\t0\tOpen;\n121\t21\t31\t5280\t8\t100\t0\tOpen;\n122\t22\t32\t5280\t6
\t100\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n9\t9\t10\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n
1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t
0\t0\n1\t0\t0\t0\t0\t0\t0\n;Demand
Change\n3\t0\t0\t0\t0\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%1
```

2.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t150\t150\t150\t1
50\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t150\t150\t150\t150\t%12.7f\t%12.
7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t100\t100\t100\t100\t%12.7f\t%12.7f\n6\t%12.7f\t%
12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%1
2.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n7\t150\t150\t150\t150\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t2
00\t200\t200\t200\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7
f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f
\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t150\t150\t150\t150\t
%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t100\t100\t100\t100\t%12.7f\t%12.7f\n
10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t100\t100\t100\t100\t%12.7f\t%12.7f\n11\t%12
.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump
Curve for Pump 9\n1\t1500\t250\n\n[CONTROLS]\nLINK 9 OPEN IF NODE 2
BELOW 110\nLINK 9 CLOSED IF NODE 2 ABOVE 140\nLINK 11 %s AT
CLOCKTIME 2 AM\nLINK 12 %s AT CLOCKTIME 2 AM\nLINK 111 %s AT
CLOCKTIME 2 AM\nLINK 112 %s AT CLOCKTIME 2 AM\nLINK 113 %s AT
CLOCKTIME 2 AM\nLINK 21 %s AT CLOCKTIME 2 AM\nLINK 22 %s AT

CLOCKTIME 2 AM\nLINK 121 %s AT CLOCKTIME 2 AM\nLINK 122 %s AT CLOCKTIME 2 AM\nLINK 31 %s AT CLOCKTIME 2 AM\n\n[ENERGY]\nGlobal Efficiency\t75\nGlobal Price\t0\nDemand Charge\t0\n\n[QUALITY]\n;Node\tInitQual\n10\t0\n11\t0\n12\t0\n13\t0\n21\t0\n22\t0\n23\t0\n31\t0\n32\t0\n9\t0\n2\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n11\tFLOWPACED\t2\t1\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0\nRoughness Correlation\t0\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nMessages\tNo\nPage\t0\nNodes\t10 11 12 13 21 22 23 31 32;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1\nViscosity\t1\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,v1,v2,v3,v4,v5,v6,v7,v8,v9,v10);

%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Code to read the output file created from EPANET
%Establishes the variables: i is the starting row in the matrix
%l is the starting line to read in the output file
i = 1;
l = 81;
%This establishes the amount of times that the output file must be read
%n begins with the time that response occurs and ends with the end
%of the 24-hr simulation, n changes value in increments of 30
%For this simulation, n begins reading the output file at 3-hr
%(180 minutes) and changes by 30 minutes until the end of the 24-hr

```matlab
%(1440 minutes)
for n = 180:30:1440
    %k is the number of nodes
    for k = 1:9
        %Establishes a variable conc which reads the output file for
        %the concentration in each node
        conc=textread('Base.rpt','%*f%f',1,'headerlines',l,'endofline','\r\n');
        conct(i)=conc;
        %Increases the i to the next row of the matrix
        i = i + 1;
        %Increases the text line to the next line to read
        l = l + 1;
    end
    %Increases text line to skip header information
    l = l + 7;
end
%Calculates the total concentration in all nodes for all times
concTot = sum(conct);
```

APPENDIX F

**EPANET INPUT FILE CREATED BY METHDOLOGY FOR EPANET
EXAMPLE 1 VALVING RESPONSE**

;EPANET input file created by optimization methodology
[TITLE]
EPANET Example Network 1

[JUNCTIONS]
;ID   Elev   Demand   Pattern
10   710   1   3;
11   710   1   4;
12   700   1   5;
13   695   1   6;
21   700   1   7;
22   695   1   8;
23   690   1   9;
31   700   1   10;
32   710   1   11;

[RESERVOIRS]
;ID   Head   Pattern
9   800;

[TANKS]
;ID   Elevation InitLevel MinLevel MaxLevel Diameter MinVol VolCurve
2   850   120   100   150   50.5   0;

[PIPES]
;ID   Node1 Node2 Length Diameter   Roughness   MinorLoss   Status
10   10   11   10530   18   100   0   Open;
11   11   12   5280   14   100   0   Open;
12   12   13   5280   10   100   0   Open;
21   21   22   5280   10   100   0   Open;
22   22   23   5280   12   100   0   Open;
31   31   32   5280   6   100   0   Open;
110   2   12   200   18   100   0   Open;
111   11   21   5280   10   100   0   Open;
112   12   22   5280   12   100   0   Open;
113   13   23   5280   8   100   0   Open;
121   21   31   5280   8   100   0   Open;
122   22   32   5280   6   100   0   Open;

[PUMPS]
;ID   Node1 Node2 Parameters
9   9   10   HEAD 1;

[PATTERNS]
;ID   Multipliers
;Injection Pattern

1	1	1	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0

;Demand Change
;Demand variables are set at the average base demand

3	0	0	0	0	0	0
3	0	0	0	0	0	0
3	0	0	0	0	0	0
3	0	0	0	0	0	0
3	0	0	0	0	0	0
3	0	0	0	0	0	0
3	0	0	0	0	0	0
3	0	0	0	0	0	0
4	150	150	150	150	150	150
4	150	150	150	150	150	150
4	150	150	150	150	150	150
4	150	150	150	150	150	150
4	150	150	150	150	150	150
4	150	150	150	150	150	150
4	150	150	150	150	150	150
4	150	150	150	150	150	150
5	150	150	150	150	150	150
5	150	150	150	150	150	150
5	150	150	150	150	150	150
5	150	150	150	150	150	150
5	150	150	150	150	150	150
5	150	150	150	150	150	150
5	150	150	150	150	150	150
5	150	150	150	150	150	150
6	100	100	100	100	100	100
6	100	100	100	100	100	100
6	100	100	100	100	100	100
6	100	100	100	100	100	100
6	100	100	100	100	100	100
6	100	100	100	100	100	100
6	100	100	100	100	100	100
6	100	100	100	100	100	100
7	150	150	150	150	150	150
7	150	150	150	150	150	150
7	150	150	150	150	150	150
7	150	150	150	150	150	150

7	150	150	150	150	150	150
7	150	150	150	150	150	150
7	150	150	150	150	150	150
7	150	150	150	150	150	150
8	200	200	200	200	200	200
8	200	200	200	200	200	200
8	200	200	200	200	200	200
8	200	200	200	200	200	200
8	200	200	200	200	200	200
8	200	200	200	200	200	200
8	200	200	200	200	200	200
8	200	200	200	200	200	200
9	150	150	150	150	150	150
9	150	150	150	150	150	150
9	150	150	150	150	150	150
9	150	150	150	150	150	150
9	150	150	150	150	150	150
9	150	150	150	150	150	150
9	150	150	150	150	150	150
9	150	150	150	150	150	150
10	100	100	100	100	100	100
10	100	100	100	100	100	100
10	100	100	100	100	100	100
10	100	100	100	100	100	100
10	100	100	100	100	100	100
10	100	100	100	100	100	100
10	100	100	100	100	100	100
10	100	100	100	100	100	100
11	100	100	100	100	100	100
11	100	100	100	100	100	100
11	100	100	100	100	100	100
11	100	100	100	100	100	100
11	100	100	100	100	100	100
11	100	100	100	100	100	100
11	100	100	100	100	100	100
11	100	100	100	100	100	100

[CURVES]
;ID   X-Value   Y-Value
;PUMP: Pump Curve for Pump 9
1   1500   250

[CONTROLS]
;Control for the closure of link 9 if the pressure at node 2 is above 140 psi,
;or open if below 110 psi
LINK 9 OPEN IF NODE 2 BELOW 110

LINK 9 CLOSED IF NODE 2 ABOVE 140
;Valve variables are placed in %s
;Determines if the pipe/link is open or closed
LINK 11 %s AT CLOCKTIME 2 AM
LINK 12 %s AT CLOCKTIME 2 AM
LINK 111 %s AT CLOCKTIME 2 AM
LINK 112 %s AT CLOCKTIME 2 AM
LINK 113 %s AT CLOCKTIME 2 AM
LINK 21 %s AT CLOCKTIME 2 AM
LINK 22 %s AT CLOCKTIME 2 AM
LINK 121 %s AT CLOCKTIME 2 AM
LINK 122 %s AT CLOCKTIME 2 AM
LINK 31 %s AT CLOCKTIME 2 AM

[ENERGY]
Global Efficiency   75
Global Price   0
Demand Charge   0

[QUALITY]
;Node InitQual
10   0
11   0
12   0
13   0
21   0
22   0
23   0
31   0
32   0
9   0
2   0

[SOURCES]
;Node Type   Quality (mg/L)   Pattern
11   FLOWPACED   2   1

[REACTIONS]
Order Bulk   0
Order Tank   0
Order Wall   0
Global Bulk   0
Global Wall   0
Limiting Potential   0
Roughness Correlation   0

```
[TIMES]
Duration                24:00:00
Hydraulic Timestep      0:30
Quality Timestep        0:30
Pattern Timestep        0:30
Pattern Start           0:00
Report Timestep         0:30
Report Start            0:00
Start ClockTime         12:00 AM
Statistic               None

[REPORT]
Status                  No
Summary                 No
Messages                No
Page                    0
Nodes                   10 11 12 13 21 22 23 31 32;
DEMAND                  No
HEAD                    No
PRESSURE                No
QUALITY                 PRECISION 10
Links                   None


[OPTIONS]
Units                   GPM
Headloss                H-W
Specific Gravity        1
Viscosity               1
Trials                  40
Accuracy                0.001
Unbalanced              Continue 10
Pattern                 1
Demand Multiplier       1
Emitter Exponent        0.5
Quality                 Chemical mg/L
Diffusivity             0
Tolerance               0.01

[END]
```

APPENDIX G

**NONLINEAR CONSTRATINT CODE FOR EPANET EXAMPLE 1 VALVING
RESPONSE**

```matlab
%MATLAB programming code version R2006a
%Creates the nonlinear constraint function, where the
%output variables being c, nonlinear inequality constraint and
%ceq, nonlinear equality constraint
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the pipes to close
function [c, ceq]=nonlconvalve(dem)

%There are no nonlinear equality constraint
c=[];

%Set demands at base value for valving only scenario

%Base demand for Node 10
d1=0;
%Base demand for Node 11
d2=150;
%Base demand for Node 12
d3=150;
%Base demand for Node 13
d4=100;
%Base demand for Node 21
d5=150;
%Base demand for Node 22
d6=200;
%Base demand for Node 23
d7=150;
%Base demand for Node 31
d8=100;
%Base demand for Node 32
d9=100;

%Process to determine the status of the pipes
%For example, if decision variable dem(1) is less than or equal to 0.5
%then first pipe (Pipe 11) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(1)<=0.5
    %Status of Pipe 11
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(2)<=0.5
```

```matlab
    %Status of Pipe 12
    v2o='OPEN';
    v2=v2o;
else
    v2c='CLOSED';
    v2=v2c;
end
if dem(3)<=0.5
    %Status of Pipe 111
    v3o='OPEN';
    v3=v3o;
else
    v3c='CLOSED';
    v3=v3c;
end
if dem(4)<=0.5
    %Status of Pipe 112
    v4o='OPEN';
    v4=v4o;
else
    v4c='CLOSED';
    v4=v4c;
end
if dem(5)<=0.5
    %Status of Pipe 113
    v5o='OPEN';
    v5=v5o;
else
    v5c='CLOSED';
    v5=v5c;
end
if dem(6)<=0.5
    %Status of Pipe 21
    v6o='OPEN';
    v6=v6o;
else
    v6c='CLOSED';
    v6=v6c;
end
if dem(7)<=0.5
    %Status of Pipe 22
    v7o='OPEN';
    v7=v7o;
else
    v7c='CLOSED';
    v7=v7c;
```

```matlab
end
if dem(8)<=0.5
    %Status of Pipe 121
    v8o='OPEN';
    v8=v8o;
else
    v8c='CLOSED';
    v8=v8c;
end
if dem(9)<=0.5
    %Status of Pipe 122
    v9o='OPEN';
    v9=v9o;
else
    v9c='CLOSED';
    v9=v9c;
end
if dem(10)<=0.5
    %Status of Pipe 31
    v10o='OPEN';
    v10=v10o;
else
    v10c='CLOSED';
    v10=v10c;
end

%Command to open the file that is going to be changed
fid = fopen('Base1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f are replaced with the demand values, while %s is replaced with pipe status
fprintf(fid, '\n[TITLE]\nEPANET Example Network
1\n\n[JUNCTIONS]\n;ID\tElev\tDemand\tPattern\n10\t710\t1\t3;\n11\t710\t1\t4;\n12\t70
0\t1\t5;\n13\t695\t1\t6;\n21\t700\t1\t7;\n22\t695\t1\t8;\n23\t690\t1\t9;\n31\t700\t1\t10;\n3
2\t710\t1\t11;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n9\t800;\n\n[TANKS]\n;ID\tElev
ation\tInitLevel\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n2\t850\t120\t100\t
150\t50.5\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughness\tMinorLos
s\tStatus\n10\t10\t11\t10530\t18\t100\t0\tOpen;\n11\t11\t12\t5280\t14\t100\t0\tOpen;\n12
\t12\t13\t5280\t10\t100\t0\tOpen;\n21\t21\t22\t5280\t10\t100\t0\tOpen;\n22\t22\t23\t5280
\t12\t100\t0\tOpen;\n31\t31\t32\t5280\t6\t100\t0\tOpen;\n110\t2\t12\t200\t18\t100\t0\tOp
en;\n111\t11\t21\t5280\t10\t100\t0\tOpen;\n112\t12\t22\t5280\t12\t100\t0\tOpen;\n113\t1
3\t23\t5280\t8\t100\t0\tOpen;\n121\t21\t31\t5280\t8\t100\t0\tOpen;\n122\t22\t32\t5280\t6
\t100\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n9\t9\t10\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n
1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t
```

0\t0\n1\t0\t0\t0\t0\t0\t0\n;Demand Change\n3\t0\t0\t0\t0\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t150\t150\t150\t150\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t150\t150\t150\t150\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t100\t100\t100\t100\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t150\t150\t150\t150\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t200\t200\t200\t200\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t150\t150\t150\t150\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t100\t100\t100\t100\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t100\t100\t100\t100\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t1500\t250\n\n\n[CONTROLS]\nLINK 9 OPEN IF NODE 2

BELOW 110\nLINK 9 CLOSED IF NODE 2 ABOVE 140\nLINK 11 %s AT CLOCKTIME 2 AM\nLINK 12 %s AT CLOCKTIME 2 AM\nLINK 111 %s AT CLOCKTIME 2 AM\nLINK 112 %s AT CLOCKTIME 2 AM\nLINK 113 %s AT CLOCKTIME 2 AM\nLINK 21 %s AT CLOCKTIME 2 AM\nLINK 22 %s AT CLOCKTIME 2 AM\nLINK 121 %s AT CLOCKTIME 2 AM\nLINK 122 %s AT CLOCKTIME 2 AM\nLINK 31 %s AT CLOCKTIME 2 AM\n\n[ENERGY]\nGlobal Efficiency\t75\nGlobal Price\t0\nDemand Charge\t0\n\n[QUALITY]\n;Node\tInitQual\n10\t0\n11\t0\n12\t0\n13\t0\n21\t0\n22\t0\n23\t0\n31\t0\n32\t0\n9\t0\n2\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n11\tFLOWPACED\t2\t1\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0\nRoughness Correlation\t0\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nMessages\tNo\nPage\t0\nNodes\t10 11 12 13 21 22 23 31 32;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1\nViscosity\t1\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,v1,v2,v3,v4,v5,v6,v7,v8,v9,v10);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Reads EPANET output file (Base.rpt) to see if any error messages were reported in
%simulation
[mesg1,mesg2]=textread('Base.rpt','%s %s',1,'headerlines',12,'endofline','\r\n');

%Compares variable mesg1 to Node, if they are the same then linetitle1 is equal to 1
linetitle1 = strcmp(mesg1, 'Node');

```matlab
%Compares variable mesg2 to Results, if they are the same then linetitle2 is equal to 1
linetitle2 = strcmp(mesg2, 'Results');
 %Adds the two variables together
disconnect = linetitle1+linetitle2;

%If disconnect is equal to zero then error messages were reported and therefore
%the nonlinear constraint was not met and ceq is equal to one
%In terms of reality, the error message means that the system was disconnected or
%caused negative pressures
if disconnect==0
    ceq=1;
else
    ceq=0;
end
```

APPENDIX H

**GENETIC ALGORITHM (GA) CODE FOR EPANET EXAMPLE 1 FLUSHING
AND VALVING RESPONSE**

```matlab
%MATLAB programming code version R2006a
%Options for GA: initial population, initial population range
%StallGenLimit and StallTimeLimit are stopping criteria set to 100
%which means the optimization is stopped for StallGenLimit if the
%weighted average change in the fitness function value over Stall
%generations (100 for this application) is less than Function tolerance
%which means the optimization is stopped for StallTimeLimit if there
%is no improvement in the best fitness value for an interval of time
%in seconds specified by Stall time (100 for this application)
options = gaoptimset('InitialPopulation', [0 0 0 250 0 250 0 200 0 150 0 200 0 150 0 100
1 900 0 1 0 1 0 0 0 0 0 0; 0 0 0 150 0 250 0 300 0 150 0 200 0 150 1 150 1 800 0 0 0 1 0
1 0 0 0 0; 1 200 0 250 0 150 1 200 1 250 0 200 1 260 1 300 0 100 0 1 0 1 0 0 0 1 0 0; 0 0
0 350 1 320 1 230 0 150 0 200 1 220 1 490 0 100 0 1 0 1 0 0 0 0 1; 1 200 0 250 0 250 1
210 1 250 0 200 1 260 1 300 0 100 0 1 0 0 0 1 0 1 0 0; 1 200 0 150 0 250 1 300 1 250 0
200 1 250 1 250 0 100 0 0 0 1 0 1 0 1 0 0; 0 0 0 150 0 250 1 300 0 150 0 200 1 250 1 550
0 100 0 0 0 1 0 1 0 0 1 0; 0 0 0 250 0 350 1 200 0 150 0 210 1 260 1 800 0 100 0 0 0 1 0
0 0 1 0 0; 0 0 0 250 0 250 0 300 1 500 0 200 0 150 0 100 1 400 0 1 1 0 0 1 0 0 0 0; 0 0 0
250 0 150 0 200 1 800 0 200 0 150 0 100 1 150 0 1 1 0 0 0 0 1 0 0; 0 0 0 150 0 250 0 200
1 800 0 200 0 150 0 100 1 200 0 0 1 1 0 0 0 1 0 0; 0 0 0 350 0 250 1 325 0 150 0 200 0
150 1 500 0 100 0 0 0 1 0 1 0 0 0 1; 0 0 0 350 1 500 1 300 0 150 0 200 1 250 1 800 0 100
0 1 0 1 0 0 0 0 1 0; 0 0 0 250 0 250 0 200 0 150 0 200 0 150 1 400 1 600 0 1 0 0 0 1 0 0 0
1; 0 0 0 350 0 250 0 300 0 150 0 200 0 150 1 760 0 100 0 1 1 0 0 0 0 0 0; 0 0 0 250 0
150 1 260 1 370 0 200 0 150 0 100 1 440 0 0 0 1 1 0 0 1 0 0; 0 0 0 250 0 250 1 130 0 150
0 200 0 160 1 620 0 100 0 1 1 0 0 0 0 0 1; 0 0 0 350 0 350 0 200 0 150 0 200 0 150 1
590 0 100 0 0 1 1 0 0 0 0 1; 0 0 0 250 0 250 1 255 0 150 0 225 1 230 1 500 0 100 0 0 0
0 1 1 0 1 0 0; 0 0 0 250 0 350 0 200 0 150 0 200 1 300 1 200 0 100 1 1 0 0 0 0 0 1 0 0],
'PopInitRange', [0 0 0 150 0 150 0 100 0 150 0 200 0 150 0 100 0 100 0 0 0 0 0 0 0 0 0 0;
1 900 1 900 1 900 1 900 1 900 1 900 1 900 1 900 1 900 1 1 1 1 1 1 1 1 1 1 ],
'StallGenLimit', 100, 'StallTimeLimit', 100);

%Lower and upper bounds on demand variables
%For decision variables whether to alter demand lower bound is 0 and
%upper bound is 1, the new demand has a lower bound of the base average demand
%and an upper bound of 1000 gallons per minute (gpm)
LB = [0; 0; 0; 150; 0; 150; 0; 100; 0; 150; 0; 200; 0; 150; 0; 100; 0; 100; 0; 0; 0; 0; 0; 0;
0; 0; 0; 0];
UB = [1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1; 1000; 1;
1; 1; 1; 1; 1; 1; 1; 1; 1];

%Linear constraint d1+d2+d3+d4+d5+d6+d7+d8+d9<=2300
%Helps ensure that the total demand in the network does not cause negative
%pressures in the network
A = [0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0];
b = 2300;

%Assigns nonlinear constraint to call the nonlinear constraint function
```

%nonlcon in this case
ConstraintFcn=@nonlcon;

%GA optimization call is in this form
%[x,fval] = ga(fitnessfcn,nvars,A,b,Aeq,beq,LB,UB,nonlcon,options)
%The output from the optimization will be the dem (the decision variables)
%and the fval, fitness function value, (the total concentration)
%The GA calls the file with the function to be minimized
%flushdec in is this case
%There are 28 variables, the inequality linear constraint information
%is contained in A and b, there are no equality linear constraint so [], the
%lower and upper bounds of the decision variables are given in LB and UB,
%the nonlinear constraints are given by variable ConstraintFcn defined
%above, and the options file information is given by the variable options
%defined above
[dem,fval] = ga(flushvalvedec,28,A,b,[],[],LB,UB,ConstraintFcn,options);

%Writes decision variables and fitness function value to Excel file
% xlswrite('ExcelFileName',[dem,fval],'TabName', 'Cell')
%For example, the ExcelFileName is GAFlushValveResults,
%the TabName is Results, and the Cell is C3
xlswrite('GAFlushValveResults',[dem,fval],'Results', 'C3')

APPENDIX I

FITNESS FUNCTION CODE FOR EPANET EXAMPLE 1 FLUSHING AND VALVING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Creates the fitness function, where the
%output variable being minimized is concTot and
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the nodes at which to alter the demand; the new demands
%for these nodes; location of pipes to close
function concTot = flushvalvedec(dem)

%Process to determine if the nodal demand is going to change
%and the value of the nodal demand to utilize in the input file
%For example, if decision variable dem(1) is less than or equal to 0.5
%then the nodal demand will not be altered and the average base demand
%of 0 gallons per minute (gpm) will be used, otherwise the nodal
%demand will be altered and the value determined in decision
%variable dem(2) will be used in the input file

if dem(1)<=0.5
    %Demand at Node 10
    %Base demand for Node 10
    d1=0;
else
    %New demand for Node 10
    d1=dem(2);
end
if dem(3)<=0.5
    %Demand at Node 11
    %Base demand for Node 11
    d2=150;
else
    %New demand for Node 11
    d2=dem(4);
end
if dem(5)<=0.5
    %Demand at Node 12
    %Base demand for Node 12
    d3=150;
else
    %New demand for Node 12
    d3=dem(6);
end
if dem(7)<=0.5
    %Demand at Node 13
    %Base demand for Node 13
    d4=100;
else
```

```
    %New demand for Node 13
    d4=dem(8);
end
if dem(9)<=0.5
    %Demand at Node 21
    %Base demand for Node 21
    d5=150;
else
    %New demand for Node 21
    d5=dem(10);
end
if dem(11)<=0.5
    %Demand at Node 22
    %Base demand for Node 22
    d6=200;
else
    %New demand for Node 22
    d6=dem(12);
end
if dem(13)<=0.5
    %Demand at Node 23
    %Base demand for Node 23
    d7=150;
else
    %New demand for Node 23
    d7=dem(14);
end
if dem(15)<=0.5
    %Demand at Node 31
    %Base demand for Node 31
    d8=100;
else
    %New demand for Node 31
    d8=dem(16);
end
if dem(17)<=0.5
    %Demand at Node 32
    %Base demand for Node 32
    d9=100;
else
    %New demand for Node 32
    d9=dem(18);
end

%Process to determine the status of the pipes
%For example, if decision variable dem(19) is less than or equal to 0.5
```

```matlab
%then first pipe (Pipe 11) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(19)<=0.5
    %Status of Pipe 11
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(20)<=0.5
    %Status of Pipe 12
    v2o='OPEN';
    v2=v2o;
else
    v2c='CLOSED';
    v2=v2c;
end
if dem(21)<=0.5
    %Status of Pipe 111
    v3o='OPEN';
    v3=v3o;
else
    v3c='CLOSED';
    v3=v3c;
end
if dem(22)<=0.5
    %Status of Pipe 112
    v4o='OPEN';
    v4=v4o;
else
    v4c='CLOSED';
    v4=v4c;
end
if dem(23)<=0.5
    %Status of Pipe 113
    v5o='OPEN';
    v5=v5o;
else
    v5c='CLOSED';
    v5=v5c;
end
if dem(24)<=0.5
    %Status of Pipe 21
    v6o='OPEN';
    v6=v6o;
```

```matlab
else
    v6c='CLOSED';
    v6=v6c;
end
if dem(25)<=0.5
    %Status of Pipe 22
    v7o='OPEN';
    v7=v7o;
else
    v7c='CLOSED';
    v7=v7c;
end
if dem(26)<=0.5
    %Status of Pipe 121
    v8o='OPEN';
    v8=v8o;
else
    v8c='CLOSED';
    v8=v8c;
end
if dem(27)<=0.5
    %Status of Pipe 122
    v9o='OPEN';
    v9=v9o;
else
    v9c='CLOSED';
    v9=v9c;
end
if dem(28)<=0.5
    %Status of Pipe 31
    v10o='OPEN';
    v10=v10o;
else
    v10c='CLOSED';
    v10=v10c;
end

%Command to open the file that is going to be changed
fid = fopen('Base1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f is replaced with demand values, while %s is replced with pipe status
%The input file is altered depending on the time of response
%Number of demand variables that are replaced are reduced when response is delayed
```

fprintf(fid, '\n[TITLE]\nEPANET Example Network 1\n\n[JUNCTIONS]\n;ID\tElev\tDemand\tPattern\n10\t710\t1\t3;\n11\t710\t1\t4;\n12\t700\t1\t5;\n13\t695\t1\t6;\n21\t700\t1\t7;\n22\t695\t1\t8;\n23\t690\t1\t9;\n31\t700\t1\t10;\n32\t710\t1\t11;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n9\t800;\n\n[TANKS]\n;ID\tElevation\tInitLevel\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n2\t850\t120\t100\t150\t50.5\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughness\tMinorLoss\tStatus\n10\t10\t11\t10530\t18\t100\t0\tOpen;\n11\t11\t12\t5280\t14\t100\t0\tOpen;\n12\t12\t13\t5280\t10\t100\t0\tOpen;\n21\t21\t22\t5280\t10\t100\t0\tOpen;\n22\t22\t23\t5280\t12\t100\t0\tOpen;\n31\t31\t32\t5280\t6\t100\t0\tOpen;\n110\t2\t12\t200\t18\t100\t0\tOpen;\n111\t11\t21\t5280\t10\t100\t0\tOpen;\n112\t12\t22\t5280\t12\t100\t0\tOpen;\n113\t13\t23\t5280\t8\t100\t0\tOpen;\n121\t21\t31\t5280\t8\t100\t0\tOpen;\n122\t22\t32\t5280\t6\t100\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n9\t9\t10\tHEAD 1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\n;Demand Change\n3\t0\t0\t0\t0\t%12.7f\t%12.7f\n3\t\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t150\t150\t150\t150\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t150\t150\t150\t150\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t100\t100\t100\t100\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t150\t150\t150\t150\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t200\t200\t200\t200\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t150\t150\t150\t150\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.

7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t100\t100\t100\t100\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t100\t100\t100\t100\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t1500\t250\n\n[CONTROLS]\nLINK 9 OPEN IF NODE 2 BELOW 110\nLINK 9 CLOSED IF NODE 2 ABOVE 140\nLINK 11 %s AT CLOCKTIME 2 AM\nLINK 12 %s AT CLOCKTIME 2 AM\nLINK 111 %s AT CLOCKTIME 2 AM\nLINK 112 %s AT CLOCKTIME 2 AM\nLINK 113 %s AT CLOCKTIME 2 AM\nLINK 21 %s AT CLOCKTIME 2 AM\nLINK 22 %s AT CLOCKTIME 2 AM\nLINK 121 %s AT CLOCKTIME 2 AM\nLINK 122 %s AT CLOCKTIME 2 AM\nLINK 31 %s AT CLOCKTIME 2 AM\n\n[ENERGY]\nGlobal Efficiency\t75\nGlobal Price\t0\nDemand Charge\t0\n\n[QUALITY]\n;Node\tInitQual\n10\t0\n11\t0\n12\t0\n13\t0\n21\t0\n22\t0\n23\t0\n31\t0\n32\t0\n9\t0\n2\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n11\tFLOWPACED\t2\t1\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0\nRoughness Correlation\t0\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nMessages\tNo\nPage\t0\nNodes\t10 11 12 13 21 22 23 31 32;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1\nViscosity\t1\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8

```matlab
,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d
9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,
d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,v1,v2,v3,v4,v5,v6,v7,v8,v9,v10);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Code to read the output file created from EPANET
%Establishes the variables: i is the starting row in the matrix
%l is the starting line to read in the output file
%For response delays, the starting line that is read for the concentration increases
i = 1;
l = 81;
%This establishes the amount of times that the output file must be read
%n begins with the time that response occurs and ends with the end
%of the 24-hr simulation, n changes value in increments of 30
%For this simulation, n begins reading the output file at 3-hr
%(180 minutes) and changes by 30 minutes until the end of the 24-hr
%(1440 minutes)
%For response delays, the starting time, n, increases
for n = 180:30:1440
    %k is the number of nodes
    for k = 1:9
        %Establishes a variable conc which reads the output file for
        %the concentration in each node
        conc=textread('Base.rpt','%*f%f',1,'headerlines',l,'endofline','\r\n');
        conct(i)=conc;
        %Increases the i to the next row of the matrix
        i = i + 1;
        %Increases the text line to the next line to read
        l = l + 1;
    end
    %Increases text line to skip header information
    l = l + 7;
end
%Calculates the total concentration in all nodes for all times
concTot = sum(conct);
```

APPENDIX J

**EPANET INPUT FILE CREATED BY METHDOLOGY FOR EPANET
EXAMPLE 1 FLUSHING AND VALVING RESPONSE**

;EPANET input file created by optimization methodology
[TITLE]
EPANET Example Network 1

[JUNCTIONS]
;ID	Elev	Demand	Pattern
10	710	1	3;
11	710	1	4;
12	700	1	5;
13	695	1	6;
21	700	1	7;
22	695	1	8;
23	690	1	9;
31	700	1	10;
32	710	1	11;

[RESERVOIRS]
;ID	Head	Pattern
9	800;	

[TANKS]
;ID	Elevation	InitLevel	MinLevel	MaxLevel	Diameter	MinVol	VolCurve
2	850	120	100	150	50.5	0;	

[PIPES]
;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status
10	10	11	10530	18	100	0	Open;
11	11	12	5280	14	100	0	Open;
12	12	13	5280	10	100	0	Open;
21	21	22	5280	10	100	0	Open;
22	22	23	5280	12	100	0	Open;
31	31	32	5280	6	100	0	Open;
110	2	12	200	18	100	0	Open;
111	11	21	5280	10	100	0	Open;
112	12	22	5280	12	100	0	Open;
113	13	23	5280	8	100	0	Open;
121	21	31	5280	8	100	0	Open;
122	22	32	5280	6	100	0	Open;

[PUMPS]
;ID	Node1	Node2	Parameters
9	9	10	HEAD 1;

[PATTERNS]
;ID   Multipliers
;Injection Pattern

1	1	1	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0

;Demand Change
;Demand variables are placed in the %12.7f spots
;Either average base demand or new demand

3	0	0	0	0	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	150	150	150	150	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	150	150	150	150	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	100	100	100	100	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	150	150	150	150	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
7	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	200	200	200	200	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	150	150	150	150	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	100	100	100	100	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
10	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	100	100	100	100	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

[CURVES]
;ID   X-Value   Y-Value
;PUMP: Pump Curve for Pump 9
1   1500   250

[CONTROLS]
;Control for the closure of link 9 if the pressure at node 2 is above 140 psi,
;or open if below 110 psi

LINK 9 OPEN IF NODE 2 BELOW 110
LINK 9 CLOSED IF NODE 2 ABOVE 140
;Valve variables are placed in %s
;Determines if the pipe/link is open or closed
LINK 11 %s AT CLOCKTIME 2 AM
LINK 12 %s AT CLOCKTIME 2 AM
LINK 111 %s AT CLOCKTIME 2 AM
LINK 112 %s AT CLOCKTIME 2 AM
LINK 113 %s AT CLOCKTIME 2 AM
LINK 21 %s AT CLOCKTIME 2 AM
LINK 22 %s AT CLOCKTIME 2 AM
LINK 121 %s AT CLOCKTIME 2 AM
LINK 122 %s AT CLOCKTIME 2 AM
LINK 31 %s AT CLOCKTIME 2 AM

[ENERGY]
Global Efficiency   75
Global Price   0
Demand Charge   0

[QUALITY]
;Node InitQual
10   0
11   0
12   0
13   0
21   0
22   0
23   0
31   0
32   0
9   0
2   0

[SOURCES]
;Node Type   Quality (mg/L)   Pattern
11   FLOWPACED   2   1

[REACTIONS]
Order Bulk   0
Order Tank   0
Order Wall   0
Global Bulk   0
Global Wall   0
Limiting Potential   0
Roughness Correlation   0

```
[TIMES]
Duration                24:00:00
Hydraulic Timestep      0:30
Quality Timestep        0:30
Pattern Timestep        0:30
Pattern Start           0:00
Report Timestep         0:30
Report Start            0:00
Start ClockTime         12:00 AM
Statistic               None


[REPORT]
Status                  No
Summary                 No
Messages                No
Page                    0
Nodes                   10 11 12 13 21 22 23 31 32;
DEMAND                  No
HEAD                    No
PRESSURE                No
QUALITY                 PRECISION 10
Links                   None



[OPTIONS]
Units                   GPM
Headloss                H-W
Specific Gravity        1
Viscosity               1
Trials                  40
Accuracy                0.001
Unbalanced              Continue 10
Pattern                 1
Demand Multiplier       1
Emitter Exponent        0.5
Quality                 Chemical mg/L
Diffusivity             0
Tolerance               0.01


[END]
```

APPENDIX K

**NONLINEAR CONSTRAINT CODE FOR EPANET EXAMPLE 1 FLUSHING
AND VALVING RESPONSE**

```matlab
%MATLAB programming code version R2006a
%Creates the nonlinear constraint function, where the
%output variables being c, nonlinear inequality constraint and
%ceq, nonlinear equality constraint
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the nodes at which to alter the demand; the new demands
%for these nodes; and the pipes to close
function [c, ceq]=nonlcon(dem)

%There are no nonlinear equality constraint
c=[];

%Process to determine if the nodal demand is going to change
%and the value of the nodal demand to utilize in the input file
%For example, if decision variable dem(1) is less than or equal to 0.5
%then the nodal demand will not be altered and the average base demand
%of 0 gallons per minute (gpm) will be used, otherwise the nodal
%demand will be altered and the value determined in decision
%variable dem(2) will be used in the input file

if dem(1)<=0.5
    %Demand at Node 10
    %Base demand for Node 10
    d1=0;
else
    %New demand for Node 10
    d1=dem(2);
end
if dem(3)<=0.5
    %Demand at Node 11
    %Base demand for Node 11
    d2=150;
else
    %New demand for Node 11
    d2=dem(4);
end
if dem(5)<=0.5
    %Demand at Node 12
    %Base demand for Node 12
    d3=150;
else
    %New demand for Node 12
    d3=dem(6);
end
if dem(7)<=0.5
```

```matlab
    %Demand at Node 13
    %Base demand for Node 13
    d4=100;
else
    %New demand for Node 13
    d4=dem(8);
end
if dem(9)<=0.5
    %Demand at Node 21
    %Base demand for Node 21
    d5=150;
else
    %New demand for Node 21
    d5=dem(10);
end
if dem(11)<=0.5
    %Demand at Node 22
    %Base demand for Node 22
    d6=200;
else
    %New demand for Node 22
    d6=dem(12);
end
if dem(13)<=0.5
    %Demand at Node 23
    %Base demand for Node 23
    d7=150;
else
    %New demand for Node 23
    d7=dem(14);
end
if dem(15)<=0.5
    %Demand at Node 31
    %Base demand for Node 31
    d8=100;
else
    %New demand for Node 31
    d8=dem(16);
end
if dem(17)<=0.5
    %Demand at Node 32
    %Base demand for Node 32
    d9=100;
else
    %New demand for Node 32
    d9=dem(18);
```

```matlab
end

%Process to determine the status of the pipes
%For example, if decision variable dem(19) is less than or equal to 0.5
%then first pipe (Pipe 11) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(19)<=0.5
    %Status of Pipe 11
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(20)<=0.5
    %Status of Pipe 12
    v2o='OPEN';
    v2=v2o;
else
    v2c='CLOSED';
    v2=v2c;
end
if dem(21)<=0.5
    %Status of Pipe 111
    v3o='OPEN';
    v3=v3o;
else
    v3c='CLOSED';
    v3=v3c;
end
if dem(22)<=0.5
    %Status of Pipe 112
    v4o='OPEN';
    v4=v4o;
else
    v4c='CLOSED';
    v4=v4c;
end
if dem(23)<=0.5
    %Status of Pipe 113
    v5o='OPEN';
    v5=v5o;
else
    v5c='CLOSED';
    v5=v5c;
end
```

```matlab
if dem(24)<=0.5
    %Status of Pipe 21
    v6o='OPEN';
    v6=v6o;
else
    v6c='CLOSED';
    v6=v6c;
end
if dem(25)<=0.5
    %Status of Pipe 22
    v7o='OPEN';
    v7=v7o;
else
    v7c='CLOSED';
    v7=v7c;
end
if dem(26)<=0.5
    %Status of Pipe 121
    v8o='OPEN';
    v8=v8o;
else
    v8c='CLOSED';
    v8=v8c;
end
if dem(27)<=0.5
    %Status of Pipe 122
    v9o='OPEN';
    v9=v9o;
else
    v9c='CLOSED';
    v9=v9c;
end
if dem(28)<=0.5
    %Status of Pipe 31
    v10o='OPEN';
    v10=v10o;
else
    v10c='CLOSED';
    v10=v10c;
end

%Command to open the file that is going to be changed
fid = fopen('Base1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
```

%The %12.7f is replaced with the demand values, while %s is replaced with pipe status
%The input file is altered depending on the time of response
%Number of demand variables that are replaced are reduced when response is delayed
fprintf(fid, '\n[TITLE]\nEPANET Example Network
1\n\n[JUNCTIONS]\n;ID\tElev\tDemand\tPattern\n10\t710\t1\t3;\n11\t710\t1\t4;\n12\t70
0\t1\t5;\n13\t695\t1\t6;\n21\t700\t1\t7;\n22\t695\t1\t8;\n23\t690\t1\t9;\n31\t700\t1\t10;\n3
2\t710\t1\t11;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n9\t800;\n\n[TANKS]\n;ID\tElev
ation\tInitLevel\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n2\t850\t120\t100\t
150\t50.5\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughness\tMinorLos
s\tStatus\n10\t10\t11\t10530\t18\t100\t0\tOpen;\n11\t11\t12\t5280\t14\t100\t0\tOpen;\n12
\t12\t13\t5280\t10\t100\t0\tOpen;\n21\t21\t22\t5280\t10\t100\t0\tOpen;\n22\t22\t23\t5280
\t12\t100\t0\tOpen;\n31\t31\t32\t5280\t6\t100\t0\tOpen;\n110\t2\t12\t200\t18\t100\t0\tOp
en;\n111\t11\t21\t5280\t10\t100\t0\tOpen;\n112\t12\t22\t5280\t12\t100\t0\tOpen;\n113\t1
3\t23\t5280\t8\t100\t0\tOpen;\n121\t21\t31\t5280\t8\t100\t0\tOpen;\n122\t22\t32\t5280\t6
\t100\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n9\t9\t10\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n
1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t
0\t0\n1\t0\t0\t0\t0\t0\t0\n;Demand
Change\n3\t0\t0\t0\t0\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%1
2.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t150\t150\t150\t1
50\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t150\t150\t150\t150\t%12.7f\t%12.
7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t100\t100\t100\t100\t%12.7f\t%12.7f\n6\t%12.7f\t%
12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%1
2.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\n7\t150\t150\t150\t150\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n7\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t2
00\t200\t200\t200\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7
f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%
12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f
\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f

\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t150\t150\t150\t150\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t100\t100\t100\t100\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t100\t100\t100\t100\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t1500\t250\n\n[CONTROLS]\nLINK 9 OPEN IF NODE 2 BELOW 110\nLINK 9 CLOSED IF NODE 2 ABOVE 140\nLINK 11 %s AT CLOCKTIME 2 AM\nLINK 12 %s AT CLOCKTIME 2 AM\nLINK 111 %s AT CLOCKTIME 2 AM\nLINK 112 %s AT CLOCKTIME 2 AM\nLINK 113 %s AT CLOCKTIME 2 AM\nLINK 21 %s AT CLOCKTIME 2 AM\nLINK 22 %s AT CLOCKTIME 2 AM\nLINK 121 %s AT CLOCKTIME 2 AM\nLINK 122 %s AT CLOCKTIME 2 AM\nLINK 31 %s AT CLOCKTIME 2 AM\n\n[ENERGY]\nGlobal Efficiency\t75\nGlobal Price\t0\nDemand Charge\t0\n\n[QUALITY]\n;Node\tInitQual\n10\t0\n11\t0\n12\t0\n13\t0\n21\t0\n22\t0\n23\t0\n31\t0\n32\t0\n9\t0\n2\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n11\tFLOWPACED\t2\t1\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0\nRoughness Correlation\t0\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nMessages\tNo\nPage\t0\nNodes\t10 11 12 13 21 22 23 31 32;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1\nViscosity\t1\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6

```
,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d
7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,
d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8
,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d
9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,
d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,v1,v2,v3,v4,v5,v6,v7,v8,v9,v10);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Reads EPANET output file (Base.rpt) to see if any error messages were reported in
%simulation
[mesg1,mesg2]=textread('Base.rpt','%s %s',1,'headerlines',12,'endofline','\r\n');

%Compares variable mesg1 to Node, if they are the same then linetitle1 is equal to 1
linetitle1 = strcmp(mesg1, 'Node');
%Compares variable mesg2 to Results, if they are the same then linetitle2 is equal to 1
linetitle2 = strcmp(mesg2, 'Results');
 %Adds the two variables together
disconnect = linetitle1+linetitle2;

%If disconnect is equal to zero then error messages were reported and therefore
%the nonlinear constraint was not met and ceq is equal to one
%In terms of reality, the error message means that the system was disconnected or
%caused negative pressures
if disconnect==0
    ceq=1;
else
    ceq=0;
end
```

APPENDIX L

INITIAL POPULATION FOR ANYTOWN FLUSHING RESPONSE

Table L-2. Initial Population for Anytown's Flushing Response.

Variable - dem

Individual	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	0	910	1	925	0	788	1	1073	1	853	0	780	0	1047	1	1163	1	662	0	647	1	910	1	745	0	1086	1	1097	0	1075	0	986
2	0	716	0	926	0	466	1	1216	0	832	0	1209	0	1043	1	1147	0	591	1	941	0	1023	0	776	0	693	1	403	0	1237	1	578
3	1	883	0	432	1	1021	1	1004	0	1154	0	1195	0	1222	0	1051	0	1080	0	887	0	857	0	406	1	1063	1	925	0	1138	1	1145
4	0	611	0	1018	1	1084	1	397	0	1188	0	1170	1	1275	0	1247	0	528	1	900	1	1238	0	686	0	718	1	514	0	1174	1	1272
5	1	724	0	724	1	559	1	827	0	808	1	948	1	1039	0	1112	1	740	1	984	0	1159	0	454	1	778	0	956	1	1019	1	1001
6	1	906	1	232	0	1124	1	1146	1	698	0	1135	0	917	0	1152	1	688	1	1205	1	955	0	252	0	691	0	1170	0	984	1	548
7	0	938	0	680	0	464	1	1229	1	755	0	987	1	1085	0	1261	1	957	0	844	1	957	1	1107	1	877	0	1029	1	1030	1	718
8	0	678	0	751	1	922	1	1179	0	835	1	1167	1	810	1	1113	1	955	0	752	0	625	0	1055	1	1028	0	494	1	1052	0	491
9	0	1124	1	803	1	1128	0	583	0	964	0	1134	0	837	1	1101	0	907	0	797	1	1112	1	569	1	1088	1	1062	1	942	1	863
10	0	1153	0	297	1	1006	0	721	0	1029	0	1108	0	726	0	1218	0	702	0	663	1	1160	1	932	1	1042	0	873	0	845	0	715
11	0	736	1	1141	0	835	1	888	0	727	0	768	1	1059	1	1094	0	976	1	1167	0	329	0	580	1	678	1	586	1	1091	0	405
12	0	739	1	668	1	491	1	811	0	647	0	892	0	845	0	1082	1	859	1	882	1	804	1	1038	1	1123	1	1118	0	1048	0	535
13	1	782	0	580	1	881	1	1206	0	1050	0	1020	0	1043	1	1223	1	1059	0	1248	0	905	0	684	0	897	1	504	1	1000	1	555
14	0	1025	1	739	1	961	1	1154	1	763	1	1032	0	1078	1	1132	0	689	0	846	1	893	1	1080	1	1023	0	456	0	868	1	704
15	1	1251	1	212	0	845	1	542	0	506	0	1203	0	1105	0	1278	1	1138	1	648	1	837	1	1045	0	278	0	634	0	1079	1	1179
16	0	594	1	475	1	892	1	1220	0	1063	1	1095	0	1140	1	1296	0	942	0	1265	0	356	1	695	0	914	1	604	0	822	1	806
17	0	1017	1	390	0	519	1	1262	0	1207	1	651	1	940	1	1016	0	681	0	965	0	819	1	887	1	508	1	1274	0	1094	0	540
18	1	1171	1	390	1	251	1	1244	1	693	1	1097	1	954	0	1105	0	674	0	1109	0	214	0	750	0	255	0	673	1	1017	0	398
19	1	1166	0	981	1	818	0	777	0	925	1	891	1	1169	1	1239	1	820	0	967	0	717	0	881	1	900	0	768	0	1066	1	943
20	0	529	0	200	0	200	0	200	0	500	1	878	0	500	1	1154	1	990	1	790	0	200	1	389	1	880	1	273	1	1069	1	231

APPENDIX M

GENETIC ALGORITHM (GA) CODE FOR ANYTOWN FLUSHING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Initial population range vector
IntPopRange=[0 500 0 200 0 200 0 200 0 500 0 500 0 500 0 1000 0 500 0 500 0 200 0
200 0 200 0 200 0 800 0 200; 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500
1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 ];

%Options for GA: initial population calls imported table FlushIntPop (See Appendix L),
%initial population range call IntPopRange from above
%StallGenLimit and StallTimeLimit are stopping criteria set to 100
%which means the optimization is stopped for StallGenLimit if the
%weighted average change in the fitness function value over Stall
%generations (100 for this application) is less than Function tolerance
%which means the optimization is stopped for StallTimeLimit if there
%is no improvement in the best fitness value for an interval of time
%in seconds specified by Stall time (100 for this application)
options = gaoptimset('InitialPopulation', FlushIntPop, 'PopInitRange', IntPopRange,
'StallGenLimit', 100, 'StallTimeLimit', 100);


%Lower and upper bounds on variables
%For decision variables whether to alter demand lower bound is 0 and
%upper bound is 1, the new demand has a lower bound of the base average demand
%and an upper bound of 1300 gallons per minute (gpm)
LB = [0; 500; 0; 200; 0; 200; 0; 200; 0; 500; 0; 500; 0; 500; 0; 1000; 0; 500; 0; 500; 0;
200; 0; 200; 0; 200; 0; 200; 0; 800; 0; 200];
UB = [1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1;
1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300];

%Linear constraint:
%d1+d2+d3+d4+d5+d6+d7+d8+d9+d10+d11+d12+d13+d14+d15+d16<=7600
%Helps ensure that the total demand in the network does not cause negative
%pressures
A = [0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1];
b = 7600;

%Assigns nonlinear constraint to call the nonlinear constraint function
%nonlconanytownflush in this case
ConstraintFcn=@nonlconanytownflush;

%GA optimization call is in this form
%[x,fval] = ga(fitnessfcn,nvars,A,b,Aeq,beq,LB,UB,nonlcon,options)
%The output from the optimization will be the dem (the decision variables)
%and the fval, fitness function value, (the total concentration)
%The GA calls the file with the function to be minimized
%flushallnodes is this case
%There are 32 variables, the inequality linear constraint information
```

%is contained in A and b, there are no equality linear constraint so [], the
%lower and upper bounds of the decision variables are given in LB and UB,
%the nonlinear constraints are given by variable ConstraintFcn defined
%above, and the options file information is given by the variable options
%defined above
[dem,fval] = ga(@flushallnodes,32,A,b,[],[],LB,UB,ConstraintFcn,options);

%Writes decision variables and fitness function value to Excel file
% xlswrite('ExcelFileName',[dem,fval],'TabName', 'Cell')
%For example, the ExcelFileName is GAFlushResults,
%the TabName is Results, and the Cell is C3
xlswrite('GAFlushResults',[dem,fval],'Results', 'C3')

APPENDIX N

FITNESS FUNCTION CODE FOR ANYTOWN FLUSHING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Creating the fitness function, where the
%output variable being minimized is concTot and
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the nodes at which to alter the demand; the new demands
%for these nodes;
function concTot = flushallnodes(dem)

%Process to determine if the nodal demand is going to change
%and the value of the nodal demand to utilize in the input file
%For example, if decision variable dem(1) is less than or equal to 0.5
%then the nodal demand will not be altered and the average base demand
%of 500 gallons per minute (gpm) will be used, otherwise the nodal
%demand will be altered and the value determined in decision
%variable dem(2) will be used in the input file
if dem(1)<=0.5
    %Demand at Node 20
    d1=500;
else
    d1=dem(2);
end
if dem(3)<=0.5
    %Demand at Node 30
    d2=200;
else
    d2=dem(4);
end
if dem(5)<=0.5
    %Demand at Node 40
    d3=200;
else
    d3=dem(6);
end
if dem(7)<=0.5
    %Demand at Node 50
    d4=200;
else
    d4=dem(8);
end
if dem(9)<=0.5
    %Demand at Node 60
    d5=500;
else
    d5=dem(10);
end
```

```matlab
if dem(11)<=0.5
    %Demand at Node 70
    d6=500;
else
    d6=dem(12);
end
if dem(13)<=0.5
    %Demand at Node 80
    d7=500;
else
    d7=dem(14);
end
if dem(15)<=0.5
    %Demand at Node 90
    d8=1000;
else
    d8=dem(16);
end
if dem(17)<=0.5
    %Demand at Node 100
    d9=500;
else
    d9=dem(18);
end
if dem(19)<=0.5
    %Demand at Node 110
    d10=500;
else
    d10=dem(20);
end
if dem(21)<=0.5
    %Demand at Node 120
    d11=200;
else
    d11=dem(22);
end
if dem(23)<=0.5
    %Demand at Node 130
    d12=200;
else
    d12=dem(24);
end
if dem(25)<=0.5
    %Demand at Node 140
    d13=200;
else
```

```matlab
        d13=dem(26);
end
if dem(27)<=0.5
    %Demand at Node 150
    d14=200;
else
    d14=dem(28);
end
if dem(29)<=0.5
    %Demand at Node 160
    d15=800;
else
    d15=dem(30);
end
if dem(31)<=0.5
    %Demand at Node 170
    d16=200;
else
    d16=dem(32);
end

%Command to open the file that is going to be changed
fid = fopen('anytown1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f is replaced with the demand,
fprintf(fid, '\n[TITLE]\nAnytown network model\n\n[JUNCTIONS]\n;ID\tElev
(ft)\tDemand
(gpm)\tPattern\n20\t20\t1\t3;\n30\t50\t1\t4;\n40\t50\t1\t5;\n50\t50\t1\t6;\n60\t50\t1\t8;\n7
0\t50\t1\t9;\n80\t50\t1\t11;\n90\t50\t1\t12;\n100\t50\t1\t13;\n110\t50\t1\t14;\n120\t120\t1
\t16;\n130\t120\t1\t17;\n140\t80\t1\t18;\n150\t120\t1\t19;\n160\t120\t1\t20;\n170\t120\t1\
t21;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n10\t10;\n\n[TANKS]\n;ID\tElevation\tInit
Level\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n65\t215\t\t10\t35\t16.3\t0;\n
165\t215\t\t10\t35\t16.3\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughn
ess\tMinorLoss\tStatus\n2\t20\t70\t12000\t16\t70\t0\tOpen;\n4\t20\t30\t12000\t12\t120\t0
\tOpen;\n6\t20\t110\t12000\t12\t70\t0\tOpen;\n8\t70\t30\t9000\t12\t70\t0\tOpen;\n10\t70\
t100\t6000\t12\t70\t0\tOpen;\n12\t70\t90\t6000\t10\t70\t0\tOpen;\n14\t70\t60\t6000\t12\t
70\t0\tOpen;\n16\t90\t60\t6000\t10\t70\t0\tOpen;\n18\t60\t80\t6000\t12\t70\t0\tOpen;\n2
0\t90\t80\t6000\t10\t70\t0\tOpen;\n22\t90\t150\t6000\t10\t70\t0\tOpen;\n24\t90\t100\t600
0\t10\t70\t0\tOpen;\n26\t100\t150\t6000\t12\t70\t0\tOpen;\n28\t150\t80\t6000\t10\t70\t0\t
Open;\n30\t60\t30\t6000\t10\t120\t0\tOpen;\n32\t30\t40\t6000\t10\t120\t0\tOpen;\n34\t30
\t50\t9000\t10\t120\t0\tOpen;\n36\t40\t50\t6000\t10\t120\t0\tOpen;\n38\t50\t80\t6000\t10
\t120\t0\tOpen;\n40\t80\t140\t6000\t10\t120\t0\tOpen;\n42\t150\t140\t6000\t8\t120\t0\tO
pen;\n44\t150\t160\t6000\t8\t120\t0\tOpen;\n46\t100\t160\t6000\t8\t120\t0\tOpen;\n48\t1
00\t110\t6000\t8\t70\t0\tOpen;\n50\t110\t160\t6000\t10\t120\t0\tOpen;\n52\t110\t120\t60
```

00\t8\t120\t0\tOpen;\n56\t120\t130\t6000\t8\t120\t0\tOpen;\n58\t130\t160\t6000\t10\t120
\t0\tOpen;\n60\t130\t170\t6000\t8\t120\t0\tOpen;\n62\t160\t140\t6000\t8\t120\t0\tOpen;\
n64\t170\t140\t12000\t80\t120\t0\tOpen;\n66\t50\t140\t12000\t8\t120\t0\tOpen;\n78\t60\t
65\t100\t12\t120\t0\tOpen;\n80\t165\t160\t100\t12\t120\t0\tOpen;\n\n[PUMPS]\n;ID\tNo
de1\tNode2\tParameters\n82\t10\t20\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Demand
Pattern\n2\t1\n2\t1\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n
1\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t
0\t0\n;Demand
Change\n3\t500\t500\t500\t500\t500\t500\n3\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f
%The variables are replaced wherever there is a %12.7f
\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t200\t200\t200\t200\t2
00\t200\n4\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n5\t200\t200\t200\t200\t200\t200\n5\t200\t200\t%12.7f\t%1
2.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t2
00\t200\t200\t200\t200\t200\n6\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\
n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\
t0\t0\n7\t0\t0\t0\t0\t0\t0\n8\t500\t500\t500\t500\t500\t500\n8\t500\t500\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.
7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t500\t
500\t500\t500\t500\t500\n9\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%1
2.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.
7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n1
0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t
0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n11\t500\t500\t500\t500\t500\t500\n11\t500\t500\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%
12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%
12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t

%12.7f\n12\t1000\t1000\t1000\t1000\t1000\t1000\n12\t1000\t1000\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t500\t500\t500\t500\t500\t500\n13\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t500\t500\t500\t500\t500\t500\n14\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n16\t200\t200\t200\t200\t200\t200\n16\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t200\t200\t200\t200\t200\t200\n17\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t200\t200\t200\t200\t200\t200\n18\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t200\t200\t200\t200\t200\t200\n19\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t800\t800\t800\t800\t800\t800\n20\t800\t800\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t200\t200\t200\t200\t200\t200\n21\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump

9\n1\t0\t300\n1\t2000\t292\n1\t4000\t270\n1\t6000\t230\n1\t8000\t181\n\n[ENERGY]\nGlobal Efficiency\t65\nGlobal Price\t0.0\nDemand Charge\t0.0\n\n[QUALITY]\n;Node\tInitQual\n20\t0\n30\t0\n40\t0\n50\t0\n55\t0\n60\t0\n70\t0\n75\t0\n80\t0\n90\t0\n100\t0\n110\t0\n115\t0\n120\t0\n130\t0\n140\t0\n150\t0\n160\t0\n170\t0\n10\t0\n65\t0\n165\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n30\tFLOWPACED\t2.0\t1\n\n[REACTIONS]\n;Type\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0.0\nRoughness Correlation\t0.0\n\n[MIXING]\n;Tank\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nPage\t0\nMessages\tYes\nNodes\t20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1.0\nViscosity\t1.0\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1.0\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d

%The variables that placed into the slots held by %12.7f

1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d1,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d1,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16);

%Command to close the file being changed

```matlab
fclose(fid);
%Command to run EPANET
!epanet.exe

%Code to read the output file created from EPANET
%Establishes the variables: i is the starting row in the matrix
%l is the starting line to read in the output file
i = 1;
l = 201;
%This establishes the amount of times that the output file must be read
%n begins with the time that response occurs and ends with the end
%of the 24-hr simulation, n changes value in increments of 30
%For this simulation, n begins reading the output file at 4-hr
%(240 minutes) and changes by 30 minutes until the end of the 24-hr
%(1440 minutes)
for n = 240:30:1440
    %k is the number of nodes
    for k = 1:16
        %Establishes a variable conc which reads the output file for
        %the concentration in each node
        conc = textread('anytown1.rpt','%*f%f',1,'headerlines',l,'endofline','\r\n');
        conct(i)=conc;
        %Increases the i to the next row of the matrix
        i = i + 1;
        %Increases the text line to the next line to read
        l = l + 1;
    end
    %Increases text line to skip header information
    l = l + 7;
end
%Calculates the total concentration in all nodes for all times
concTot = sum(conct);
```

APPENDIX O

**EPANET INPUT FILE CREATED BY METHODOLOGY FOR ANYTOWN
FLUSHING RESPONSE**

; EPANET input file created by methodology for flushing scenario
[TITLE]
Anytown network model

[JUNCTIONS]
;ID	Elev (ft)	Demand (gpm)	Pattern
20	20	1	3;
30	50	1	4;
40	50	1	5;
50	50	1	6;
60	50	1	8;
70	50	1	9;
80	50	1	11;
90	50	1	12;
100	50	1	13;
110	50	1	14;
120	120	1	16;
130	120	1	17;
140	80	1	18;
150	120	1	19;
160	120	1	20;
170	120	1	21;

[RESERVOIRS]
;ID	Head	Pattern
10	10;	

[TANKS]
;ID	Elevation	InitLevel	MinLevel	MaxLevel	Diameter	MinVol	VolCurve
65	215		10	35	16.3	0;	
165	215		10	35	16.3	0;	

[PIPES]
;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status
2	20	70	12000	16	70	0	Open;
4	20	30	12000	12	120	0	Open;
6	20	110	12000	12	70	0	Open;
8	70	30	9000	12	70	0	Open;
10	70	100	6000	12	70	0	Open;
12	70	90	6000	10	70	0	Open;
14	70	60	6000	12	70	0	Open;
16	90	60	6000	10	70	0	Open;
18	60	80	6000	12	70	0	Open;
20	90	80	6000	10	70	0	Open;

22	90	150	6000	10	70	0	Open;
24	90	100	6000	10	70	0	Open;
26	100	150	6000	12	70	0	Open;
28	150	80	6000	10	70	0	Open;
30	60	30	6000	10	120	0	Open;
32	30	40	6000	10	120	0	Open;
34	30	50	9000	10	120	0	Open;
36	40	50	6000	10	120	0	Open;
38	50	80	6000	10	120	0	Open;
40	80	140	6000	10	120	0	Open;
42	150	140	6000	8	120	0	Open;
44	150	160	6000	8	120	0	Open;
46	100	160	6000	8	120	0	Open;
48	100	110	6000	8	70	0	Open;
50	110	160	6000	10	120	0	Open;
52	110	120	6000	8	120	0	Open;
56	120	130	6000	8	120	0	Open;
58	130	160	6000	10	120	0	Open;
60	130	170	6000	8	120	0	Open;
62	160	140	6000	8	120	0	Open;
64	170	140	12000	80	120	0	Open;
66	50	140	12000	8	120	0	Open;
78	60	65	100	12	120	0	Open;
80	165	160	100	12	120	0	Open;

[PUMPS]
;ID   Node1   Node2   Parameters
82   10   20   HEAD 1;

[PATTERNS]
;ID   Multipliers
;Injection

1	1	1	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0

;Demand Change
;%12.7f is replaced with demand variables; either average base or the new demand

| 3 | 500 | 500 | 500 | 500 | 500 | 500 |
| 3 | 500 | 500 | %12.7f | %12.7f | %12.7f | %12.7f |

3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	200	200	200	200	200	200
4	200	200	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	200	200	200	200	200	200
5	200	200	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	200	200	200	200	200	200
6	200	200	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	500	500	500	500	500	500
8	500	500	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	500	500	500	500	500	500
9	500	500	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	500	500	500	500	500	500
11	500	500	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	1000	1000	1000	1000	1000	1000
12	1000	1000	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	500	500	500	500	500	500
13	500	500	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	500	500	500	500	500	500
14	500	500	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	200	200	200	200	200	200
16	200	200	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	200	200	200	200	200	200
17	200	200	%12.7f	%12.7f	%12.7f	%12.7f

17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	200	200	200	200	200	200
18	200	200	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	200	200	200	200	200	200
19	200	200	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	800	800	800	800	800	800
20	800	800	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	200	200	200	200	200	200
21	200	200	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

[CURVES]
;ID   X-Value   Y-Value
;PUMP: Pump Curve for Pump 9
1   0   300
1   2000   292

1	4000	270
1	6000	230
1	8000	181

[ENERGY]
Global Efficiency	65
Global Price	0
Demand Charge	0

[QUALITY]

;Node	InitQual
20	0
30	0
40	0
50	0
55	0
60	0
70	0
75	0
80	0
90	0
100	0
110	0
115	0
120	0
130	0
140	0
150	0
160	0
170	0
10	0
65	0
165	0

[SOURCES]

;Node	Type	Quality	Pattern
30	FLOWPACED	2	1

[REACTIONS]
Order Bulk	0
Order Tank	0
Order Wall	0
Global Bulk	0

Global Wall	0
Limiting Potential	0
Roughness Correlation	0

[TIMES]

Duration	24:00:00
Hydraulic Timestep	0:30
Quality Timestep	0:30
Pattern Timestep	0:30
Pattern Start	0:00
Report Timestep	0:30
Report Start	0:00
Start ClockTime	12:00 AM
Statistic	None

[REPORT]

Status	No
Summary	No
Page	0
Messages	No
Nodes	20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;
DEMAND	No
HEAD	No
PRESSURE	No
QUALITY	PRECISION 10
Links	None

[OPTIONS]

Units	GPM
Headloss	H-W
Specific Gravity	1
Viscosity	1
Trials	40
Accuracy	0.001
Unbalanced	Continue 10
Pattern	1
Demand Multiplier	1
Emitter Exponent	0.5
Quality	Chemical mg/L
Diffusivity	0
Tolerance	0.01

[END]

APPENDIX P

NONLINEAR CONSTRAINT CODE FOR ANYTOWN FLUSHING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Creating the nonlinear constraint function, where the
%output variables being c, nonlinear inequality constraint and
%ceq, nonlinear equality constraint
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the nodes at which to alter the demand; the new demands
%for these nodes;
function [c, ceq]=nonlconanytownflush(dem)

%There are no nonlinear equality constraint
c=[];

%Process to determine if the nodal demand is going to change
%and the value of the nodal demand to utilize in the input file
%For example, if decision variable dem(1) is less than or equal to 0.5
%then the nodal demand will not be altered and the average base demand
%of 500 gallons per minute (gpm) will be used, otherwise the nodal
%demand will be altered and the value determined in decision
%variable dem(2) will be used in the input file
if dem(1)<=0.5
    %Demand at Node 20
    d1=500;
else
    d1=dem(2);
end
if dem(3)<=0.5
    %Demand at Node 30
    d2=200;
else
    d2=dem(4);
end
if dem(5)<=0.5
    %Demand at Node 40
    d3=200;
else
    d3=dem(6);
end
if dem(7)<=0.5
    %Demand at Node 50
    d4=200;
else
    d4=dem(8);
end
if dem(9)<=0.5
    %Demand at Node 60
```

```matlab
    d5=500;
else
    d5=dem(10);
end
if dem(11)<=0.5
    %Demand at Node 70
    d6=500;
else
    d6=dem(12);
end
if dem(13)<=0.5
    %Demand at Node 80
    d7=500;
else
    d7=dem(14);
end
if dem(15)<=0.5
    %Demand at Node 90
    d8=1000;
else
    d8=dem(16);
end
if dem(17)<=0.5
    %Demand at Node 100
    d9=500;
else
    d9=dem(18);
end
if dem(19)<=0.5
    %Demand at Node 110
    d10=500;
else
    d10=dem(20);
end
if dem(21)<=0.5
    %Demand at Node 120
    d11=200;
else
    d11=dem(22);
end
if dem(23)<=0.5
    %Demand at Node 130
    d12=200;
else
    d12=dem(24);
end
```

```matlab
if dem(25)<=0.5
    %Demand at Node 140
    d13=200;
else
    d13=dem(26);
end
if dem(27)<=0.5
    %Demand at Node 150
    d14=200;
else
    d14=dem(28);
end
if dem(29)<=0.5
    %Demand at Node 160
    d15=800;
else
    d15=dem(30);
end
if dem(31)<=0.5
    %Demand at Node 170
    d16=200;
else
    d16=dem(32);
end

%Command to open the file that is going to be changed
fid = fopen('anytown1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f is replaced with the demand values
fprintf(fid, '\n[TITLE]\nAnytown network model\n\n[JUNCTIONS]\n;ID\tElev
(ft)\tDemand
(gpm)\tPattern\n20\t20\t1\t3;\n30\t50\t1\t4;\n40\t50\t1\t5;\n50\t50\t1\t6;\n60\t50\t1\t8;\n7
0\t50\t1\t9;\n80\t50\t1\t11;\n90\t50\t1\t12;\n100\t50\t1\t13;\n110\t50\t1\t14;\n120\t120\t1
\t16;\n130\t120\t1\t17;\n140\t80\t1\t18;\n150\t120\t1\t19;\n160\t120\t1\t20;\n170\t120\t1\
t21;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n10\t10;\n\n[TANKS]\n;ID\tElevation\tInit
Level\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n65\t215\t\t10\t35\t16.3\t0;\n
165\t215\t\t10\t35\t16.3\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughn
ess\tMinorLoss\tStatus\n2\t20\t70\t12000\t16\t70\t0\tOpen;\n4\t20\t30\t12000\t12\t120\t0
\tOpen;\n6\t20\t110\t12000\t12\t70\t0\tOpen;\n8\t70\t30\t9000\t12\t70\t0\tOpen;\n10\t70\
t100\t6000\t12\t70\t0\tOpen;\n12\t70\t90\t6000\t10\t70\t0\tOpen;\n14\t70\t60\t6000\t12\t
70\t0\tOpen;\n16\t90\t60\t6000\t10\t70\t0\tOpen;\n18\t60\t80\t6000\t12\t70\t0\tOpen;\n2
0\t90\t80\t6000\t10\t70\t0\tOpen;\n22\t90\t150\t6000\t10\t70\t0\tOpen;\n24\t90\t100\t600
0\t10\t70\t0\tOpen;\n26\t100\t150\t6000\t12\t70\t0\tOpen;\n28\t150\t80\t6000\t10\t70\t0\t
Open;\n30\t60\t30\t6000\t10\t120\t0\tOpen;\n32\t30\t40\t6000\t10\t120\t0\tOpen;\n34\t30
```

\t50\t9000\t10\t120\t0\tOpen;\n36\t40\t50\t6000\t10\t120\t0\tOpen;\n38\t50\t80\t6000\t10\t120\t0\tOpen;\n40\t80\t140\t6000\t10\t120\t0\tOpen;\n42\t150\t140\t6000\t8\t120\t0\tOpen;\n44\t150\t160\t6000\t8\t120\t0\tOpen;\n46\t100\t160\t6000\t8\t120\t0\tOpen;\n48\t100\t110\t6000\t8\t70\t0\tOpen;\n50\t110\t160\t6000\t10\t120\t0\tOpen;\n52\t110\t120\t6000\t8\t120\t0\tOpen;\n56\t120\t130\t6000\t8\t120\t0\tOpen;\n58\t130\t160\t6000\t10\t120\t0\tOpen;\n60\t130\t170\t6000\t8\t120\t0\tOpen;\n62\t160\t140\t6000\t8\t120\t0\tOpen;\n64\t170\t140\t12000\t80\t120\t0\tOpen;\n66\t50\t140\t12000\t8\t120\t0\tOpen;\n78\t60\t65\t100\t12\t120\t0\tOpen;\n80\t165\t160\t100\t12\t120\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n82\t10\t20\tHEAD 1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Demand Pattern\n2\t1\n2\t1\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n;Demand Change\n3\t500\t500\t500\t500\t500\t500\n3\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f
%The variables are replaced wherever there is a %12.7f
\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t200\t200\t200\t200\t200\t200\n4\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t200\t200\t200\t200\t200\t200\n5\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t200\t200\t200\t200\t200\t200\n6\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n8\t500\t500\t500\t500\t500\t500\n8\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t500\t500\t500\t500\t500\t500\n9\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n11\t500\t500\t500\t500\t500\t500\n11\t500\t500\t%12.7f\t

%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t1000\t1000\t1000\t1000\t1000\t1000\n12\t1000\t1000\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t500\t500\t500\t500\t500\t500\n13\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t500\t500\t500\t500\t500\t500\n14\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n16\t200\t200\t200\t200\t200\t200\n16\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t200\t200\t200\t200\t200\t200\n17\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t200\t200\t200\t200\t200\t200\n18\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t200\t200\t200\t200\t200\t200\n19\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t800\t800\t800\t800\t800\t800\n20\t800\t800\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t200\t200\t200\t200\t200\t200\n21\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1

2.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%1 2.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t0\t300\n1\t2000\t292\n1\t4000\t270\n1\t6000\t230\n1\t8000\t181\n\n[ENERGY]\n Global Efficiency\t65\nGlobal Price\t0.0\nDemand Charge\t0.0\n\n[QUALITY]\n;Node\tInitQual\n20\t0\n30\t0\n40\t0\n50\t0\n55\t0\n60\t0\ n70\t0\n75\t0\n80\t0\n90\t0\n100\t0\n110\t0\n115\t0\n120\t0\n130\t0\n140\t0\n150\t0\n1 60\t0\n170\t0\n10\t0\n65\t0\n165\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n30\ tFLOWPACED\t2.0\t1\n\n[REACTIONS]\n;Type\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0.0\nRoughness Correlation\t0.0\n\n[MIXING]\n;Tank\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nPage\t0\nMessages\tYe s\nNodes\t20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1.0\nViscosity\t1.0\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1.0\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d %The variables that placed into the slots held by %12.7f
1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2, d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2 ,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d 3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4, d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4 ,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d 5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6, d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7 ,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d 7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8, d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9 ,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d 9,d9,d9,d9,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10, d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d1 0,d10,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11, d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d1 1,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12, d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d1 3,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13, d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d14,d1 4,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14, d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d15,d15,d1 5,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,

d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d16,d16,d16,d1
6,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,
d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Reads EPANET output file (anytown1.rpt)to see if any error messages were reported in
%simulation
[mesg1,mesg2]=textread('anytown1.rpt','%s %s',1,'headerlines',11,'endofline','\r\n');

%Compares variable mesg1 to Node, if they are the same then linetitle1 is equal to 1
linetitle1 = strcmp(mesg1, 'Node');
%Compares variable mesg2 to Results, if they are the same then linetitle2 is equal to 1
linetitle2 = strcmp(mesg2, 'Results');
 %Adds the two variables together
disconnect = linetitle1+linetitle2;

%If disconnect is equal to zero then error messages were reported and therefore
%the nonlinear constraint was not met and ceq is equal to one
%In terms of reality, the error message means that the system was disconnected or
%caused negative pressures
if disconnect==0
   ceq=1;
else
   ceq=0;
end

APPENDIX Q

GENETIC ALGORITHM (GA) CODE FOR ANYTOWN VALVING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Options for GA: initial population, initial population range
%StallGenLimit and StallTimeLimit are stopping criteria set to 100
%which means the optimization is stopped for StallGenLimit if the
%weighted average change in the fitness function value over Stall
%generations (100 for this application) is less than Function tolerance
%which means the optimization is stopped for StallTimeLimit if there
%is no improvement in the best fitness value for an interval of time
%in seconds specified by Stall time (100 for this application)
options = gaoptimset('InitialPopulation', [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0; 1 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 1 0 0 0 0 0 1 0
0 0 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0; 0 1 0 0 0 0 0 0 1 0 0 0 0 0 0 1 0 0 0 0 1 0 0
0 0 1 0 0 0 0 0; 1 1 0 1 1 1 0 0 0 1 0 1 1 1 0 0 1 0 1 1 1 1 0 0 1 0 0 1 1 0 0 0; 1 1 0 1 1 1 0
0 0 1 0 1 1 1 1 0 0 1 0 0 1 0 0 1 0 1 0 0; 1 1 0 1 1 1 0 0 0 1 0 1 1 1 0 0 1 0 1 1 1 1
0 0 1 0 0 1 0 0 1 0; 1 1 0 1 1 1 0 0 0 1 0 1 1 1 0 0 1 0 0 0 1 1 0 0 1 0 0 1 0 0 1 1; 1 1 0 1 1
0 1 0 0 1 0 1 1 1 0 0 1 0 0 0 1 1 0 0 1 0 0 1 0 0 1 1; 1 1 0 1 1 0 0 1 0 1 0 1 1 1 0 0 1 0 0 0
1 1 0 0 1 0 0 1 0 0 1 1; 1 1 0 1 0 1 1 1 0 0 0 1 1 1 0 0 1 0 0 0 1 1 0 0 1 0 0 1 0 0 1 1; 1 1 0
1 0 1 1 1 0 0 0 1 1 1 0 0 1 0 1 1 1 1 0 0 1 0 0 1 0 0 1 0; 1 1 0 1 0 1 1 1 0 0 0 1 1 1 0 0 1 0
1 1 1 1 0 0 1 0 0 1 0 1 0 0; 1 1 0 1 0 1 1 1 0 0 0 1 1 1 0 0 1 0 1 1 1 1 0 0 1 0 0 1 1 0 0 0; 1
1 0 1 1 0 1 0 0 1 0 1 1 1 0 0 1 0 0 0 1 1 0 0 1 0 1 0 1 0 0 0 1 1; 1 1 0 1 1 0 0 1 0 1 0 1 1 1 0 0
1 0 0 0 1 1 0 0 1 0 1 0 0 0 1 1; 1 1 0 1 1 1 0 0 0 1 0 1 1 1 0 0 1 0 1 1 1 1 0 0 1 0 1 0 1 0 0
0; 1 1 0 1 1 0 0 0 0 1 0 1 1 1 0 0 1 0 1 1 1 1 0 0 1 0 1 0 0 0 1 0; 1 1 0 1 1 0 1 0 0 1 0 1 1 1
0 0 1 0 1 1 1 1 0 0 1 0 1 0 0 1 0 0; 1 1 0 1 1 0 0 1 0 1 0 1 1 1 0 0 1 0 1 1 1 1 0 0 1 0 1 0 1
0 0 0], 'PopInitRange', [0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0; 1 1 1
1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 ], 'StallGenLimit', 100,
'StallTimeLimit', 100);

%Lower and upper bounds on demand variables
%For decision variables whether to close pipe lower bound is 0 and upper bound is 1
LB = [0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0];
UB = [1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1];

%Assigns nonlinear constraint to call the nonlinear constraint function
%nonlconvalves in this case
ConstraintFcn=@nonlconvalves;

%GA optimization call is in this form
%[x,fval] = ga(fitnessfcn,nvars,A,b,Aeq,beq,LB,UB,nonlcon,options)
%The output from the optimization will be the dem (the decision variables)
%and the fval, fitness function value, (the total concentration)
%The GA calls the file with the function to be minimized
%valvegaany is this case
%There are 32 variables, there are no in/equality linear constraint so [], the
%lower and upper bounds of the decision variables are given in LB and UB,
%the nonlinear constraints are given by variable ConstraintFcn defined
%above, and the options file information is given by the variable options
```

```matlab
%defined above

[dem,fval] = ga(@valvegaany,32,[],[],[],[],LB,UB,ConstraintFcn,options);

%Writes decision variables and fitness function value to Excel file
% xlswrite('ExcelFileName',[dem,fval],'TabName', 'Cell')
%For example, the ExcelFileName is GAValveResults,
%the TabName is Results, and the Cell is C3
xlswrite('GAValveResults',[dem,fval],'Results', 'C3')
```

APPENDIX R

FITNESS FUNCTION CODE FOR ANYTOWN VALVING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Creating the fitness function, where the
%output variable being minimized is concTot and
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%which pipes to turn off or on
function concTot=valvegaany(dem)

d1=500;
d2=200;
d3=200;
d4=200;
d5=500;
d6=500;
d7=500;
d8=1000;
d9=500;
d10=500;
d11=200;
d12=200;
d13=200;
d14=200;
d15=800;
d16=200;

%Process to determine the status of the pipes
%For example, if decision variable dem(1) is less than or equal to 0.5
%then first pipe (Pipe 2) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(1)<=0.5
    %Status of Pipe 2
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(2)<=0.5
    %Status of Pipe 4
    v2o='OPEN';
    v2=v2o;
else
    v2c='CLOSED';
    v2=v2c;
end
if dem(3)<=0.5
```

```matlab
    %Status of Pipe 6
    v3o='OPEN';
    v3=v3o;
else
    v3c='CLOSED';
    v3=v3c;
end
if dem(4)<=0.5
    %Status of Pipe 8
    v4o='OPEN';
    v4=v4o;
else
    v4c='CLOSED';
    v4=v4c;
end
if dem(5)<=0.5
    %Status of Pipe 10
    v5o='OPEN';
    v5=v5o;
else
    v5c='CLOSED';
    v5=v5c;
end
if dem(6)<=0.5
    %Status of Pipe 12
    v6o='OPEN';
    v6=v6o;
else
    v6c='CLOSED';
    v6=v6c;
end
if dem(7)<=0.5
    %Status of Pipe 14
    v7o='OPEN';
    v7=v7o;
else
    v7c='CLOSED';
    v7=v7c;
end
if dem(8)<=0.5
    %Status of Pipe 16
    v8o='OPEN';
    v8=v8o;
else
    v8c='CLOSED';
    v8=v8c;
```

```matlab
end
if dem(9)<=0.5
    %Status of Pipe 18
    v9o='OPEN';
    v9=v9o;
else
    v9c='CLOSED';
    v9=v9c;
end
if dem(10)<=0.5
    %Status of Pipe 20
    v10o='OPEN';
    v10=v10o;
else
    v10c='CLOSED';
    v10=v10c;
end
if dem(11)<=0.5
    %Status of Pipe 22
    v11o='OPEN';
    v11=v11o;
else
    v11c='CLOSED';
    v11=v11c;
end
if dem(12)<=0.5
    %Status of Pipe 24
    v12o='OPEN';
    v12=v12o;
else
    v12c='CLOSED';
    v12=v12c;
end
if dem(13)<=0.5
    %Status of Pipe 26
    v13o='OPEN';
    v13=v13o;
else
    v13c='CLOSED';
    v13=v13c;
end
if dem(14)<=0.5
    %Status of Pipe 28
    v14o='OPEN';
    v14=v14o;
else
```

```matlab
        v14c='CLOSED';
        v14=v14c;
end
if dem(15)<=0.5
        %Status of Pipe 30
        v15o='OPEN';
        v15=v15o;
else
        v15c='CLOSED';
        v15=v15c;
end
if dem(16)<=0.5
        %Status of Pipe 32
        v16o='OPEN';
        v16=v16o;
else
        v16c='CLOSED';
        v16=v16c;
end
if dem(17)<=0.5
        %Status of Pipe 34
        v17o='OPEN';
        v17=v17o;
else
        v17c='CLOSED';
        v17=v17c;
end
if dem(18)<=0.5
        %Status of Pipe 36
        v18o='OPEN';
        v18=v18o;
else
        v18c='CLOSED';
        v18=v18c;
end
if dem(19)<=0.5
        %Status of Pipe 38
        v19o='OPEN';
        v19=v19o;
else
        v19c='CLOSED';
        v19=v19c;
end
if dem(20)<=0.5
        %Status of Pipe 40
        v20o='OPEN';
```

```matlab
    v20=v20o;
else
    v20c='CLOSED';
    v20=v20c;
end
if dem(21)<=0.5
    %Status of Pipe 42
    v21o='OPEN';
    v21=v21o;
else
    v21c='CLOSED';
    v21=v21c;
end
if dem(22)<=0.5
    %Status of Pipe 44
    v22o='OPEN';
    v22=v22o;
else
    v22c='CLOSED';
    v22=v22c;
end
if dem(23)<=0.5
    %Status of Pipe 46
    v23o='OPEN';
    v23=v23o;
else
    v23c='CLOSED';
    v23=v23c;
end
if dem(24)<=0.5
    %Status of Pipe 48
    v24o='OPEN';
    v24=v24o;
else
    v24c='CLOSED';
    v24=v24c;
end
if dem(25)<=0.5
    %Status of Pipe 50
    v25o='OPEN';
    v25=v25o;
else
    v25c='CLOSED';
    v25=v25c;
end
if dem(26)<=0.5
```

```matlab
    %Status of Pipe 52
    v26o='OPEN';
    v26=v26o;
else
    v26c='CLOSED';
    v26=v26c;
end
if dem(27)<=0.5
    %Status of Pipe 56
    v27o='OPEN';
    v27=v27o;
else
    v27c='CLOSED';
    v27=v27c;
end
if dem(28)<=0.5
    %Status of Pipe 58
    v28o='OPEN';
    v28=v28o;
else
    v28c='CLOSED';
    v28=v28c;
end
if dem(29)<=0.5
    %Status of Pipe 60
    v29o='OPEN';
    v29=v29o;
else
    v29c='CLOSED';
    v29=v29c;
end
if dem(30)<=0.5
    %Status of Pipe 62
    v30o='OPEN';
    v30=v30o;
else
    v30c='CLOSED';
    v30=v30c;
end
if dem(31)<=0.5
    %Status of Pipe 64
    v31o='OPEN';
    v31=v31o;
else
    v31c='CLOSED';
    v31=v31c;
```

```matlab
end
if dem(32)<=0.5
    %Status of Pipe 66
    v32o='OPEN';
    v32=v32o;
else
    v32c='CLOSED';
    v32=v32c;
end


%Command to open the file that is going to be changed
fid = fopen('anytown1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f is replaced by the demand value, while %s is replaced with pipe status
fprintf(fid, '\n[TITLE]\nAnytown network model\n\n[JUNCTIONS]\n;ID\tElev
(ft)\tDemand
(gpm)\tPattern\n20\t20\t1\t3;\n30\t50\t1\t4;\n40\t50\t1\t5;\n50\t50\t1\t6;\n60\t50\t1\t8;\n70\t50\t1\t9;\n80\t50\t1\t11;\n90\t50\t1\t12;\n100\t50\t1\t13;\n110\t50\t1\t14;\n120\t120\t1\t16;\n130\t120\t1\t17;\n140\t80\t1\t18;\n150\t120\t1\t19;\n160\t120\t1\t20;\n170\t120\t1\t21;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n10\t10;\n\n[TANKS]\n;ID\tElevation\tInitLevel\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n65\t215\t\t10\t35\t16.3\t0;\n165\t215\t\t10\t35\t16.3\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughness\tMinorLoss\tStatus\n2\t20\t70\t12000\t16\t70\t0\tOpen;\n4\t20\t30\t12000\t12\t120\t0\tOpen;\n6\t20\t110\t12000\t12\t70\t0\tOpen;\n8\t70\t30\t9000\t12\t70\t0\tOpen;\n10\t70\t100\t6000\t12\t70\t0\tOpen;\n12\t70\t90\t6000\t10\t70\t0\tOpen;\n14\t70\t60\t6000\t12\t70\t0\tOpen;\n16\t90\t60\t6000\t10\t70\t0\tOpen;\n18\t60\t80\t6000\t12\t70\t0\tOpen;\n20\t90\t80\t6000\t10\t70\t0\tOpen;\n22\t90\t150\t6000\t10\t70\t0\tOpen;\n24\t90\t100\t6000\t10\t70\t0\tOpen;\n26\t100\t150\t6000\t12\t70\t0\tOpen;\n28\t150\t80\t6000\t10\t70\t0\tOpen;\n30\t60\t30\t6000\t10\t120\t0\tOpen;\n32\t30\t40\t6000\t10\t120\t0\tOpen;\n34\t30\t50\t9000\t10\t120\t0\tOpen;\n36\t40\t50\t6000\t10\t120\t0\tOpen;\n38\t50\t80\t6000\t10\t120\t0\tOpen;\n40\t80\t140\t6000\t10\t120\t0\tOpen;\n42\t150\t140\t6000\t8\t120\t0\tOpen;\n44\t150\t160\t6000\t8\t120\t0\tOpen;\n46\t100\t160\t6000\t8\t120\t0\tOpen;\n48\t100\t110\t6000\t8\t70\t0\tOpen;\n50\t110\t160\t6000\t10\t120\t0\tOpen;\n52\t110\t120\t6000\t8\t120\t0\tOpen;\n56\t120\t130\t6000\t8\t120\t0\tOpen;\n58\t130\t160\t6000\t10\t120\t0\tOpen;\n60\t130\t170\t6000\t8\t120\t0\tOpen;\n62\t160\t140\t6000\t8\t120\t0\tOpen;\n64\t170\t140\t12000\t80\t120\t0\tOpen;\n66\t50\t140\t12000\t8\t120\t0\tOpen;\n78\t60\t65\t100\t12\t120\t0\tOpen;\n80\t165\t160\t100\t12\t120\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n82\t10\t20\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Demand
Pattern\n2\t1\n2\t1\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n;Demand
Change\n3\t500\t500\t500\t500\t500\t500\n3\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f
%The variables are placed into the input code wherever there is a %12.7f
```

\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t200\t200\t200\t200\t200\t200\n4\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t200\t200\t200\t200\t200\t200\n5\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t200\t200\t200\t200\t200\t200\n6\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n8\t500\t500\t500\t500\t500\t500\n8\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t500\t500\t500\t500\t500\t500\n9\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n11\t500\t500\t500\t500\t500\t500\n11\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t1000\t1000\t1000\t1000\t1000\t1000\n12\t1000\t1000\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t500\t500\t500\t500\t500\t500\n13\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t500\t500\t500\t500\t500\t500\n14\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%

12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n16\t200\t200\t200\t200\t200\t200\n16\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t200\t200\t200\t200\t200\t200\n17\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t200\t200\t200\t200\t200\t200\n18\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t200\t200\t200\t200\t200\t200\n19\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t800\t800\t800\t800\t800\t800\n20\t800\t800\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t200\t200\t200\t200\t200\t200\n21\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t0\t300\n1\t2000\t292\n1\t4000\t270\n1\t6000\t230\n1\t8000\t181\n\n\n[CONTROLS]\nLINK 2 %s AT CLOCKTIME 4 AM\nLINK 4 %s AT CLOCKTIME 4 AM\nLINK 6 %s AT CLOCKTIME 4 AM\nLINK 8 %s AT CLOCKTIME 4 AM\nLINK 10 %s AT CLOCKTIME 4 AM\nLINK 12 %s AT CLOCKTIME 4 AM\nLINK 14 %s AT CLOCKTIME 4 AM\nLINK 16 %s AT CLOCKTIME 4 AM\nLINK 18 %s AT CLOCKTIME 4 AM\nLINK 20 %s AT CLOCKTIME 4 AM\nLINK 22 %s AT CLOCKTIME 4 AM\nLINK 24 %s AT CLOCKTIME 4 AM\nLINK 26 %s AT CLOCKTIME 4 AM\nLINK 28 %s AT CLOCKTIME 4 AM\nLINK 30 %s AT CLOCKTIME 4 AM\nLINK 32 %s AT CLOCKTIME 4 AM\nLINK 34 %s AT CLOCKTIME 4 AM\nLINK 36 %s AT CLOCKTIME 4 AM\nLINK 38 %s AT CLOCKTIME 4 AM\nLINK 40 %s AT CLOCKTIME 4 AM\nLINK 42 %s AT

CLOCKTIME 4 AM\nLINK 44 %s AT CLOCKTIME 4 AM\nLINK 46 %s AT CLOCKTIME 4 AM\nLINK 48 %s AT CLOCKTIME 4 AM\nLINK 50 %s AT CLOCKTIME 4 AM\nLINK 52 %s AT CLOCKTIME 4 AM\nLINK 56 %s AT CLOCKTIME 4 AM\nLINK 58 %s AT CLOCKTIME 4 AM\nLINK 60 %s AT CLOCKTIME 4 AM\nLINK 62 %s AT CLOCKTIME 4 AM\nLINK 64 %s AT CLOCKTIME 4 AM\nLINK 66 %s AT CLOCKTIME 4 AM\n\n\n[ENERGY]\nGlobal Efficiency\t65\nGlobal Price\t0.0\nDemand Charge\t0.0\n\n[QUALITY]\n;Node\tInitQual\n20\t0\n30\t0\n40\t0\n50\t0\n55\t0\n60\t0\n70\t0\n75\t0\n80\t0\n90\t0\n100\t0\n110\t0\n115\t0\n120\t0\n130\t0\n140\t0\n150\t0\n160\t0\n170\t0\n10\t0\n65\t0\n165\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n30\tFLOWPACED\t2.0\t1\n\n[REACTIONS]\n;Type\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0.0\nRoughness Correlation\t0.0\n\n[MIXING]\n;Tank\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nPage\t0\nMessages\tYes\nNodes\t20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1.0\nViscosity\t1.0\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1.0\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d
%The d# variables that are being placed into the %12.7f spots, while v# variables are
%placed in %s spots
1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,

d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d15,d15,d1
5,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,
d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d16,d16,d16,d1
6,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,
d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,v1,v2,v3,v4,v5,v6,v
7,v8,v9,v10,v11,v12,v13,v14,v15,v16,v17,v18,v19,v20,v21,v22,v23,v24,v25,v26,v27,v2
8,v29,v30,v31,v32);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Code to read the output file created from EPANET
%Establishes the variables: i is the starting row in the matrix
%l is the starting line to read in the output file
i = 1;
l = 201;
%This establishes the amount of times that the output file must be read
%n begins with the time that response occurs and ends with the end
%of the 24-hr simulation, n changes value in increments of 30
%For this simulation, n begins reading the output file at 4-hr
%(240 minutes) and changes by 30 minutes until the end of the 24-hr
%(1440 minutes)
for n = 240:30:1440
    %k is the number of nodes
    for k = 1:16
        %Establishes a variable conc which reads the output file for
        %the concentration in each node
        conc = textread('anytown1.rpt','%*f%f',1,'headerlines',l,'endofline','\r\n');
        conct(i)=conc;
        %Increases the i to the next row of the matrix
        i = i + 1;
        %Increases the text line to the next line to read
        l = l + 1;
    end
    %Increases text line to skip header information
    l = l + 7;
end
%Calculates the total concentration in all nodes for all times
concTot = sum(conct);

APPENDIX S

EPANET INPUT FILE CREATED BY METHODOLOGY FOR ANYTOWN VALVING RESPONSE

; EPANET input file created by methodology for valving scenario
[TITLE]
Anytown network model

[JUNCTIONS]
;ID	Elev (ft)	Demand (gpm)	Pattern
20	20	1	3;
30	50	1	4;
40	50	1	5;
50	50	1	6;
60	50	1	8;
70	50	1	9;
80	50	1	11;
90	50	1	12;
100	50	1	13;
110	50	1	14;
120	120	1	16;
130	120	1	17;
140	80	1	18;
150	120	1	19;
160	120	1	20;
170	120	1	21;

[RESERVOIRS]
;ID	Head	Pattern
10	10;	

[TANKS]
;ID	Elevation	InitLevel	MinLevel	MaxLevel	Diameter	MinVol	VolCurve
65	215		10	35	16.3	0;	
165	215		10	35	16.3	0;	

[PIPES]
;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status
2	20	70	12000	16	70	0	Open;
4	20	30	12000	12	120	0	Open;
6	20	110	12000	12	70	0	Open;
8	70	30	9000	12	70	0	Open;
10	70	100	6000	12	70	0	Open;
12	70	90	6000	10	70	0	Open;
14	70	60	6000	12	70	0	Open;
16	90	60	6000	10	70	0	Open;
18	60	80	6000	12	70	0	Open;

20	90	80	6000	10	70	0	Open;
22	90	150	6000	10	70	0	Open;
24	90	100	6000	10	70	0	Open;
26	100	150	6000	12	70	0	Open;
28	150	80	6000	10	70	0	Open;
30	60	30	6000	10	120	0	Open;
32	30	40	6000	10	120	0	Open;
34	30	50	9000	10	120	0	Open;
36	40	50	6000	10	120	0	Open;
38	50	80	6000	10	120	0	Open;
40	80	140	6000	10	120	0	Open;
42	150	140	6000	8	120	0	Open;
44	150	160	6000	8	120	0	Open;
46	100	160	6000	8	120	0	Open;
48	100	110	6000	8	70	0	Open;
50	110	160	6000	10	120	0	Open;
52	110	120	6000	8	120	0	Open;
56	120	130	6000	8	120	0	Open;
58	130	160	6000	10	120	0	Open;
60	130	170	6000	8	120	0	Open;
62	160	140	6000	8	120	0	Open;
64	170	140	12000	80	120	0	Open;
66	50	140	12000	8	120	0	Open;
78	60	65	100	12	120	0	Open;
80	165	160	100	12	120	0	Open;

[PUMPS]
;ID   Node1   Node2   Parameters
82   10   20   HEAD 1;

[PATTERNS]
;ID   Multipliers
;Injection

1	1	1	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0

;Demand Change
;%12.7f is replaced with demand variables; either average base or the new demand

3	500	500	500	500	500	500
3	500	500	500	500	500	500
3	500	500	500	500	500	500
3	500	500	500	500	500	500
3	500	500	500	500	500	500
3	500	500	500	500	500	500
3	500	500	500	500	500	500
3	500	500	500	500	500	500
4	200	200	200	200	200	200
4	200	200	200	200	200	200
4	200	200	200	200	200	200
4	200	200	200	200	200	200
4	200	200	200	200	200	200
4	200	200	200	200	200	200
4	200	200	200	200	200	200
4	200	200	200	200	200	200
5	200	200	200	200	200	200
5	200	200	200	200	200	200
5	200	200	200	200	200	200
5	200	200	200	200	200	200
5	200	200	200	200	200	200
5	200	200	200	200	200	200
5	200	200	200	200	200	200
5	200	200	200	200	200	200
6	200	200	200	200	200	200
6	200	200	200	200	200	200
6	200	200	200	200	200	200
6	200	200	200	200	200	200
6	200	200	200	200	200	200
6	200	200	200	200	200	200
6	200	200	200	200	200	200
6	200	200	200	200	200	200
8	500	500	500	500	500	500
8	500	500	500	500	500	500
8	500	500	500	500	500	500
8	500	500	500	500	500	500
8	500	500	500	500	500	500
8	500	500	500	500	500	500
8	500	500	500	500	500	500
8	500	500	500	500	500	500
9	500	500	500	500	500	500
9	500	500	500	500	500	500
9	500	500	500	500	500	500

9	500	500	500	500	500	500
9	500	500	500	500	500	500
9	500	500	500	500	500	500
9	500	500	500	500	500	500
9	500	500	500	500	500	500
11	500	500	500	500	500	500
11	500	500	500	500	500	500
11	500	500	500	500	500	500
11	500	500	500	500	500	500
11	500	500	500	500	500	500
11	500	500	500	500	500	500
11	500	500	500	500	500	500
11	500	500	500	500	500	500
12	1000	1000	1000	1000	1000	1000
12	1000	1000	1000	1000	1000	1000
12	1000	1000	1000	1000	1000	1000
12	1000	1000	1000	1000	1000	1000
12	1000	1000	1000	1000	1000	1000
12	1000	1000	1000	1000	1000	1000
12	1000	1000	1000	1000	1000	1000
12	1000	1000	1000	1000	1000	1000
13	500	500	500	500	500	500
13	500	500	500	500	500	500
13	500	500	500	500	500	500
13	500	500	500	500	500	500
13	500	500	500	500	500	500
13	500	500	500	500	500	500
13	500	500	500	500	500	500
13	500	500	500	500	500	500
14	500	500	500	500	500	500
14	500	500	500	500	500	500
14	500	500	500	500	500	500
14	500	500	500	500	500	500
14	500	500	500	500	500	500
14	500	500	500	500	500	500
14	500	500	500	500	500	500
14	500	500	500	500	500	500
16	200	200	200	200	200	200
16	200	200	200	200	200	200
16	200	200	200	200	200	200
16	200	200	200	200	200	200
16	200	200	200	200	200	200
16	200	200	200	200	200	200

16	200	200	200	200	200	200
16	200	200	200	200	200	200
17	200	200	200	200	200	200
17	200	200	200	200	200	200
17	200	200	200	200	200	200
17	200	200	200	200	200	200
17	200	200	200	200	200	200
17	200	200	200	200	200	200
17	200	200	200	200	200	200
18	200	200	200	200	200	200
18	200	200	200	200	200	200
18	200	200	200	200	200	200
18	200	200	200	200	200	200
18	200	200	200	200	200	200
18	200	200	200	200	200	200
18	200	200	200	200	200	200
18	200	200	200	200	200	200
19	200	200	200	200	200	200
19	200	200	200	200	200	200
19	200	200	200	200	200	200
19	200	200	200	200	200	200
19	200	200	200	200	200	200
19	200	200	200	200	200	200
19	200	200	200	200	200	200
19	200	200	200	200	200	200
20	800	800	800	800	800	800
20	800	800	800	800	800	800
20	800	800	800	800	800	800
20	800	800	800	800	800	800
20	800	800	800	800	800	800
20	800	800	800	800	800	800
20	800	800	800	800	800	800
20	800	800	800	800	800	800
21	200	200	200	200	200	200
21	200	200	200	200	200	200
21	200	200	200	200	200	200
21	200	200	200	200	200	200
21	200	200	200	200	200	200
21	200	200	200	200	200	200
21	200	200	200	200	200	200
21	200	200	200	200	200	200

[CURVES]
;ID   X-Value   Y-Value
;PUMP: Pump Curve for Pump 9
1   0   300
1   2000   292
1   4000   270
1   6000   230
1   8000   181

[CONTROLS]
; %s is replaced with the pipe status; either OPEN or CLOSED
LINK 2 %s AT CLOCKTIME 4 AM
LINK 4 %s AT CLOCKTIME 4 AM
LINK 6 %s AT CLOCKTIME 4 AM
LINK 8 %s AT CLOCKTIME 4 AM
LINK 10 %s AT CLOCKTIME 4 AM
LINK 12 %s AT CLOCKTIME 4 AM
LINK 14 %s AT CLOCKTIME 4 AM
LINK 16 %s AT CLOCKTIME 4 AM
LINK 18 %s AT CLOCKTIME 4 AM
LINK 20 %s AT CLOCKTIME 4 AM
LINK 22 %s AT CLOCKTIME 4 AM
LINK 24 %s AT CLOCKTIME 4 AM
LINK 26 %s AT CLOCKTIME 4 AM
LINK 28 %s AT CLOCKTIME 4 AM
LINK 30 %s AT CLOCKTIME 4 AM
LINK 32 %s AT CLOCKTIME 4 AM
LINK 34 %s AT CLOCKTIME 4 AM
LINK 36 %s AT CLOCKTIME 4 AM
LINK 38 %s AT CLOCKTIME 4 AM
LINK 40 %s AT CLOCKTIME 4 AM
LINK 42 %s AT CLOCKTIME 4 AM
LINK 44 %s AT CLOCKTIME 4 AM
LINK 46 %s AT CLOCKTIME 4 AM
LINK 48 %s AT CLOCKTIME 4 AM
LINK 50 %s AT CLOCKTIME 4 AM
LINK 52 %s AT CLOCKTIME 4 AM
LINK 56 %s AT CLOCKTIME 4 AM
LINK 58 %s AT CLOCKTIME 4 AM
LINK 60 %s AT CLOCKTIME 4 AM
LINK 62 %s AT CLOCKTIME 4 AM
LINK 64 %s AT CLOCKTIME 4 AM
LINK 66 %s AT CLOCKTIME 4 AM

[ENERGY]
Global Efficiency   65
Global Price   0
Demand Charge   0

[QUALITY]
;Node   InitQual
20   0
30   0
40   0
50   0
55   0
60   0
70   0
75   0
80   0
90   0
100   0
110   0
115   0
120   0
130   0
140   0
150   0
160   0
170   0
10   0
65   0
165   0

[SOURCES]
;Node   Type   Quality   Pattern
30   FLOWPACED   2   1

[REACTIONS]
Order Bulk   0
Order Tank   0
Order Wall   0
Global Bulk   0
Global Wall   0
Limiting Potential   0
Roughness Correlation   0

[TIMES]
Duration   24:00:00
Hydraulic Timestep   0:30
Quality Timestep   0:30
Pattern Timestep   0:30
Pattern Start   0:00
Report Timestep   0:30
Report Start   0:00
Start ClockTime   12:00 AM
Statistic   None

[REPORT]
Status   No
Summary   No
Page   0
Messages   No
Nodes   20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;
DEMAND   No
HEAD   No
PRESSURE   No
QUALITY   PRECISION 10
Links   None

[OPTIONS]
Units   GPM
Headloss   H-W
Specific Gravity   1
Viscosity   1
Trials   40
Accuracy   0.001
Unbalanced   Continue 10
Pattern   1
Demand Multiplier   1
Emitter Exponent   0.5
Quality   Chemical mg/L
Diffusivity   0
Tolerance   0.01

[END]

APPENDIX T

NONLINEAR CONSTRAINT CODE FOR ANYTOWN FOR VALVING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Creating the nonlinear constraint function, where the
%output variables being c, nonlinear inequality constraint and
%ceq, nonlinear equality constraint
%the design variables being altered are dem, where
%dem is composed of the location of pipe closures
function [c, ceq]=nonlconvalves(dem)

%There are no nonlinear equality constraint
c=[];

d1=500;
d2=200;
d3=200;
d4=200;
d5=500;
d6=500;
d7=500;
d8=1000;
d9=500;
d10=500;
d11=200;
d12=200;
d13=200;
d14=200;
d15=800;
d16=200;

%Process to determine the status of the pipes
%For example, if decision variable dem(1) is less than or equal to 0.5
%then first pipe (Pipe 2) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(1)<=0.5
    %Status of Pipe 2
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(2)<=0.5
    %Status of Pipe 4
    v2o='OPEN';
    v2=v2o;
else
    v2c='CLOSED';
```

```matlab
    v2=v2c;
end
if dem(3)<=0.5
    %Status of Pipe 6
    v3o='OPEN';
    v3=v3o;
else
    v3c='CLOSED';
    v3=v3c;
end
if dem(4)<=0.5
    %Status of Pipe 8
    v4o='OPEN';
    v4=v4o;
else
    v4c='CLOSED';
    v4=v4c;
end
if dem(5)<=0.5
    %Status of Pipe 10
    v5o='OPEN';
    v5=v5o;
else
    v5c='CLOSED';
    v5=v5c;
end
if dem(6)<=0.5
    %Status of Pipe 12
    v6o='OPEN';
    v6=v6o;
else
    v6c='CLOSED';
    v6=v6c;
end
if dem(7)<=0.5
    %Status of Pipe 14
    v7o='OPEN';
    v7=v7o;
else
    v7c='CLOSED';
    v7=v7c;
end
if dem(8)<=0.5
    %Status of Pipe 16
    v8o='OPEN';
    v8=v8o;
```

```matlab
else
    v8c='CLOSED';
    v8=v8c;
end
if dem(9)<=0.5
    %Status of Pipe 18
    v9o='OPEN';
    v9=v9o;
else
    v9c='CLOSED';
    v9=v9c;
end
if dem(10)<=0.5
    %Status of Pipe 20
    v10o='OPEN';
    v10=v10o;
else
    v10c='CLOSED';
    v10=v10c;
end
if dem(11)<=0.5
    %Status of Pipe 22
    v11o='OPEN';
    v11=v11o;
else
    v11c='CLOSED';
    v11=v11c;
end
if dem(12)<=0.5
    %Status of Pipe 24
    v12o='OPEN';
    v12=v12o;
else
    v12c='CLOSED';
    v12=v12c;
end
if dem(13)<=0.5
    %Status of Pipe 26
    v13o='OPEN';
    v13=v13o;
else
    v13c='CLOSED';
    v13=v13c;
end
if dem(14)<=0.5
    %Status of Pipe 28
```

```matlab
    v14o='OPEN';
    v14=v14o;
else
    v14c='CLOSED';
    v14=v14c;
end
if dem(15)<=0.5
    %Status of Pipe 30
    v15o='OPEN';
    v15=v15o;
else
    v15c='CLOSED';
    v15=v15c;
end
if dem(16)<=0.5
    %Status of Pipe 32
    v16o='OPEN';
    v16=v16o;
else
    v16c='CLOSED';
    v16=v16c;
end
if dem(17)<=0.5
    %Status of Pipe 34
    v17o='OPEN';
    v17=v17o;
else
    v17c='CLOSED';
    v17=v17c;
end
if dem(18)<=0.5
    %Status of Pipe 36
    v18o='OPEN';
    v18=v18o;
else
    v18c='CLOSED';
    v18=v18c;
end
if dem(19)<=0.5
    %Status of Pipe 38
    v19o='OPEN';
    v19=v19o;
else
    v19c='CLOSED';
    v19=v19c;
end
```

```matlab
if dem(20)<=0.5
    %Status of Pipe 40
    v20o='OPEN';
    v20=v20o;
else
    v20c='CLOSED';
    v20=v20c;
end
if dem(21)<=0.5
    %Status of Pipe 42
    v21o='OPEN';
    v21=v21o;
else
    v21c='CLOSED';
    v21=v21c;
end
if dem(22)<=0.5
    %Status of Pipe 44
    v22o='OPEN';
    v22=v22o;
else
    v22c='CLOSED';
    v22=v22c;
end
if dem(23)<=0.5
    %Status of Pipe 46
    v23o='OPEN';
    v23=v23o;
else
    v23c='CLOSED';
    v23=v23c;
end
if dem(24)<=0.5
    %Status of Pipe 48
    v24o='OPEN';
    v24=v24o;
else
    v24c='CLOSED';
    v24=v24c;
end
if dem(25)<=0.5
    %Status of Pipe 50
    v25o='OPEN';
    v25=v25o;
else
    v25c='CLOSED';
```

```matlab
    v25=v25c;
end
if dem(26)<=0.5
    %Status of Pipe 52
    v26o='OPEN';
    v26=v26o;
else
    v26c='CLOSED';
    v26=v26c;
end
if dem(27)<=0.5
    %Status of Pipe 56
    v27o='OPEN';
    v27=v27o;
else
    v27c='CLOSED';
    v27=v27c;
end
if dem(28)<=0.5
    %Status of Pipe 58
    v28o='OPEN';
    v28=v28o;
else
    v28c='CLOSED';
    v28=v28c;
end
if dem(29)<=0.5
    %Status of Pipe 60
    v29o='OPEN';
    v29=v29o;
else
    v29c='CLOSED';
    v29=v29c;
end
if dem(30)<=0.5
    %Status of Pipe 62
    v30o='OPEN';
    v30=v30o;
else
    v30c='CLOSED';
    v30=v30c;
end
if dem(31)<=0.5
    %Status of Pipe 64
    v31o='OPEN';
    v31=v31o;
```

```matlab
else
    v31c='CLOSED';
    v31=v31c;
end
if dem(32)<=0.5
    %Status of Pipe 66
    v32o='OPEN';
    v32=v32o;
else
    v32c='CLOSED';
    v32=v32c;
end

%Command to open the file that is going to be changed
fid = fopen('anytown1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f is replaced with demand value, while the %s is replaced with pipe status
fprintf(fid, '\n[TITLE]\nAnytown network model\n\n[JUNCTIONS]\n;ID\tElev
(ft)\tDemand
(gpm)\tPattern\n20\t20\t1\t3;\n30\t50\t1\t4;\n40\t50\t1\t5;\n50\t50\t1\t6;\n60\t50\t1\t8;\n7
0\t50\t1\t9;\n80\t50\t1\t11;\n90\t50\t1\t12;\n100\t50\t1\t13;\n110\t50\t1\t14;\n120\t120\t1
\t16;\n130\t120\t1\t17;\n140\t80\t1\t18;\n150\t120\t1\t19;\n160\t120\t1\t20;\n170\t120\t1\
t21;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n10\t10;\n\n[TANKS]\n;ID\tElevation\tInit
Level\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n65\t215\t\t10\t35\t16.3\t0;\n
165\t215\t\t10\t35\t16.3\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughn
ess\tMinorLoss\tStatus\n2\t20\t70\t12000\t16\t70\t0\tOpen;\n4\t20\t30\t12000\t12\t120\t0
\tOpen;\n6\t20\t110\t12000\t12\t70\t0\tOpen;\n8\t70\t30\t9000\t12\t70\t0\tOpen;\n10\t70\
t100\t6000\t12\t70\t0\tOpen;\n12\t70\t90\t6000\t10\t70\t0\tOpen;\n14\t70\t60\t6000\t12\t
70\t0\tOpen;\n16\t90\t60\t6000\t10\t70\t0\tOpen;\n18\t60\t80\t6000\t12\t70\t0\tOpen;\n2
0\t90\t80\t6000\t10\t70\t0\tOpen;\n22\t90\t150\t6000\t10\t70\t0\tOpen;\n24\t90\t100\t600
0\t10\t70\t0\tOpen;\n26\t100\t150\t6000\t12\t70\t0\tOpen;\n28\t150\t80\t6000\t10\t70\t0\t
Open;\n30\t60\t30\t6000\t10\t120\t0\tOpen;\n32\t30\t40\t6000\t10\t120\t0\tOpen;\n34\t30
\t50\t9000\t10\t120\t0\tOpen;\n36\t40\t50\t6000\t10\t120\t0\tOpen;\n38\t50\t80\t6000\t10
\t120\t0\tOpen;\n40\t80\t140\t6000\t10\t120\t0\tOpen;\n42\t150\t140\t6000\t8\t120\t0\tO
pen;\n44\t150\t160\t6000\t8\t120\t0\tOpen;\n46\t100\t160\t6000\t8\t120\t0\tOpen;\n48\t1
00\t110\t6000\t8\t70\t0\tOpen;\n50\t110\t160\t6000\t10\t120\t0\tOpen;\n52\t110\t120\t60
00\t8\t120\t0\tOpen;\n56\t120\t130\t6000\t8\t120\t0\tOpen;\n58\t130\t160\t6000\t10\t120
\t0\tOpen;\n60\t130\t170\t6000\t8\t120\t0\tOpen;\n62\t160\t140\t6000\t8\t120\t0\tOpen;\
n64\t170\t140\t12000\t80\t120\t0\tOpen;\n66\t50\t140\t12000\t8\t120\t0\tOpen;\n78\t60\t
65\t100\t12\t120\t0\tOpen;\n80\t165\t160\t100\t12\t120\t0\tOpen;\n\n[PUMPS]\n;ID\tNo
de1\tNode2\tParameters\n82\t10\t20\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Demand
Pattern\n2\t1\n2\t1\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n
1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t
```

0\t0\n;Demand
Change\n3\t500\t500\t500\t500\t500\t500\n3\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f
%The variables are placed into the input file wherever there is a%12.7f
\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t200\t200\t200\t200\t200\t200\n4\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t200\t200\t200\t200\t200\t200\n5\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t200\t200\t200\t200\t200\t200\n6\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n8\t500\t500\t500\t500\t500\t500\n8\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t500\t500\t500\t500\t500\t500\n9\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n11\t500\t500\t500\t500\t500\t500\n11\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t1000\t1000\t1000\t1000\t1000\t1000\n12\t1000\t1000\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t500\t500\t500\t500\t500\t500\n13\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.

7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t500\t500\t500\t500\t500\t500\n14\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n16\t200\t200\t200\t200\t200\t200\n16\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t200\t200\t200\t200\t200\t200\n17\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t200\t200\t200\t200\t200\t200\n18\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t200\t200\t200\t200\t200\t200\n19\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t800\t800\t800\t800\t800\t800\n20\t800\t800\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t200\t200\t200\t200\t200\t200\n21\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t0\t300\n1\t2000\t292\n1\t4000\t270\n1\t6000\t230\n1\t8000\t181\n\n[CONTROLS]\nLINK 2 %s AT CLOCKTIME 4 AM\nLINK 4 %s AT CLOCKTIME 4 AM\nLINK 6 %s AT CLOCKTIME 4 AM\nLINK 8 %s AT CLOCKTIME 4 AM\nLINK 10 %s AT CLOCKTIME 4 AM\nLINK 12 %s AT CLOCKTIME 4 AM\nLINK 14 %s AT CLOCKTIME 4 AM\nLINK 16 %s AT CLOCKTIME 4 AM\nLINK 18 %s AT CLOCKTIME 4 AM\nLINK 20 %s AT CLOCKTIME 4 AM\nLINK 22 %s AT CLOCKTIME 4 AM\nLINK 24 %s AT CLOCKTIME 4 AM\nLINK 26 %s AT CLOCKTIME 4 AM\nLINK 28 %s AT CLOCKTIME 4 AM\nLINK 30 %s AT

225

CLOCKTIME 4 AM\nLINK 32 %s AT CLOCKTIME 4 AM\nLINK 34 %s AT CLOCKTIME 4 AM\nLINK 36 %s AT CLOCKTIME 4 AM\nLINK 38 %s AT CLOCKTIME 4 AM\nLINK 40 %s AT CLOCKTIME 4 AM\nLINK 42 %s AT CLOCKTIME 4 AM\nLINK 44 %s AT CLOCKTIME 4 AM\nLINK 46 %s AT CLOCKTIME 4 AM\nLINK 48 %s AT CLOCKTIME 4 AM\nLINK 50 %s AT CLOCKTIME 4 AM\nLINK 52 %s AT CLOCKTIME 4 AM\nLINK 56 %s AT CLOCKTIME 4 AM\nLINK 58 %s AT CLOCKTIME 4 AM\nLINK 60 %s AT CLOCKTIME 4 AM\nLINK 62 %s AT CLOCKTIME 4 AM\nLINK 64 %s AT CLOCKTIME 4 AM\nLINK 66 %s AT CLOCKTIME 4 AM\n\n\n[ENERGY]\nGlobal Efficiency\t65\nGlobal Price\t0.0\nDemand Charge\t0.0\n\n[QUALITY]\n;Node\tInitQual\n20\t0\n30\t0\n40\t0\n50\t0\n55\t0\n60\t0\n70\t0\n75\t0\n80\t0\n90\t0\n100\t0\n110\t0\n115\t0\n120\t0\n130\t0\n140\t0\n150\t0\n160\t0\n170\t0\n10\t0\n65\t0\n165\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n30\tFLOWPACED\t2.0\t1\n\n[REACTIONS]\n;Type\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0.0\nRoughness Correlation\t0.0\n\n[MIXING]\n;Tank\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nPage\t0\nMessages\tNo\nNodes\t20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1.0\nViscosity\t1.0\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1.0\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d

%d# variables that are placed into the %12.7f spots in the input file
%v# variables that are placed into the %s spots in the input file

1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,
d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2
,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d
3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,
d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4
,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d
5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,
d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7
,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d
7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,
d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9,d9
,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d
9,d9,d9,d9,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,
d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d1
0,d10,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,
d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d1
1,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,
d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d1

3,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,
d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d14,d1
4,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,
d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d15,d15,d1
5,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,
d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d16,d16,d16,d1
6,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,
d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,v1,v2,v3,v4,v5,v6,v
7,v8,v9,v10,v11,v12,v13,v14,v15,v16,v17,v18,v19,v20,v21,v22,v23,v24,v25,v26,v27,v2
8,v29,v30,v31,v32);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Reads output file to see if any error messages were reported in simulation
[mesg1,mesg2]=textread('anytown1.rpt','%s %s',1,'headerlines',11,'endofline','\r\n');

%Compares variable mesg1 to Node, if they are the same then linetitle1 is equal to 1
linetitle1 = strcmp(mesg1, 'Node');
%Compares variable mesg2 to Results, if they are the same then linetitle2 is equal to 1
linetitle2 = strcmp(mesg2, 'Results');
 %Adds the two variables together
disconnect = linetitle1+linetitle2;

%If disconnect is equal to zero then error messages were reported and therefore
%the nonlinear constraint was not met and ceq is equal to one
%In terms of reality, the error message means that the system was disconnected or
%caused negative pressures
if disconnect==0
   ceq=1;
else
   ceq=0;
end

APPENDIX U

GENETIC ALGORITHM (GA) CODE FOR ANYTOWN FLUSHING AND VALVING RESPONSE

```matlab
%MATLAB programming code version R2006a
%Initial population range vector
IntPopRange=[0 500 0 200 0 200 0 200 0 500 0 500 0 500 0 1000 0 500 0 500 0 200 0
200 0 200 0 200 0 800 0 200 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0;
1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500 1 1500
1 1500 1 1500 1 1500 1 1500 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1
];

%Options for GA: initial population calls imported table MyIntPop,
%initial population range call IntPopRange from above
%StallGenLimit and StallTimeLimit are stopping criteria set to 100
%which means the optimization is stopped for StallGenLimit if the
%weighted average change in the fitness function value over Stall
%generations (100 for this application) is less than Function tolerance
%which means the optimization is stopped for StallTimeLimit if there
%is no improvement in the best fitness value for an interval of time
%in seconds specified by Stall time (100 for this application)
options = gaoptimset('InitialPopulation', MyIntPop, 'PopInitRange', IntPopRange,
'StallGenLimit', 100, 'StallTimeLimit', 100);

%Lower and upper bounds on variables
%For decision variables whether to alter demand lower bound is 0 and
%upper bound is 1, the new demand has a lower bound of the base average demand
%and an upper bound of 1300 gallons per minute (gpm), the decision to close
%a pipe has a lower bound of 0 and an upper bound of 1
LB = [0; 500; 0; 200; 0; 200; 0; 200; 0; 500; 0; 500; 0; 500; 0; 1000; 0; 500; 0; 500; 0;
200; 0; 200; 0; 200; 0; 200; 0; 800; 0; 200; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0;
0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0; 0];
UB = [1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1;
1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1300; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1;
1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1; 1];

%Linear constraint:
%d1+d2+d3+d4+d5+d6+d7+d8+d9+d10+d11+d12+d13+d14+d15+d16<=7600
%Helps ensure that the total demand in the network does not cause negative
%pressures
A = [0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0];
b = 7600;

%Assigns nonlinear constraint to call the nonlinear constraint function
%nonlconanytown in this case
ConstraintFcn=@nonlconanytown;

%GA optimization call is in this form
%[x,fval] = ga(fitnessfcn,nvars,A,b,Aeq,beq,LB,UB,nonlcon,options)
```

%The output from the optimization will be the dem (the decision variables)
%and the fval, fitness function value, (the total concentration)
%The GA calls the file with the function to be minimized
%anyflushvalves is this case
%There are 64 variables, the inequality linear constraint information
%is contained in A and b, there are no equality linear constraint so [], the
%lower and upper bounds of the decision variables are given in LB and UB,
%the nonlinear constraints are given by variable ConstraintFcn defined
%above, and the options file information is given by the variable options
%defined above
[dem,fval] = ga(@anyflushvalves,64,A,b,[],[],LB,UB,ConstraintFcn,options);

%Writes decision variables and fitness function value to Excel file
% xlswrite('ExcelFileName',[dem,fval],'TabName', 'Cell')
%For example, the ExcelFileName is GAFlushValveResults,
%the TabName is Results, and the Cell is C3
xlswrite('GAFlushValveResults',[dem,fval],'Results', 'C3')

APPENDIX V

**FITNESS FUNCTION CODE FOR ANYTOWN FLUSHING AND VALVING
RESPONSE**

```matlab
%MATLAB programming code version R2006a
%Creating the fitness function, where the
%output variable being minimized is concTot and
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the nodes at which to alter the demand; the new demands
%for these nodes; and the location of pipe closures
function concTot = anyflushvalves (dem)

%Process to determine if the nodal demand is going to change
%and the value of the nodal demand to utilize in the input file
%For example, if decision variable dem(1) is less than or equal to 0.5
%then the nodal demand will not be altered and the average base demand
%of 500 gallons per minute (gpm) will be used, otherwise the nodal
%demand will be altered and the value determined in decision
%variable dem(2) will be used in the input file
if dem(1)<=0.5
    %Demand at Node 20
    d1=500;
else
    d1=dem(2);
end
if dem(3)<=0.5
    %Demand at Node 30
    d2=200;
else
    d2=dem(4);
end
if dem(5)<=0.5
    %Demand at Node 40
    d3=200;
else
    d3=dem(6);
end
if dem(7)<=0.5
    %Demand at Node 50
    d4=200;
else
    d4=dem(8);
end
if dem(9)<=0.5
    %Demand at Node 60
    d5=500;
else
    d5=dem(10);
end
```

```matlab
if dem(11)<=0.5
    %Demand at Node 70
    d6=500;
else
    d6=dem(12);
end
if dem(13)<=0.5
    %Demand at Node 80
    d7=500;
else
    d7=dem(14);
end
if dem(15)<=0.5
    %Demand at Node 90
    d8=1000;
else
    d8=dem(16);
end
if dem(17)<=0.5
    %Demand at Node 100
    d9=500;
else
    d9=dem(18);
end
if dem(19)<=0.5
    %Demand at Node 110
    d10=500;
else
    d10=dem(20);
end
if dem(21)<=0.5
    %Demand at Node 120
    d11=200;
else
    d11=dem(22);
end
if dem(23)<=0.5
    %Demand at Node 130
    d12=200;
else
    d12=dem(24);
end
if dem(25)<=0.5
    %Demand at Node 140
    d13=200;
else
```

```matlab
        d13=dem(26);
end
if dem(27)<=0.5
    %Demand at Node 150
    d14=200;
else
    d14=dem(28);
end
if dem(29)<=0.5
    %Demand at Node 160
    d15=800;
else
    d15=dem(30);
end
if dem(31)<=0.5
    %Demand at Node 170
    d16=200;
else
    d16=dem(32);
end

%Process to determine the status of the pipes
%For example, if decision variable dem(33) is less than or equal to 0.5
%then first pipe (Pipe 2) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(33)<=0.5
    %Status of Pipe 2
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(34)<=0.5
    %Status of Pipe 4
    v2o='OPEN';
    v2=v2o;
else
    v2c='CLOSED';
    v2=v2c;
end
if dem(35)<=0.5
    %Status of Pipe 6
    v3o='OPEN';
    v3=v3o;
else
```

```matlab
        v3c='CLOSED';
        v3=v3c;
end
if dem(36)<=0.5
        %Status of Pipe 8
        v4o='OPEN';
        v4=v4o;
else
        v4c='CLOSED';
        v4=v4c;
end
if dem(37)<=0.5
        %Status of Pipe 10
        v5o='OPEN';
        v5=v5o;
else
        v5c='CLOSED';
        v5=v5c;
end
if dem(38)<=0.5
        %Status of Pipe 12
        v6o='OPEN';
        v6=v6o;
else
        v6c='CLOSED';
        v6=v6c;
end
if dem(39)<=0.5
        %Status of Pipe 14
        v7o='OPEN';
        v7=v7o;
else
        v7c='CLOSED';
        v7=v7c;
end
if dem(40)<=0.5
        %Status of Pipe 16
        v8o='OPEN';
        v8=v8o;
else
        v8c='CLOSED';
        v8=v8c;
end
if dem(41)<=0.5
        %Status of Pipe 18
        v9o='OPEN';
```

```matlab
    v9=v9o;
else
    v9c='CLOSED';
    v9=v9c;
end
if dem(42)<=0.5
    %Status of Pipe 20
    v10o='OPEN';
    v10=v10o;
else
    v10c='CLOSED';
    v10=v10c;
end
if dem(43)<=0.5
    %Status of Pipe 22
    v11o='OPEN';
    v11=v11o;
else
    v11c='CLOSED';
    v11=v11c;
end
if dem(44)<=0.5
    %Status of Pipe 24
    v12o='OPEN';
    v12=v12o;
else
    v12c='CLOSED';
    v12=v12c;
end
if dem(45)<=0.5
    %Status of Pipe 26
    v13o='OPEN';
    v13=v13o;
else
    v13c='CLOSED';
    v13=v13c;
end
if dem(46)<=0.5
    %Status of Pipe 28
    v14o='OPEN';
    v14=v14o;
else
    v14c='CLOSED';
    v14=v14c;
end
if dem(47)<=0.5
```

```matlab
    %Status of Pipe 30
    v15o='OPEN';
    v15=v15o;
else
    v15c='CLOSED';
    v15=v15c;
end
if dem(48)<=0.5
    %Status of Pipe 32
    v16o='OPEN';
    v16=v16o;
else
    v16c='CLOSED';
    v16=v16c;
end
if dem(49)<=0.5
    %Status of Pipe 34
    v17o='OPEN';
    v17=v17o;
else
    v17c='CLOSED';
    v17=v17c;
end
if dem(50)<=0.5
    %Status of Pipe 36
    v18o='OPEN';
    v18=v18o;
else
    v18c='CLOSED';
    v18=v18c;
end
if dem(51)<=0.5
    %Status of Pipe 38
    v19o='OPEN';
    v19=v19o;
else
    v19c='CLOSED';
    v19=v19c;
end
if dem(52)<=0.5
    %Status of Pipe 40
    v20o='OPEN';
    v20=v20o;
else
    v20c='CLOSED';
    v20=v20c;
```

```matlab
end
if dem(53)<=0.5
    %Status of Pipe 42
    v21o='OPEN';
    v21=v21o;
else
    v21c='CLOSED';
    v21=v21c;
end
if dem(54)<=0.5
    %Status of Pipe 44
    v22o='OPEN';
    v22=v22o;
else
    v22c='CLOSED';
    v22=v22c;
end
if dem(55)<=0.5
    %Status of Pipe 46
    v23o='OPEN';
    v23=v23o;
else
    v23c='CLOSED';
    v23=v23c;
end
if dem(56)<=0.5
    %Status of Pipe 48
    v24o='OPEN';
    v24=v24o;
else
    v24c='CLOSED';
    v24=v24c;
end
if dem(57)<=0.5
    %Status of Pipe 50
    v25o='OPEN';
    v25=v25o;
else
    v25c='CLOSED';
    v25=v25c;
end
if dem(58)<=0.5
    %Status of Pipe 52
    v26o='OPEN';
    v26=v26o;
else
```

```matlab
    v26c='CLOSED';
    v26=v26c;
end
if dem(59)<=0.5
    %Status of Pipe 56
    v27o='OPEN';
    v27=v27o;
else
    v27c='CLOSED';
    v27=v27c;
end
if dem(60)<=0.5
    %Status of Pipe 58
    v28o='OPEN';
    v28=v28o;
else
    v28c='CLOSED';
    v28=v28c;
end
if dem(61)<=0.5
    %Status of Pipe 60
    v29o='OPEN';
    v29=v29o;
else
    v29c='CLOSED';
    v29=v29c;
end
if dem(62)<=0.5
    %Status of Pipe 62
    v30o='OPEN';
    v30=v30o;
else
    v30c='CLOSED';
    v30=v30c;
end
if dem(63)<=0.5
    %Status of Pipe 64
    v31o='OPEN';
    v31=v31o;
else
    v31c='CLOSED';
    v31=v31c;
end
if dem(64)<=0.5
    %Status of Pipe 66
    v32o='OPEN';
```

```matlab
    v32=v32o;
else
    v32c='CLOSED';
    v32=v32c;
end

%Command to open the file that is going to be changed
fid = fopen('anytown1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f values are replaced by demand, while %s are replaced by pipe status
fprintf(fid, '\n[TITLE]\nAnytown network model\n\n[JUNCTIONS]\n;ID\tElev
(ft)\tDemand
(gpm)\tPattern\n20\t20\t1\t3;\n30\t50\t1\t4;\n40\t50\t1\t5;\n50\t50\t1\t6;\n60\t50\t1\t8;\n7
0\t50\t1\t9;\n80\t50\t1\t11;\n90\t50\t1\t12;\n100\t50\t1\t13;\n110\t50\t1\t14;\n120\t120\t1
\t16;\n130\t120\t1\t17;\n140\t80\t1\t18;\n150\t120\t1\t19;\n160\t120\t1\t20;\n170\t120\t1\
t21;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n10\t10;\n\n[TANKS]\n;ID\tElevation\tInit
Level\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n65\t215\t\t10\t35\t16.3\t0;\n
165\t215\t\t10\t35\t16.3\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughn
ess\tMinorLoss\tStatus\n2\t20\t70\t12000\t16\t70\t0\tOpen;\n4\t20\t30\t12000\t12\t120\t0
\tOpen;\n6\t20\t110\t12000\t12\t70\t0\tOpen;\n8\t70\t30\t9000\t12\t70\t0\tOpen;\n10\t70\
t100\t6000\t12\t70\t0\tOpen;\n12\t70\t90\t6000\t10\t70\t0\tOpen;\n14\t70\t60\t6000\t12\t
70\t0\tOpen;\n16\t90\t60\t6000\t10\t70\t0\tOpen;\n18\t60\t80\t6000\t12\t70\t0\tOpen;\n2
0\t90\t80\t6000\t10\t70\t0\tOpen;\n22\t90\t150\t6000\t10\t70\t0\tOpen;\n24\t90\t100\t600
0\t10\t70\t0\tOpen;\n26\t100\t150\t6000\t12\t70\t0\tOpen;\n28\t150\t80\t6000\t10\t70\t0\t
Open;\n30\t60\t30\t6000\t10\t120\t0\tOpen;\n32\t30\t40\t6000\t10\t120\t0\tOpen;\n34\t30
\t50\t9000\t10\t120\t0\tOpen;\n36\t40\t50\t6000\t10\t120\t0\tOpen;\n38\t50\t80\t6000\t10
\t120\t0\tOpen;\n40\t80\t140\t6000\t10\t120\t0\tOpen;\n42\t150\t140\t6000\t8\t120\t0\tO
pen;\n44\t150\t160\t6000\t8\t120\t0\tOpen;\n46\t100\t160\t6000\t8\t120\t0\tOpen;\n48\t1
00\t110\t6000\t8\t70\t0\tOpen;\n50\t110\t160\t6000\t10\t120\t0\tOpen;\n52\t110\t120\t60
00\t8\t120\t0\tOpen;\n56\t120\t130\t6000\t8\t120\t0\tOpen;\n58\t130\t160\t6000\t10\t120
\t0\tOpen;\n60\t130\t170\t6000\t8\t120\t0\tOpen;\n62\t160\t140\t6000\t8\t120\t0\tOpen;\
n64\t170\t140\t12000\t80\t120\t0\tOpen;\n66\t50\t140\t12000\t8\t120\t0\tOpen;\n78\t60\t
65\t100\t12\t120\t0\tOpen;\n80\t165\t160\t100\t12\t120\t0\tOpen;\n\n[PUMPS]\n;ID\tNo
de1\tNode2\tParameters\n82\t10\t20\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Demand
Pattern\n2\t1\n2\t1\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n
1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t
0\t0\n;Demand
Change\n3\t500\t500\t500\t500\t500\t500\n3\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f
%The variables are placed into the input file wherever there is a%12.7f
\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%1
2.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t
%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t
%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t200\t200\t200\t200\t2
```

00\t200\n4\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t200\t200\t200\t200\t200\t200\n5\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t200\t200\t200\t200\t200\n6\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n8\t500\t500\t500\t500\t500\t500\n8\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t500\t500\t500\t500\t500\t500\n9\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n11\t500\t500\t500\t500\t500\t500\n11\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t1000\t1000\t1000\t1000\t1000\t1000\n12\t1000\t1000\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t500\t500\t500\t500\t500\t500\n13\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t500\t500\t500\t500\t500\n14\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n15\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0

\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n16\t200\t200\t200\t200\t200\t200\n16\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t200\t200\t200\t200\t200\t200\n17\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t200\t200\t200\t200\t200\t200\n18\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t200\t200\t200\t200\t200\t200\n19\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t800\t800\t800\t800\t800\t800\n20\t800\t800\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t200\t200\t200\t200\t200\t200\n21\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t0\t300\n1\t2000\t292\n1\t4000\t270\n1\t6000\t230\n1\t8000\t181\n\n[CONTROLS]\nLINK 2 %s AT CLOCKTIME 4 AM\nLINK 4 %s AT CLOCKTIME 4 AM\nLINK 6 %s AT CLOCKTIME 4 AM\nLINK 8 %s AT CLOCKTIME 4 AM\nLINK 10 %s AT CLOCKTIME 4 AM\nLINK 12 %s AT CLOCKTIME 4 AM\nLINK 14 %s AT CLOCKTIME 4 AM\nLINK 16 %s AT CLOCKTIME 4 AM\nLINK 18 %s AT CLOCKTIME 4 AM\nLINK 20 %s AT CLOCKTIME 4 AM\nLINK 22 %s AT CLOCKTIME 4 AM\nLINK 24 %s AT CLOCKTIME 4 AM\nLINK 26 %s AT CLOCKTIME 4 AM\nLINK 28 %s AT CLOCKTIME 4 AM\nLINK 30 %s AT CLOCKTIME 4 AM\nLINK 32 %s AT CLOCKTIME 4 AM\nLINK 34 %s AT CLOCKTIME 4 AM\nLINK 36 %s AT CLOCKTIME 4 AM\nLINK 38 %s AT CLOCKTIME 4 AM\nLINK 40 %s AT CLOCKTIME 4 AM\nLINK 42 %s AT CLOCKTIME 4 AM\nLINK 44 %s AT CLOCKTIME 4 AM\nLINK 46 %s AT CLOCKTIME 4 AM\nLINK 48 %s AT CLOCKTIME 4 AM\nLINK 50 %s AT CLOCKTIME 4 AM\nLINK 52 %s AT CLOCKTIME 4 AM\nLINK 56 %s AT CLOCKTIME 4 AM\nLINK 58 %s AT CLOCKTIME 4 AM\nLINK 60 %s AT

CLOCKTIME 4 AM\nLINK 62 %s AT CLOCKTIME 4 AM\nLINK 64 %s AT CLOCKTIME 4 AM\nLINK 66 %s AT CLOCKTIME 4 AM\n\n\n[ENERGY]\nGlobal Efficiency\t65\nGlobal Price\t0.0\nDemand Charge\t0.0\n\n[QUALITY]\n;Node\tInitQual\n20\t0\n30\t0\n40\t0\n50\t0\n55\t0\n60\t0\n70\t0\n75\t0\n80\t0\n90\t0\n100\t0\n110\t0\n115\t0\n120\t0\n130\t0\n140\t0\n150\t0\n160\t0\n170\t0\n10\t0\n65\t0\n165\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n30\tFLOWPACED\t2.0\t1\n\n[REACTIONS]\n;Type\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0.0\nRoughness Correlation\t0.0\n\n[MIXING]\n;Tank\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nPage\t0\nMessages\tNo\nNodes\t20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1.0\nViscosity\t1.0\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1.0\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d

%d# variables that are placed into the %12.7f spots in the input file

%v# variables that are placed into the %s spots in the input file

1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d1,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,

```
d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,v1,v2,v3,v4,v5,v6,v
7,v8,v9,v10,v11,v12,v13,v14,v15,v16,v17,v18,v19,v20,v21,v22,v23,v24,v25,v26,v27,v2
8,v29,v30,v31,v32);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Code to read the output file created from EPANET
%Establishes the variables: i is the starting row in the matrix
%l is the starting line to read in the output file
i = 1;
l = 201;
%This establishes the amount of times that the output file must be read
%n begins with the time that response occurs and ends with the end
%of the 24-hr simulation, n changes value in increments of 30
%For this simulation, n begins reading the output file at 4-hr
%(240 minutes) and changes by 30 minutes until the end of the 24-hr
%(1440 minutes)
for n = 240:30:1440
    %k is the number of nodes
    for k = 1:16
        %Establishes a variable conc which reads the output file for
        %the concentration in each node
        conc = textread('anytown1.rpt','%*f%f',1,'headerlines',l,'endofline','\r\n');
        conct(i)=conc;
        %Increases the i to the next row of the matrix
        i = i + 1;
        %Increases the text line to the next line to read
        l = l + 1;
    end
    %Increases text line to skip header information
    l = l + 7;
end
%Calculates the total concentration in all nodes for all times
concTot = sum(conct);
```

APPENDIX W

**EPANET INPUT FILE CREATED BY METHODOLOGY FOR ANYTOWN
FLUSHING AND VALVING RESPONSE**

; EPANET input file created by methodology for flushing and valving scenario
[TITLE]
Anytown network model

[JUNCTIONS]
;ID	Elev (ft)	Demand (gpm)	Pattern
20	20	1	3;
30	50	1	4;
40	50	1	5;
50	50	1	6;
60	50	1	8;
70	50	1	9;
80	50	1	11;
90	50	1	12;
100	50	1	13;
110	50	1	14;
120	120	1	16;
130	120	1	17;
140	80	1	18;
150	120	1	19;
160	120	1	20;
170	120	1	21;

[RESERVOIRS]
;ID	Head	Pattern
10	10;	

[TANKS]
;ID	Elevation	InitLevel	MinLevel	MaxLevel	Diameter	MinVol	VolCurve
65	215		10	35	16.3	0;	
165	215		10	35	16.3	0;	

[PIPES]
;ID	Node1	Node2	Length	Diameter	Roughness	MinorLoss	Status
2	20	70	12000	16	70	0	Open;
4	20	30	12000	12	120	0	Open;
6	20	110	12000	12	70	0	Open;
8	70	30	9000	12	70	0	Open;
10	70	100	6000	12	70	0	Open;
12	70	90	6000	10	70	0	Open;
14	70	60	6000	12	70	0	Open;
16	90	60	6000	10	70	0	Open;
18	60	80	6000	12	70	0	Open;
20	90	80	6000	10	70	0	Open;
22	90	150	6000	10	70	0	Open;
24	90	100	6000	10	70	0	Open;
26	100	150	6000	12	70	0	Open;
28	150	80	6000	10	70	0	Open;
30	60	30	6000	10	120	0	Open;
32	30	40	6000	10	120	0	Open;

34	30	50	9000	10	120	0	Open;
36	40	50	6000	10	120	0	Open;
38	50	80	6000	10	120	0	Open;
40	80	140	6000	10	120	0	Open;
42	150	140	6000	8	120	0	Open;
44	150	160	6000	8	120	0	Open;
46	100	160	6000	8	120	0	Open;
48	100	110	6000	8	70	0	Open;
50	110	160	6000	10	120	0	Open;
52	110	120	6000	8	120	0	Open;
56	120	130	6000	8	120	0	Open;
58	130	160	6000	10	120	0	Open;
60	130	170	6000	8	120	0	Open;
62	160	140	6000	8	120	0	Open;
64	170	140	12000	80	120	0	Open;
66	50	140	12000	8	120	0	Open;
78	60	65	100	12	120	0	Open;
80	165	160	100	12	120	0	Open;

[PUMPS]
;ID   Node1   Node2   Parameters
82   10   20   HEAD 1;

[PATTERNS]
;ID   Multipliers
;Injection
1	1	1	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0
1	0	0	0	0	0	0

;Demand Change
;%12.7f is replaced with demand variables; either average base or the new demand
3	500	500	500	500	500	500
3	500	500	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
3	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	200	200	200	200	200	200
4	200	200	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
4	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	200	200	200	200	200	200
5	200	200	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
5	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	200	200	200	200	200	200
6	200	200	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
6	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	500	500	500	500	500	500
8	500	500	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
8	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	500	500	500	500	500	500
9	500	500	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
9	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	500	500	500	500	500	500
11	500	500	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
11	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	1000	1000	1000	1000	1000	1000
12	1000	1000	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
12	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

13	500	500	500	500	500	500
13	500	500	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
13	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	500	500	500	500	500	500
14	500	500	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
14	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	200	200	200	200	200	200
16	200	200	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
16	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	200	200	200	200	200	200
17	200	200	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
17	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	200	200	200	200	200	200
18	200	200	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
18	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	200	200	200	200	200	200
19	200	200	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
19	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	800	800	800	800	800	800
20	800	800	%12.7f	%12.7f	%12.7f	%12.7f

20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
20	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	200	200	200	200	200	200
21	200	200	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f
21	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f	%12.7f

[CURVES]
;ID   X-Value   Y-Value
;PUMP: Pump Curve for Pump 9
1   0   300
1   2000   292
1   4000   270
1   6000   230
1   8000   181

[CONTROLS]
; %s is replaced with the pipe status; either OPEN or CLOSED
LINK 2 %s AT CLOCKTIME 4 AM
LINK 4 %s AT CLOCKTIME 4 AM
LINK 6 %s AT CLOCKTIME 4 AM
LINK 8 %s AT CLOCKTIME 4 AM
LINK 10 %s AT CLOCKTIME 4 AM
LINK 12 %s AT CLOCKTIME 4 AM
LINK 14 %s AT CLOCKTIME 4 AM
LINK 16 %s AT CLOCKTIME 4 AM
LINK 18 %s AT CLOCKTIME 4 AM
LINK 20 %s AT CLOCKTIME 4 AM
LINK 22 %s AT CLOCKTIME 4 AM
LINK 24 %s AT CLOCKTIME 4 AM
LINK 26 %s AT CLOCKTIME 4 AM
LINK 28 %s AT CLOCKTIME 4 AM
LINK 30 %s AT CLOCKTIME 4 AM
LINK 32 %s AT CLOCKTIME 4 AM
LINK 34 %s AT CLOCKTIME 4 AM
LINK 36 %s AT CLOCKTIME 4 AM
LINK 38 %s AT CLOCKTIME 4 AM
LINK 40 %s AT CLOCKTIME 4 AM
LINK 42 %s AT CLOCKTIME 4 AM
LINK 44 %s AT CLOCKTIME 4 AM
LINK 46 %s AT CLOCKTIME 4 AM
LINK 48 %s AT CLOCKTIME 4 AM

LINK 50 %s AT CLOCKTIME 4 AM
LINK 52 %s AT CLOCKTIME 4 AM
LINK 56 %s AT CLOCKTIME 4 AM
LINK 58 %s AT CLOCKTIME 4 AM
LINK 60 %s AT CLOCKTIME 4 AM
LINK 62 %s AT CLOCKTIME 4 AM
LINK 64 %s AT CLOCKTIME 4 AM
LINK 66 %s AT CLOCKTIME 4 AM

[ENERGY]
Global Efficiency   65
Global Price   0
Demand Charge   0

[QUALITY]
;Node   InitQual
20   0
30   0
40   0
50   0
55   0
60   0
70   0
75   0
80   0
90   0
100   0
110   0
115   0
120   0
130   0
140   0
150   0
160   0
170   0
10   0
65   0
165   0

[SOURCES]
;Node   Type   Quality   Pattern
30   FLOWPACED   2   1

[REACTIONS]
Order Bulk   0
Order Tank   0
Order Wall   0
Global Bulk   0
Global Wall   0
Limiting Potential   0

Roughness Correlation   0

[TIMES]
Duration   24:00:00
Hydraulic Timestep   0:30
Quality Timestep   0:30
Pattern Timestep   0:30
Pattern Start   0:00
Report Timestep   0:30
Report Start   0:00
Start ClockTime   12:00 AM
Statistic   None

[REPORT]
Status   No
Summary   No
Page   0
Messages   No
Nodes   20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;
DEMAND   No
HEAD   No
PRESSURE   No
QUALITY   PRECISION 10
Links   None

[OPTIONS]
Units   GPM
Headloss   H-W
Specific Gravity   1
Viscosity   1
Trials   40
Accuracy   0.001
Unbalanced   Continue 10
Pattern   1
Demand Multiplier   1
Emitter Exponent   0.5
Quality   Chemical mg/L
Diffusivity   0
Tolerance   0.01

[END]

APPENDIX X

**NONLINEAR CONSTRAINT CODE FOR ANYTOWN FLUSHING AND
VALVING RESPONSE**

```matlab
%MATLAB programming code version R2006a
%Creating the nonlinear constraint function, where the
%output variables being c, nonlinear inequality constraint and
%ceq, nonlinear equality constraint
%the design variables being altered are dem, where
%dem is composed of the decision variables to determine
%the nodes at which to alter the demand; the new demands
%for these nodes; and the location of pipe closures
function [c, ceq]=nonlconanytown (dem)

%There are no nonlinear equality constraint
c=[];

%Process to determine if the nodal demand is going to change
%and the value of the nodal demand to utilize in the input file
%For example, if decision variable dem(1) is less than or equal to 0.5
%then the nodal demand will not be altered and the average base demand
%of 500 gallons per minute (gpm) will be used, otherwise the nodal
%demand will be altered and the value determined in decision
%variable dem(2) will be used in the input file
if dem(1)<=0.5
    %Demand at Node 20
    d1=500;
else
    d1=dem(2);
end
if dem(3)<=0.5
    %Demand at Node 30
    d2=200;
else
    d2=dem(4);
end
if dem(5)<=0.5
    %Demand at Node 40
    d3=200;
else
    d3=dem(6);
end
if dem(7)<=0.5
    %Demand at Node 50
    d4=200;
else
    d4=dem(8);
end
if dem(9)<=0.5
    %Demand at Node 60
```

```matlab
    d5=500;
else
    d5=dem(10);
end
if dem(11)<=0.5
    %Demand at Node 70
    d6=500;
else
    d6=dem(12);
end
if dem(13)<=0.5
    %Demand at Node 80
    d7=500;
else
    d7=dem(14);
end
if dem(15)<=0.5
    %Demand at Node 90
    d8=1000;
else
    d8=dem(16);
end
if dem(17)<=0.5
    %Demand at Node 100
    d9=500;
else
    d9=dem(18);
end
if dem(19)<=0.5
    %Demand at Node 110
    d10=500;
else
    d10=dem(20);
end
if dem(21)<=0.5
    %Demand at Node 120
    d11=200;
else
    d11=dem(22);
end
if dem(23)<=0.5
    %Demand at Node 130
    d12=200;
else
    d12=dem(24);
end
```

```matlab
if dem(25)<=0.5
    %Demand at Node 140
    d13=200;
else
    d13=dem(26);
end
if dem(27)<=0.5
    %Demand at Node 150
    d14=200;
else
    d14=dem(28);
end
if dem(29)<=0.5
    %Demand at Node 160
    d15=800;
else
    d15=dem(30);
end
if dem(31)<=0.5
    %Demand at Node 170
    d16=200;
else
    d16=dem(32);
end

%Process to determine the status of the pipes
%For example, if decision variable dem(33) is less than or equal to 0.5
%then first pipe (Pipe 2) will be open, otherwise it will be closed
%This information is then used in the input file
if dem(33)<=0.5
    %Status of Pipe 2
    v1o='OPEN';
    v1=v1o;
else
    v1c='CLOSED';
    v1=v1c;
end
if dem(34)<=0.5
    %Status of Pipe 4
    v2o='OPEN';
    v2=v2o;
else
    v2c='CLOSED';
    v2=v2c;
end
if dem(35)<=0.5
```

```matlab
    %Status of Pipe 6
    v3o='OPEN';
    v3=v3o;
else
    v3c='CLOSED';
    v3=v3c;
end
if dem(36)<=0.5
    %Status of Pipe 8
    v4o='OPEN';
    v4=v4o;
else
    v4c='CLOSED';
    v4=v4c;
end
if dem(37)<=0.5
    %Status of Pipe 10
    v5o='OPEN';
    v5=v5o;
else
    v5c='CLOSED';
    v5=v5c;
end
if dem(38)<=0.5
    %Status of Pipe 12
    v6o='OPEN';
    v6=v6o;
else
    v6c='CLOSED';
    v6=v6c;
end
if dem(39)<=0.5
    %Status of Pipe 14
    v7o='OPEN';
    v7=v7o;
else
    v7c='CLOSED';
    v7=v7c;
end
if dem(40)<=0.5
    %Status of Pipe 16
    v8o='OPEN';
    v8=v8o;
else
    v8c='CLOSED';
    v8=v8c;
```

```matlab
end
if dem(41)<=0.5
    %Status of Pipe 18
    v9o='OPEN';
    v9=v9o;
else
    v9c='CLOSED';
    v9=v9c;
end
if dem(42)<=0.5
    %Status of Pipe 20
    v10o='OPEN';
    v10=v10o;
else
    v10c='CLOSED';
    v10=v10c;
end
if dem(43)<=0.5
    %Status of Pipe 22
    v11o='OPEN';
    v11=v11o;
else
    v11c='CLOSED';
    v11=v11c;
end
if dem(44)<=0.5
    %Status of Pipe 24
    v12o='OPEN';
    v12=v12o;
else
    v12c='CLOSED';
    v12=v12c;
end
if dem(45)<=0.5
    %Status of Pipe 26
    v13o='OPEN';
    v13=v13o;
else
    v13c='CLOSED';
    v13=v13c;
end
if dem(46)<=0.5
    %Status of Pipe 28
    v14o='OPEN';
    v14=v14o;
else
```

```matlab
    v14c='CLOSED';
    v14=v14c;
end
if dem(47)<=0.5
    %Status of Pipe 30
    v15o='OPEN';
    v15=v15o;
else
    v15c='CLOSED';
    v15=v15c;
end
if dem(48)<=0.5
    %Status of Pipe 32
    v16o='OPEN';
    v16=v16o;
else
    v16c='CLOSED';
    v16=v16c;
end
if dem(49)<=0.5
    %Status of Pipe 34
    v17o='OPEN';
    v17=v17o;
else
    v17c='CLOSED';
    v17=v17c;
end
if dem(50)<=0.5
    %Status of Pipe 36
    v18o='OPEN';
    v18=v18o;
else
    v18c='CLOSED';
    v18=v18c;
end
if dem(51)<=0.5
    %Status of Pipe 38
    v19o='OPEN';
    v19=v19o;
else
    v19c='CLOSED';
    v19=v19c;
end
if dem(52)<=0.5
    %Status of Pipe 40
    v20o='OPEN';
```

```matlab
    v20=v20o;
else
    v20c='CLOSED';
    v20=v20c;
end
if dem(53)<=0.5
    %Status of Pipe 42
    v21o='OPEN';
    v21=v21o;
else
    v21c='CLOSED';
    v21=v21c;
end
if dem(54)<=0.5
    %Status of Pipe 44
    v22o='OPEN';
    v22=v22o;
else
    v22c='CLOSED';
    v22=v22c;
end
if dem(55)<=0.5
    %Status of Pipe 46
    v23o='OPEN';
    v23=v23o;
else
    v23c='CLOSED';
    v23=v23c;
end
if dem(56)<=0.5
    %Status of Pipe 48
    v24o='OPEN';
    v24=v24o;
else
    v24c='CLOSED';
    v24=v24c;
end
if dem(57)<=0.5
    %Status of Pipe 50
    v25o='OPEN';
    v25=v25o;
else
    v25c='CLOSED';
    v25=v25c;
end
if dem(58)<=0.5
```

```matlab
    %Status of Pipe 52
    v26o='OPEN';
    v26=v26o;
else
    v26c='CLOSED';
    v26=v26c;
end
if dem(59)<=0.5
    %Status of Pipe 56
    v27o='OPEN';
    v27=v27o;
else
    v27c='CLOSED';
    v27=v27c;
end
if dem(60)<=0.5
    %Status of Pipe 58
    v28o='OPEN';
    v28=v28o;
else
    v28c='CLOSED';
    v28=v28c;
end
if dem(61)<=0.5
    %Status of Pipe 60
    v29o='OPEN';
    v29=v29o;
else
    v29c='CLOSED';
    v29=v29c;
end
if dem(62)<=0.5
    %Status of Pipe 62
    v30o='OPEN';
    v30=v30o;
else
    v30c='CLOSED';
    v30=v30c;
end
if dem(63)<=0.5
    %Status of Pipe 64
    v31o='OPEN';
    v31=v31o;
else
    v31c='CLOSED';
    v31=v31c;
```

```matlab
end
if dem(64)<=0.5
    %Status of Pipe 66
    v32o='OPEN';
    v32=v32o;
else
    v32c='CLOSED';
    v32=v32c;
end

%Command to open the file that is going to be changed
fid = fopen('anytown1.inp', 'wt');
%Command to print the information to the file just opened
%This line recreates the input file for the program EPANET
%Replacing unknown values with the values determined in the above code
%The %12.7f are replaced by the demand variables, while %s are replaced by pipe status
fprintf(fid, '\n[TITLE]\nAnytown network model\n\n[JUNCTIONS]\n;ID\tElev
(ft)\tDemand
(gpm)\tPattern\n20\t20\t1\t3;\n30\t50\t1\t4;\n40\t50\t1\t5;\n50\t50\t1\t6;\n60\t50\t1\t8;\n70\t50\t1\t9;\n80\t50\t1\t11;\n90\t50\t1\t12;\n100\t50\t1\t13;\n110\t50\t1\t14;\n120\t120\t1\t16;\n130\t120\t1\t17;\n140\t80\t1\t18;\n150\t120\t1\t19;\n160\t120\t1\t20;\n170\t120\t1\t21;\n\n[RESERVOIRS]\n;ID\tHead\tPattern\n10\t10;\n\n[TANKS]\n;ID\tElevation\tInit
Level\tMinLevel\tMaxLevel\tDiameter\tMinVol\tVolCurve\n65\t215\t\t10\t35\t16.3\t0;\n165\t215\t\t10\t35\t16.3\t0;\n\n[PIPES]\n;ID\tNode1\tNode2\tLength\tDiameter\tRoughness\tMinorLoss\tStatus\n2\t20\t70\t12000\t16\t70\t0\tOpen;\n4\t20\t30\t12000\t12\t120\t0\tOpen;\n6\t20\t110\t12000\t12\t70\t0\tOpen;\n8\t70\t30\t9000\t12\t70\t0\tOpen;\n10\t70\t100\t6000\t12\t70\t0\tOpen;\n12\t70\t90\t6000\t10\t70\t0\tOpen;\n14\t70\t60\t6000\t12\t70\t0\tOpen;\n16\t90\t60\t6000\t10\t70\t0\tOpen;\n18\t60\t80\t6000\t12\t70\t0\tOpen;\n20\t90\t80\t6000\t10\t70\t0\tOpen;\n22\t90\t150\t6000\t10\t70\t0\tOpen;\n24\t90\t100\t6000\t10\t70\t0\tOpen;\n26\t100\t150\t6000\t12\t70\t0\tOpen;\n28\t150\t80\t6000\t10\t70\t0\tOpen;\n30\t60\t30\t6000\t10\t120\t0\tOpen;\n32\t30\t40\t6000\t10\t120\t0\tOpen;\n34\t30\t50\t9000\t10\t120\t0\tOpen;\n36\t40\t50\t6000\t10\t120\t0\tOpen;\n38\t50\t80\t6000\t10\t120\t0\tOpen;\n40\t80\t140\t6000\t10\t120\t0\tOpen;\n42\t150\t140\t6000\t8\t120\t0\tOpen;\n44\t150\t160\t6000\t8\t120\t0\tOpen;\n46\t100\t160\t6000\t8\t120\t0\tOpen;\n48\t100\t110\t6000\t8\t70\t0\tOpen;\n50\t110\t160\t6000\t10\t120\t0\tOpen;\n52\t110\t120\t6000\t8\t120\t0\tOpen;\n56\t120\t130\t6000\t8\t120\t0\tOpen;\n58\t130\t160\t6000\t10\t120\t0\tOpen;\n60\t130\t170\t6000\t8\t120\t0\tOpen;\n62\t160\t140\t6000\t8\t120\t0\tOpen;\n64\t170\t140\t12000\t80\t120\t0\tOpen;\n66\t50\t140\t12000\t8\t120\t0\tOpen;\n78\t60\t65\t100\t12\t120\t0\tOpen;\n80\t165\t160\t100\t12\t120\t0\tOpen;\n\n[PUMPS]\n;ID\tNode1\tNode2\tParameters\n82\t10\t20\tHEAD
1;\n\n[PATTERNS]\n;ID\tMultipliers\n;Demand
Pattern\n2\t1\n2\t1\n;Injection\n1\t1\t1\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n1\t0\t0\t0\t0\t0\t0\n;Demand
Change\n3\t500\t500\t500\t500\t500\t500\n3\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f
%The variables are placed into the input file wherever there is a%12.7f
```

262

\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n3\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t200\t200\t200\t200\t200\t200\n4\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n4\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t200\t200\t200\t200\t200\t200\n5\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n5\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t200\t200\t200\t200\t200\t200\n6\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n6\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n7\t0\t0\t0\t0\n7\t0\t0\t0\t0\t0\t0\n8\t500\t500\t500\t500\t500\t500\n8\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n8\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t500\t500\t500\t500\t500\t500\n9\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n9\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n10\t0\t0\t0\t0\t0\t0\n11\t500\t500\t500\t500\t500\t500\n11\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n11\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t1000\t1000\t1000\t1000\t1000\t1000\n12\t1000\t1000\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n12\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t500\t500\t500\t500\t500\t500\n13\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n13\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t500\t500\t500\t500\t500\t500\n14\t500\t500\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%

12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n14\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n15\t0\t0\t0\t0\t0\t0\n16\t200\t200\t200\t200\t200\t200\n16\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n16\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t200\t200\t200\t200\t200\t200\n17\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n17\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t200\t200\t200\t200\t200\t200\n18\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n18\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t200\t200\t200\t200\t200\t200\n19\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n19\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t800\t800\t800\t800\t800\t800\n20\t800\t800\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n20\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t200\t200\t200\t200\t200\t200\n21\t200\t200\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n21\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\t%12.7f\n\n[CURVES]\n;ID\tX-Value\tY-Value\n;PUMP: Pump Curve for Pump 9\n1\t0\t300\n1\t2000\t292\n1\t4000\t270\n1\t6000\t230\n1\t8000\t181\n\n[CONTROLS]\nLINK 2 %s AT CLOCKTIME 4 AM\nLINK 4 %s AT CLOCKTIME 4 AM\nLINK 6 %s AT CLOCKTIME 4 AM\nLINK 8 %s AT CLOCKTIME 4 AM\nLINK 10 %s AT CLOCKTIME 4 AM\nLINK 12 %s AT CLOCKTIME 4 AM\nLINK 14 %s AT CLOCKTIME 4 AM\nLINK 16 %s AT CLOCKTIME 4 AM\nLINK 18 %s AT CLOCKTIME 4 AM\nLINK 20 %s AT CLOCKTIME 4 AM\nLINK 22 %s AT CLOCKTIME 4 AM\nLINK 24 %s AT CLOCKTIME 4 AM\nLINK 26 %s AT CLOCKTIME 4 AM\nLINK 28 %s AT CLOCKTIME 4 AM\nLINK 30 %s AT CLOCKTIME 4 AM\nLINK 32 %s AT CLOCKTIME 4 AM\nLINK 34 %s AT CLOCKTIME 4 AM\nLINK 36 %s AT CLOCKTIME 4 AM\nLINK 38 %s AT CLOCKTIME 4 AM\nLINK 40 %s AT CLOCKTIME 4 AM\nLINK 42 %s AT

CLOCKTIME 4 AM\nLINK 44 %s AT CLOCKTIME 4 AM\nLINK 46 %s AT CLOCKTIME 4 AM\nLINK 48 %s AT CLOCKTIME 4 AM\nLINK 50 %s AT CLOCKTIME 4 AM\nLINK 52 %s AT CLOCKTIME 4 AM\nLINK 56 %s AT CLOCKTIME 4 AM\nLINK 58 %s AT CLOCKTIME 4 AM\nLINK 60 %s AT CLOCKTIME 4 AM\nLINK 62 %s AT CLOCKTIME 4 AM\nLINK 64 %s AT CLOCKTIME 4 AM\nLINK 66 %s AT CLOCKTIME 4 AM\n\n\n[ENERGY]\nGlobal Efficiency\t65\nGlobal Price\t0.0\nDemand Charge\t0.0\n\n[QUALITY]\n;Node\tInitQual\n20\t0\n30\t0\n40\t0\n50\t0\n55\t0\n60\t0\n70\t0\n75\t0\n80\t0\n90\t0\n100\t0\n110\t0\n115\t0\n120\t0\n130\t0\n140\t0\n150\t0\n160\t0\n170\t0\n10\t0\n65\t0\n165\t0\n\n[SOURCES]\n;Node\tType\tQuality\tPattern\n30\tFLOWPACED\t2.0\t1\n\n[REACTIONS]\n;Type\n\n[REACTIONS]\nOrder Bulk\t0\nOrder Tank\t0\nOrder Wall\t0\nGlobal Bulk\t0\nGlobal Wall\t0\nLimiting Potential\t0.0\nRoughness Correlation\t0.0\n\n[MIXING]\n;Tank\n\n[TIMES]\nDuration\t24:00:00\nHydraulic Timestep\t0:30\nQuality Timestep\t0:30\nPattern Timestep\t0:30\nPattern Start\t0:00\nReport Timestep\t0:30\nReport Start\t0:00\nStart ClockTime\t12:00 AM\nStatistic\tNone\n\n[REPORT]\nStatus\tNo\nSummary\tNo\nPage\t0\nMessages\tNo\nNodes\t20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170;\nDEMAND\tNo\nHEAD\tNo\nPRESSURE\tNo\nQUALITY\tPRECISION 10\nLinks\tNone\n\n[OPTIONS]\nUnits\tGPM\nHeadloss\tH-W\nSpecific Gravity\t1.0\nViscosity\t1.0\nTrials\t40\nAccuracy\t0.001\nUnbalanced\tContinue 10\nPattern\t1\nDemand Multiplier\t1.0\nEmitter Exponent\t0.5\nQuality\tChemical mg/L\nDiffusivity\t0\nTolerance\t0.01\n\n[END]',d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d
%d# variables that are placed into the %12.7f spots in the input file
%v# variables that are placed into the %s spots in the input file
1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d1,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d2,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d3,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d4,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d5,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d6,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d7,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d8,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d9,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d10,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d11,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d12,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d13,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,

```matlab
d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d14,d15,d15,d1
5,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,
d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d15,d16,d16,d16,d1
6,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,
d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,d16,v1,v2,v3,v4,v5,v6,v
7,v8,v9,v10,v11,v12,v13,v14,v15,v16,v17,v18,v19,v20,v21,v22,v23,v24,v25,v26,v27,v2
8,v29,v30,v31,v32);
%Command to close the file being changed
fclose(fid);
%Command to run EPANET
!epanet.exe

%Reads output file to see if any error messages were reported in simulation
[mesg1,mesg2]=textread('anytown1.rpt','%s %s',1,'headerlines',11,'endofline','\r\n');

%Compares variable mesg1 to Node, if they are the same then linetitle1 is equal to 1
linetitle1 = strcmp(mesg1, 'Node');
%Compares variable mesg2 to Results, if they are the same then linetitle2 is equal to 1
linetitle2 = strcmp(mesg2, 'Results');
 %Adds the two variables together
disconnect = linetitle1+linetitle2;

%If disconnect is equal to zero then error messages were reported and therefore
%the nonlinear constraint was not met and ceq is equal to one
%In terms of reality, the error message means that the system was disconnected or
%caused negative pressures
if disconnect==0
    ceq=1;
else
    ceq=0;
end
```

REFERENCES

106th U.S. Congress, Subcommittee on Water Resources and Environment Hearing, "Terrorism: Are America's Water Resources and Environment at Risk?" 10 October 2001.

American Institute of Chemical Engineers (AIChE). (1995). *Guidelines for Chemical Transportation Risk Analysis*. Center for Chemical Process Safety (CCPS). Wiley-AIChE.

Al-qurashi, F. (2004). "New vision of emergency response planning." Process Safety Progress **23**(1): 56-61.

Andreev, I., M. Hittenberger, et al. (1998). "Risks due to beyond design base accidents of nuclear power plants in Europe - the methodology of riskmap." Journal of Hazardous Materials **61**(1-3): 257-262.

Association of Metropolitan Sewerage Agencies (AMSA). (2003). Vulnerability Self-Assessment Tool (VSAT). Available at: http://www.vsatusers.net/index.html.

Awwa Research Foundation (AwwaRF) and Sandia National Laboratories. (2002). Risk Assessment Methodology for Water Utilities (RAM-W). Second Edition, Awwa Research Foundation, Denver, CO.

Axworthy, D. H. and B. W. Karney. (1996). "Modeling Low Velocity/High Dispersion Flow In Water Distribution Systems." *Journal of Water Resources Planning and Management*, 122(3), 218 - 221.

Baginska, B., W. Milne-Home and P. S. Cornish. (2003). "Modelling nutrient transport in Currency Creek, NSW with AnnAGNPS and PEST." *Environmental Modelling & Software*, 18(8-9), 801-808.

Bahadur, R., W.B. Samuels, et al. (2003). "PipelineNet: A Model for Monitoring Introduced Contaminants in a Distribution System." *Proc., World Water & Environmental Resources Congress 2003,* (CD-ROM), ASCE, Reston, VA.

Baklanov, A. A. and A. G. Mahura (2004). "Assessment of possible airborne impact from risk sites: methodology for probabilistic atmospheric studies." Atmospheric Chemistry and Physics **4**: 485-495.

Baranowski, T. M. and E. J. LeBoeuf. (2006). "Consequence management detection optimization for contaminant and isolation." *Journal of Water Resources Planning and Management-Asce*, 132(4), 274-282.

Baranowski, T. M. and E. J. LeBoeuf. (*in review*). "Consequence management utilizing optimization." *Journal of Water Resources Planning and Management-Asce, in review*.

Bentley Systems. (2003). *WaterCAD: Water Distribution System Modeling Software. 6.* Watertown, CT: Haestad Methods Solution Center.

Bentley Systems. (2007). *WaterGEMS: Water Distribution Modeling and Management Software.* Watertown, CT: Haestad Methods Solution Center.

Berry, J., W. E. Hart, C. A. Phillips, J. G. Uber and J. P. Watson. (2006). "Sensor placement in municipal water networks with temporal integer programming models." *Journal of Water Resources Planning and Management-Asce*, 132(4), 218-224.

Cech, I. and J. Montera. (2000). "Spatial variations in total aluminum concentrations in drinking water supplies studied by geographic information system (GIS) methods." *Water Research*, 34(10), 2703-2712.

Chang, N.-B., Y. L. Wei, et al. (1997). "The Design of a GIS-Based Decision Support System for Chemical Emergency Preparedness and Response in an Urban Environment." Computers, Environment and Urban Systems **21**(1): 67-94.

Clark, R.M., E.E. Geldreich, et al. (1996). 'A Waterborne Salmonella typhimurium Outbreak in Gideon, Missouri: Results from a Field Investigation." International Journal of Environmental Health Research 6: 187-193.

Cullinane, M. J., K. E. Lansey, et al. (1992). "Optimization-Availability-Based Design of Water-Distribution Networks." Journal of Hydraulic Engineering **118**(3): 420-441.

Cunha, M. D. and J. Sousa (1999). "Water distribution network design optimization: Simulated annealing approach." Journal of Water Resources Planning and Management-Asce **125**(4): 215-221.

Dangendorf, F., S. Herbst, R. Reintjes and T. Kistemann. (2002). "Spatial patterns of diarrhoeal illnesses with regard to water supply structures - a GIS analysis." *International Journal of Hygiene and Environmental Health*, 205(3), 183-191.

Danneels, J. J. and R. E. Finley. (2004). "Assessing the Vulnerabilities of U.S. Drinking Water Systems." *Journal of Contemporary Water Research and Education*, (129), 8-12.

DeNileon, G. P. (2001). "The who, what, why, and how of counterterrorism issues." *Journal American Water Works Association*, 93(5), 78-+.

Dobson, J. E., E. A. Bright, et al. (2000). "LandScan: A global population database for estimating populations at risk." Photogrammetric Engineering and Remote Sensing **66**(7): 849-857.

Doherty, J. (2003). "Ground water model calibration using pilot points and regularization." *Ground Water*, 41(2), 170-177.

Doherty, J. (2004a). "PEST - Model Indepedent Parameter Estimation, User's Manual. 5th." Brisbane, Australia: Watermark Numerical Computing. <http://www.sspa.com/pest>

Doherty, J. (2004b). *PEST-Model Independent Parameter Estimation. 9.* Brisbane, Australia: Watermark Numerical Computing. <http://www.sspa.com/pest>

Doherty, J. and J. M. Johnston. (2003). "Methodologies for calibration and predictive analysis of a watershed model." *Journal of the American Water Resources Association*, 39(2), 251-265.

ESRI. (2001). *Dictionary of GIS Terminology*. ESRI Press, Redlands, CA.

Eusuff, M. M. and K. E. Lansey (2003). "Optimization of water distribution network design using the Shuffled Frog Leaping Algorithm." Journal of Water Resources Planning and Management-Asce **129**(3): 210-225.

Galmarini, S., R. Bianconi, et al. (2001). "Forecasting the consequences of accidental releases of radionuclides in the atmosphere from ensemble dispersion modelling." Journal of Environmental Radioactivity **57**(3): 203-219.

Goldberg, D. E. (1989). *Genetic Algorithms in Search, Optimization and Machine Learning*. Kluwer Academic Publishers, Boston, MA.

Haestad, M., T. M. Walski, D. V. Chase, D. A. Savic, W. Grayman, S. Beckwith, E. Koelle. (2003). *Advanced Water Distribution Modeling and Management*. Haestad Press, Waterbury, CT. 673-677.

Haldar, A. and S. Mahadevan. (2000). *Reliability Assessment Using Stochastic Finite Element Analysis*. John Wiley & Sons, Inc., New York.

Holland, J. H. (1975). *Adaptation in Natural and Artificial Systems*. University of Michigan Press, Ann Arbor, MI.

Islam, M. R. and M. H. Chaudhry. (1998). "Modeling Of Constituent Transport In Unsteady Flows In Pipe Networks." *Journal of Hydraulic Engineering*, 124(11), 1115 - 1124.

Kessler, A., A. Ostfeld and G. Sinai. (1998). "Detecting accidental contaminations in municipal water networks." *Journal of Water Resources Planning and Management-Asce*, 124(4), 192-198.

Kirkpatrick, J. S., J. M. Howard, et al. (2002). "Assessing homeland chemical hazards outside the military gates: industrial hazard threat assessments for department of defense installations." Science of the Total Environment **288**(1-2): 111-117.

Kistemann, T., S. Herbst, F. Dangendorf and M. Exner. (2001). "GIS-based analysis of drinking-water supply structures: a module for microbial risk assessment." *International Journal of Hygiene and Environmental Health*, 203(4), 301-310.

Kumar, A., M. L. Kansal and G. Arora. (1997). "Identification of monitoring stations in water distribution system." *Journal of Environmental Engineering-Asce*, 123(8), 746-752.

Laird, C. D., L. T. Biegler and B. Waanders. (2006). "Mixed-integer approach for obtaining unique solutions in source inversion of water networks." *Journal of Water Resources Planning and Management-Asce*, 132(4), 242-251.

Maier, H. R., A. R. Simpson, A. C. Zecchin, W. K. Foong, K. Y. Phang, H. Y. Seah and C. L. Tan. (2003). "Ant colony optimization distribution for design of water systems." *Journal of Water Resources Planning and Management-Asce*, 129(3), 200-209.

Maier, H. R., B. J. Lence, B. A. Tolson and R. O. Foschi. (2001). "First-order reliability method for estimating reliability, vulnerability, and resilience." *Water Resources Research*, 37(3), 779-790.

Martin, P. H., E. J. LeBoeuf, et al. (2004). "Development of a GIS-based Spill Management Information System." Journal of Hazardous Materials **112**(3): 239-252.

MathWorks. (2006). *MATLAB. 7.2.0.232 (R2006a)*. Natick, Massachusetts:

Mays, L. W., Ed. (2000). *Water Distribution Systems Handbook*. McGraw-Hill, New York.

Murray, R., R. Janke, et al. (2004). "The Threat Ensemble Vulnerability Assessment (TEVA) Program for Drinking Water Distribution System Security." *Proc., World Water & Environmental Resources Congress 2004,* (CD-ROM), ASCE, Reston, Va.

Murray, V. and F. Goodfellow (2002). "Mass casualty chemical incidents - towards guidance for public health management." Public Health **116**(1): 2-14.

MWH Soft. (2007). *H₂OMap Water*. Broomfield, CO.

National Oceanic and Atmospheric Administration (NOAA). (2004). General NOAA Oil Modeling Environment (GNOME). Available at: http://response.restoration.noaa.gov/software/gnome/gnome.html.

Nilsson, K. A., S. G. Buchberger and R. M. Clark. (2005). "Simulating exposures to deliberate intrusions into water distribution systems." *Journal of Water Resources Planning and Management-Asce*, 131(3), 228-236.

Nivolianitou, Z. S. (1998). "Hazard review of a pesticides formulation plant and consequence assessment of accident scenarios in it." Journal of Loss Prevention in the Process Industries **11**(2): 123-134.

ORNL, O. R. N. L. (2000). *LandScan 2000 Global Population Database.* Oakridge, TN: Oak Ridge National Laboratory. <http://sedac.ciesin.columbia.edu/plue/gpw/landscan>

Ostfeld, A. and E. Salomons. (2004). "Optimal layout of early warning detection stations for water distribution systems security." *Journal of Water Resources Planning and Management-Asce*, 130(5), 377-385.

Parris, T. M. (2002). "Tools for Environmental Emergency Response." *Environment*, 44(8), 3-4.

Pechinger, U., M. Langer, et al. (2001). "The Austrian emergency response modelling system TAMOS." Physics and Chemistry of the Earth Part B-Hydrology Oceans and Atmosphere **26**(2): 99-103.

Poulin, A., A. Mailhot, P. Grondin, L. Delorme and J. Villeneuve. (2006). Optimization of Operational Response to Contamination in Water Networks. 8th Annual Water Distribution Systems Analysis Symposium, Cincinnati, OH.

Preis, A. and A. Ostfeld. (2006). "Contamination source identification in water systems: A hybrid model trees-linear programming scheme." *Journal of Water Resources Planning and Management-Asce*, 132(4), 263-273.

Propato, M. (2006). "Contamination warning in water networks: General mixed-integer linear models for sensor location design." *Journal of Water Resources Planning and Management-Asce*, 132(4), 225-233.

Propato, M. and J. G. Uber. (2004). "Vulnerability of water distribution systems to pathogen intrusion: How effective is a disinfectant residual?" *Environmental Science & Technology*, 38(13), 3713-3722.

Rackwitz, R. and B. Fiessler. (1978). "Structural Reliability under Combined Random Load Sequences." *Computers & Structures*, 9(5), 489-494.

Rigas, F. and S. Sklavounos (2002). "Risk and consequence analyses of hazardous chemicals in marshalling yards and warehouses at Ikonio/Piraeus harbour, Greece." Journal of Loss Prevention in the Process Industries **15**(6): 531-544.

Rossman, L. A. (2000). "EPANET 2.0, User's Manual. Cincinnati, OH: National Risk Management Research Laboratory, U.S. EPA. <http://www.epa.gov/ORD/NRMRL/wswrd/epanet.html>

Rossman, L. A. and P. F. Boulos. (1996). "Numerical Methods For Modeling Water Quality In Distribution Systems: A Comparison." *Journal of Water Resources Planning and Management*, 122(2), 137 - 146.

Sadiq, R., Y. Kleiner and B. Rajani. (2006). "Estimating risk of contaminant intrusion in water distribution networks using Dempster-Shafer theory of evidence." *Civil Engineering and Environmental Systems*, 23(3), 129-141.

Savic, D. A. and G. A. Walters. (1997). "Genetic algorithms for least-cost design of water distribution networks." *Journal of Water Resources Planning and Management-Asce*, 123(2), 67-77.

Science Applications International Corporation (SAIC). (2003). RiverSpill. Available at: http://eh2o.saic.com/iwqss/.

Sinske, S. A. and H. L. Zietsman. (2004). "A spatial decision support system for pipe-break susceptibility analysis of municipal water distribution systems." *Water Sa*, 30(1), 71-79.

Tolson, B. A., H. R. Maier, A. R. Simpson and B. J. Lence. (2004). "Genetic algorithms for reliability-based optimization of water distribution systems." *Journal of Water Resources Planning and Management-Asce*, 130(1), 63-72.

Tzatchkov, V. G., A. A. Aldama and F. I. Arreguin. (2002). "Advection-Dispersion-Reaction Modeling in Water Distribution Networks." *Journal of Water Resources Planning and Management*, 128(5), 334 - 342.

Uber, J., R. Murray and R. Janke. (2004). "Use of Systems Analysis to Assess and Minimize Water Security Risks." *Journal of Contemporary Water Research and Education*, (129), 34-40.

U.S. Department of Transportation (DOT). (2004). "2004 Emergency Response Guidebook." Available at http://hazmat.dot.gov/pubs/erg2004/gydebook.htm.

U.S. EPA. (1997). Hydrocarbon Spill Screening Model (HSSM). Available at: http://www.epa.gov/ada/csmos/models/hssmwin.html

U.S. EPA. (2002). *EPANET 2.0.* Cincinnati, OH: National Risk Management Research Laboratory, U.S. EPA. <http://www.epa.gov/ORD/NRMRL/wswrd/epanet.html>

U.S. EPA. (2002). "EPA Needs to Assess the Quality of Vulnerability Assessments Related to the Security of the Nation's Water Supply." Office of Inspector General Report No. 2003-M-00013, September 24, 2003. Available at: http://www.epa.gov/oig/reports/2003/Report2003M000013.pdf.

U.S. EPA. (2003). Response Protocol Toolbox: Planning for and Responding to Drinking Water Contamination Threats and Incidents - Overview and Application, US Environmental Protection Agency.

U.S. EPA. (2004a). Response Protocol Toolbox: Planning for and Responding to Drinking Water Contamination Threats and Incidents - Module 5: Public Health Response Guide, US Environmental Protection Agency.

U.S. EPA. (2004b). Response Protocol Toolbox: Planning for and Responding to Drinking Water Contamination Threats and Incidents - Module 6: Remediation and Recovery Guide, US Environmental Protection Agency.

U.S. EPA. (2004c). "EPA's Role in Water Security Research: The Water Security Research and Technical Support Action Plan." Available at: http://www.epa.gov/safewater/watersecurity/pubs/water_exec_summ.pdf.

U.S. EPA. (2004d). Computer-Aided Management of Emergency Operations (CAMEO). Available at: http://www.epa.gov/ceppo/cameo/index.htm

Walski, T. M. (2001). "Water Distribution Models for Emergency Response." *Water Security Summit Proceedings*. Haestad Press, Waterbury, CT. 259-269.

Walski, T. M., E. D. Brill, J. Gessler, I. C. Goulter, R. M. Jeppson, K. Lansey, H. L. Lee, J. C. Liebman, L. Mays, D. R. Morgan and L. Ormsbee. (1987). "Battle of the Network Models - Epilogue." *Journal of Water Resources Planning and Management-Asce*, 113(2), 191-203.

Wu, Z. Y. and A. R. Simpson. (2001). "Competent genetic-evolutionary optimization of water distribution systems." *Journal of Computing in Civil Engineering*, 15(2), 89-101.

Xu, C. G., I. C. Goulter and K. S. Tickle. (2003). "Assessing the capacity reliability of ageing water distribution systems." *Civil Engineering and Environmental Systems*, 20(2), 119-1